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Abstract

In Thailand, cassava waste is one of the main biomass residues and has the potential to be used as a biomass fuel. However, currently, most cassava waste in Thailand is left in the agricultural fields or burnt on site and is not utilised for any energy-related purposes. This research investigates the environmental impacts associated with three Cassava Waste Management practices which include: i) ploughing the waste to the soil, ii) burning the waste in the field, iii) collecting and using the waste in cassava-based bioethanol plant. The environmental impact assessment and material flow analysis associated with these management practices were conducted using the Global Emissions Model for Integrated Systems (GEMIS) package. The outcomes of this study reveal that the CO_2 emissions associated with these waste management practices are about 0.195, 0.243 and 0.361 kg CO_2-eq/kg of as received (wet) cassava waste, respectively. Compared to other cassava waste disposal methods such as ploughing and burning, cassava waste collection would result in the most significant environmental impact, emitting nearly 85% more GHGs than ploughing and 48% more than burning.

Keywords: Plant, environmental impact

1 Introduction

Cassava (Manihot esculenta Crantz.), commonly known as 'tapioca,' is one of Thailand's four main agricultural products, alongside rice, sugarcane and palm oil. In recent years, Thailand has been ranked the second largest global cassava producer, next to Nigeria (29.85 MT and 54 MT in 2012, respectively),[1]. According to the Office of Agricultural Economics (OAE), Thailand produces approximately 24 million tonnes of cassava annually, with a yield of 0.52 tonnes per hectare [2]. Besides rice, cassava is Thailand's second largest agricultural export, which ranked as the fourth most important economic crop behind rice, rubber and sugarcane [1]. As is one of the main feedstocks for the production of bioethanol, the cassava waste could potentially be used as a processing fuel. To examine the potential benefits in terms of emissions, this field of work is concerned with an environmental impact assessment associated with the production and collection of cassava waste.

1.1 Cassava waste

The most commonly used part of the Cassava plant is the root, which is primarily employed for industrial and commercial purposes and as a feedstock for bioethanol production. Cassava stems and rhizomes are not typically used, and thus ends up as waste. By weight, the cassava stem and rhizome comprise 9% and 20% of the cassava plant respectively. In 2009, Thailand's agricultural economics office reported that more than 4 million tonnes of cassava waste remained annually in the agrarian fields [3].

Typically, 20% of cassava stem residue is collected for use as planting stock, 29% is employed as fertiliser, and nearly 10% is lost during harvest. As a result, almost 41% of total cassava stem production, remains unused. Similarly, the rhizomes of the cassava plant are not employed for any practical purpose, as their hard shells contain a high percentage of silica, making them difficult to break [4]. Farmers normally dispose of cassava rhizomes by ploughing them into the soil (23%) or burning them in situ (66%). However, the collection and combustion/co-firing of the 66% of cassava rhizomes which are typically burnt in Thai fields (2.89 million tonnes) could potentially generate up to 146.77MWh of electricity per year [4].

1.2 Cassava waste composition and characteristics

Both the physical and chemical characteristics of biomass present significant challenges for energy conversion [5]. Cassava waste properties have been investigated in previous studies. Some of their results regarding the fuel properties of cassava waste (including ultimate and proximate analyses) are provided in Table 1. Also, Yin, Rosendahl [6] suggested that biomass characteristics, including those of cassava waste, typically vary by location, climate and species.

Compared with fossil fuels, cassava waste also has a relatively high moisture content and therefore a significantly lower calorific value and bulk density. On a dry basis, the calorific value of cassava stems and rhizomes are approximately 17.34 and 17.62 $MJ.kg^{-1}$, respectively [7], which is lower than the heating value of lignite coal (27-31 $MJ.kg^{-1}$) and oil (42.5 $MJ.kg^{-1}$) [8]. However, cassava waste exhibits a comparable heating value with other biomass residues.

In terms of its properties (i.e. proximate analysis), the composition of cassava waste is similar to other biomass residues, such as

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wood chips, palm oil shells and bagasse. However, some of these properties may vary, as shown in Table 2 [9]. Also, Pattiya, Titiloye [10] demonstrated that when compared to other biomass residues, cassava rhizome exhibits a comparable calorific value and volatiles content (77.7% on a dry weight basis), is easier to convert to gas, and has a higher carbon content. However, the shells of cassava rhizomes contain a large quantity of silica which is difficult to ignite [4, 11].

It should be noted that Cassava rhizomes and stems relatively contains low alkali and chlorine (0.122%) [7] and low nitrogen, sulphur and ash content (1.27 %, <0.1 % and 4.05% on the dry weight basis, respectively). The nitrogen, sulphur, carbon and ash contents of fuels directly affect the greenhouse gas (GHG) emissions, corrosion levels and ash deposition [12].

Table 1 Comparison of as received (wet) cassava waste analysis from the literature

Reference	Type	Moisture	Volatile Matter	Fixed Carbon	Ash	Carbon	Hydrogen	Nitrogen	Oxygen	Sulphur	HHV	LHV
		(wt%, dry basis)				(wt%, dry ash free basis)					(MJ/kg, dry basis)	
(Pattya et al., 2006; Pattiya et al., 2008)	Cassava rhizome	8.31	77.75	18.20	4.05	51.59	6.69	2.17	40.45	<0.1	23.67	18.47
	Cassava stem	15.54	79.90	14.09	60.1	51.12	6.87	0.67	41.34	<0.1	17.99	17.58
(Pattya et al., 2006; Pattiya et al., 2008)	Cassava rhizome	8.31	71.29	16.69	3.71	51.59	6.69	1.27	40.45	<0.1	-	-
(Arjhan, 2001)	Cassava rhizome	1.80	75.80	14.00	8.40	46.12	7.55	1.13	57.83	0.03	-	14.74
(DEDE, 2006)	Cassava rhizome	-	75.00	-	5.60	-	-	-	-	0.08	17.48	-
	Cassava rhizome	62.30	74.20	14.90	11.58	-	-	-	-	<0.01	8.28	6.87
	Cassava stem	59.30	72.00	12.80	12.94	-	-	-	-	<0.01	7.34	6.01
(FINPRO, 2002)	Cassava rhizome	-	75.30	-	5.6	46.9	5.73	0.78	40.73	0.082	-	17.62
	Cassava stem	-	77.00	-	5.1	46.9	5.94	0.79	40.98	0.07	-	17.34
(DEDE, 2009)	Cassava rhizome	-	-	-	-	-	-	-	-	-	-	10.61
	Cassava stem	-	-	-	-	-	-	-	-	-	-	13.38
(TISTR, 2009)	Cassava stem	-	-	-	-	-	-	-	-	-	-	17.39
	Cassava root	-	-	-	-	-	-	-	-	-	-	18.42
(Jarinee and Kiatfa, 2011)	Cassava rhizome	34.73	53.49	8.23	3.55	-	-	-	-	-	-	11.64

Table 2 Composition and characteristics of biomass produced in Thailand [9]

Proximate Analysis	Rice Husk	Rice straw	Bagasse	Sugarcane leaf	Rubber stem	palm fiber	palm sheel	Palm empty bunch	palm tree	palm leaf	Corn cob	Corn stem	Cassava rhizome	Eculyptus
Moisture, %	12	10	50.73	9.2	45.00	38.50	12	58.6	48.4	78.4	40	41.7	59.4	60
Ash, %	12.65	10.39	1.43	6.1	1.59	4.42	68.2	30.46	38.7	0.7	45.42	46.46	1.5	2.44
Volatile Matter, %	56.46	60.7	41.98	67.8	45.7	42.68	68.2	30.46	38.7	16.3	45.42	46.46	31	28
Fixed Carbon, %	18.88	18.9	5.86	16.9	7.71	14.39	16.3	8.9	11.7	4.6	13.68	8.14	8.1	9.56
Ultimate Analysis														
Carbon, %	37.48	38.17	21.33	41.6	25.58	30.82	44.14	21.15	23.9	10.13	28.19	27.83	18.76	18.6
Hydrogen, %	4.41	5.02	3.06	5.08	3.19	3.74	5.01	2.56	3.04	1.25	3.36	4.06	2.48	2.12
Oxygen, %	33.27	35.28	23.29	37.42	24.48	21.61	34.7	15.34	22.91	9.44	27.42	22.47	17.5	16.68
Nitrogen, %	0.17	0.58	0.12	0.4	0.14	0.84	0.28	0.27	0.56	0.07	0.12	0.13	0.32	0.15
Sulfur, %	0.04	0.09	0.03	0.17	0.02	0.08	0.02	0.04	0.06	0.02	0.03	na	0.04	0.02
Chlorine, %	0.09	na	na	0.01	0.01	0.11	0.02	0.16	na	0.12	0.05	na	0.05	0.1
Ash, %	12.56	10.39	1.43	6.1	1.6	4.42	3.52	2.03	1.2	0.7	0.9	3.7	1.5	2.44
Moisture, %	12	10	50.73	9.2	45	38.5	12	58.6	48.4	78.4	40	41.7	59.4	60
Other Characteristics														
Bulk Density, Kg/m3	150	125	120	100	450	250	400	380	na	na	na	na	250	na
Higher heating value, kj/kg	14,755	13,650	9,243	16,794	10,365	13,127	18,267	9,196	9,370	3,908	11,298	11,704	7,451	6,811
Lower heating value, kj/kg	13,517	12,330	7,368	15,479	8,600	11,400	16,900	7,240	7,556	1,760	9,615	9,830	5,494	4,917

2 Bioethanol plants in Thailand

The main sources for bioethanol production in Thailand are cane molasses as a by-product of sugarcane production and cassava root [13]. Roughly 30% of cassava production is consumed domestically, and 60% is exported. Less than 10% of cassava produced is converted into bioethanol.

Department of Alternative Energy Development and Efficiency (DEDE) reported that 48 factories in Thailand are licensed to produce bioethanol, with a total production capacity of 12.5 million litres per day, or 4,125 million litres annually [14]. Of these 48 registered plants, 16 use molasses and have a total bioethanol production capacity of 2.89 million litres per day; 24 use cassava, with a total production capacity of 8.39 million litres/day; and the remaining eight use both feedstocks with a total bioethanol production capacity of 1.22 million litres/day [15]. Over 21 bioethanol plants are in operation, with a total capacity of over 4.19 million litres per day. These plants supply bioethanol that is mixed with gasoline to make bioethanol blended gasoline, or 'gasohol'.

In bioethanol production, most of the energy is consumed in the bioethanol conversion stage, which accounts for approximately 78% of total energy usage [16]. Furthermore, bringing additional Thai bioethanol plants online would also mean an increase in demand for imported fuel. Sriroth, Piyachomkwan [17] found that a 130,000 litre/day cassava-based bioethanol plant requires 25,000–47,000 kWh of electricity per day and 300-500 tonnes of steam, and emits approximately 120 tonnes of CO_2 daily.

3 Research design

This study aims to assess the environmental impacts associated with three different Cassava Waste Management practices. This assessment will help to identify opportunities to decrease the environmental impacts at various points in the life cycles of cassava farming processes and to support future decision-making with regards to the management of cassava waste.

Data for the environmental impact assessment was collected based on the energy and material inputs and outputs required to cultivate one hectare of cassava.

The system boundary chosen for this study comprises all field operations and diesel and fertiliser inputs used in the studied agricultural practices. The eight agricultural practices included in this study:

1. land preparation,
2. cultivation,
3. weed management,
4. disease control,
5. fertilisation application,
6. harvesting,
7. waste management and
8. transportation.

In this study three scenarios for the cassava waste production life cycle were assessed:

1. Scenario A: The current cassava farming practice, in which cassava waste is disposed of by ploughing it into the soil, thus contributing to the nutrient replenishment and soil health.
2. Scenario B: The most common current cassava farming practice, in which cassava waste is dried and burned in the field. This in-situ burning of cassava waste produces GHG emissions that exacerbate environmental impacts.
3. Scenario C: A new cassava farming practice, in which waste is collected and transported to cassava-based bioethanol plants factory gate (for co-firing).

Figure 1 summarises the system boundaries for cassava waste production used in this study. For this research, the cassava crop life cycle begins at land preparation and ends after its waste is transported to the gate of cassava-based bioethanol plants.

3.1 The environmental impact assessment

The inventory parameters in this study relate to the life cycle of cassava waste production for the above three waste management practices: ploughing (Scenario A), burning (Scenario B) and collection (Scenario C). To ensure the reliability of the study, varying methods and sources were used for data collection, including interviews, field data, research reports and relevant literature. Types of data collected include cassava cultivars, machinery employed, fertiliser and herbicide applications and transport systems. Data analysis included material and energy inputs and outputs for each cassava farming practice. Material and energy data were normalised to 1 kg of cassava waste.

The primary operation, material and energy inputs for the production of 1 kg of cassava waste are presented in Figure 1. This study also included subsystem boundaries, which encompassed the output of processing materials, such as fertiliser, pesticides and fuel for cassava farming practices, as well as the transportation of waste to the bioethanol plants.

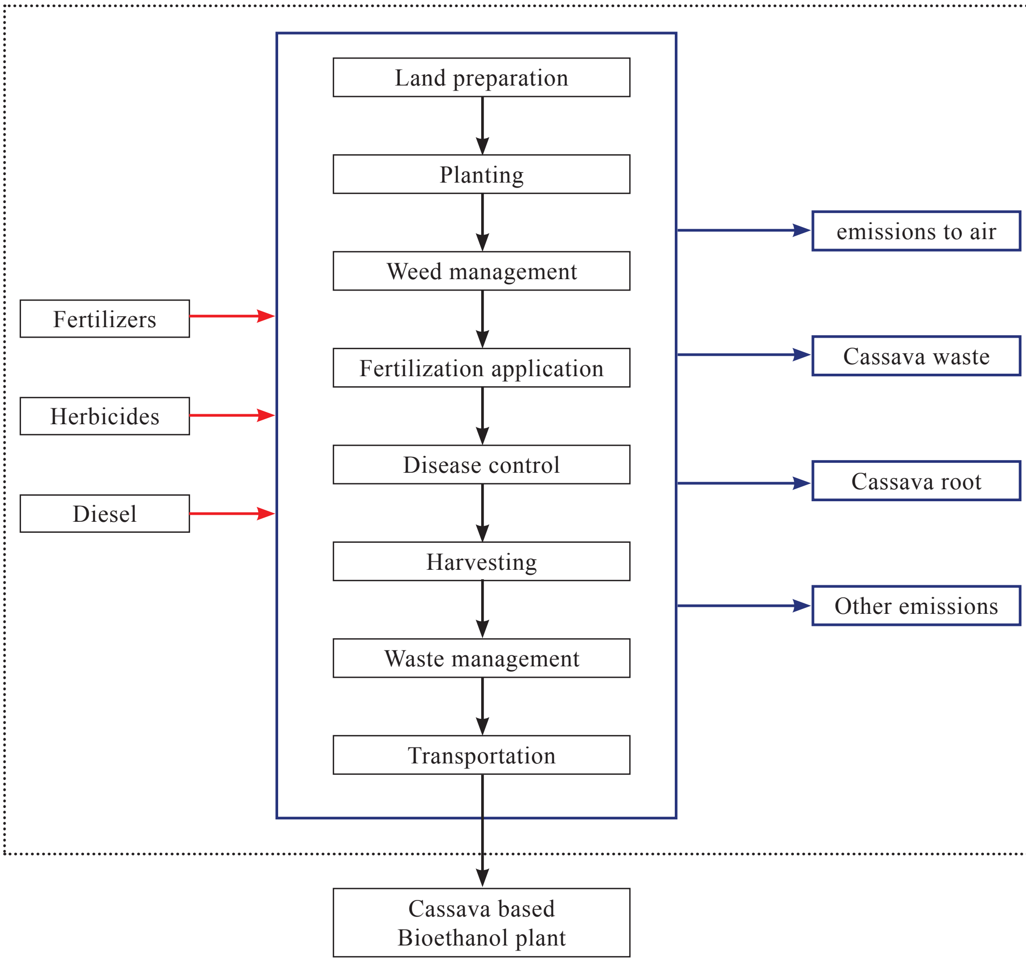


Figure 1 System boundary for cassava waste production. Here three waste management practices are studied i) ploughing the waste to the soil, ii) burning the waste in the field, iii) collecting and using the waste in cassava-based bioethanol plant.

3.2 Input and output inventory for cassava waste production

3.2.1 Site description

In 2013, the total Thai cassava harvest area comprised 1.446 million hectares, for which the average production yield was 0.559 tonnes per hectare [2]. Typically, most farmers grow cassava seasonally on the same fields without implementing the soil erosion control and applying sufficient fertiliser inputs. For the past several decades, this has led to a decline in soil productivity, leading to an imbalance of soil nutrients, a corresponding decrease in cassava yields and environmental degradation [18]. In Thailand, cassava is planted year-round, with the most abundant crop cultivated in May, followed by smaller crops at the end of the rainy season, during October or November [19]. Primary cassava farming practices in Thailand include land preparation, planting, fertilisation application, weed management, disease control, harvesting, waste management and transportation.

3.2.2 Land preparation

Land preparation practices differ due to the technology and techniques employed, level of agricultural expertise and soil type. In this study, for all the three scenarios it was assumed that tractors were used for ploughing, which requires one pass per field. Double ploughing (with 3-5-disk ploughs and 5-7 disk ploughs) and ridging methods were selected because of their common usage in the Thai cassava agriculture. Cassava farmers typically till once to a depth of 15-20cm to bury previous crop residues, and followed by harrowing the soil. For Scenario C, due to the nutrient losses when cassava waste is removed from the field, prior to cultivation 500 kg of chicken manure was applied to help restore soil nutrients [2, 20]. This study assumed a 10km distance by light truck for chicken manure delivery to cassava farms. Besides, when agricultural land is prepared in this manner, cassava stems can be planted directly in the soil, eliminating the need for furrows. The choice of the cultivation method is consistent with Thailand's Office of Agricultural Economics (OAE) guidance and literature [16, 21].

3.2.3 Planting

Cassava is cultivated from cassava stems stored from the previous crop or neighbours' fields. However, only 20% of the total cassava stems are removed from the field for propagation. Cassava is planted either on a flat or ridged grounds, depending upon precipitation, soil texture, the presence of weeds, method of harvest and tradition. The most common and effective approach to plant cassava in Thailand is by manually planting on flat areas with a spacing of 80-100cm × 80-100cm [2]. As a result, it is assumed for analysis that no fuel inputs are required for this process.

3.2.4 Fertiliser application

Each fertiliser type is applied according to specific requirements, including the desired yield, plant strength, etc. Fertiliser application techniques vary based on expertise, experience and budget, and the amount and frequency of application depending on soil quality. In general, fertiliser application practices for Thai cassava production include chemical fertilisers containing approximate N-P_2O_5-K_2O elemental mass fractions of 15–15–15, 13–13–21, or 15–7–18. Fertilisers are typically manually applied to plants after the first weeding of the cassava crop. The general fertiliser application recommendation for cassava is 50 kg/ha each of N, P_2O_5 and K_2O for fertile soils and 100 kg/ha of each nutrient for soils. Organic fertiliser is rarely used, with an application rate of only about 200–600 kg/ha typically applied as a base during field preparation [18]. Therefore, it is assumed that chemical fertiliser is applied once a year with no subsequent fertiliser applications. After the harvest, cassava roots and stems are generally removed from the field, whereas stock and leaves are ploughed into the soil. Cassava farmers seldom apply sufficient amounts of fertiliser or manure to replace the depleted soil nutrients [20, 22].

Cassava waste removal could potentially affect the soil conditions and nutrition, so 100 kg/ha of fertiliser was applied in Scenario C. Fertilizer production data were taken from the GEMIS database [23]. This study found no difference in required fertiliser inputs for Scenarios A and B as shown in Table 3. However, removing cassava waste from fields involves the application of more than twice the standard amount of fertilisers.

3.2.5 Weed management

The widely used herbicides, paraquat, glyphosate are commonly used on cassava farms for weed control. Generally, farmers weed their fields chemically 1–1.5 months and manually at 2 and 3 months again after planting, respectively. According to the information obtained through extensive interviews with Thai cassava farmers, they typically apply herbicides during the first weeding period in one pass using a sprayer with a 24m spray boom, but due to health concerns weeding is done manually on the second and third interval. Typically, farmers apply paraquat only once during the season, because absorbent herbicides can damage the cassava roots and reduce its yields. This study assumes that 0.94 kg/ha of paraquat and 2.2 kg/ha of glyphosate were applied for the baseline case. Scenario A (ploughing) increases the growth of weeds and unused stems in the cassava fields. Thus, under this scenario, more significant amounts of herbicides and time were required, as shown in Table 3. Emissions data for glyphosate production are assumed to be the same as those for paraquat production.

3.2.6 Disease control

Most Thai cassava farmers attempt to avoid pesticide use, as pesticides are toxic and expensive. They prefer to manually remove in diseased plants or allow rain to inhibit the pests. Thus, this study assumes that pesticides were not applied to cassava fields.

3.2.7 Harvesting

Various early matured cassava can be harvested about 9-12 months after planting. Other varieties, which contain a higher starch content, can be harvested 12-18 months after planting. Cassava harvest techniques depend on the farmer's expertise and experience. This study assumed that small tractors were used to harvest and collect the cassava crop. On average, the cassava harvest yields 21 tonnes per hectare [2] and stems are reused as stock to propagate the next crop.

3.2.8 Waste management

After the harvest, cassava waste is typically left in the field. By weight, this waste usually accounts for 20% of cassava production [3] or a yield of approximately 4.375 tonnes/ha. Currently, the main methods of Thai cassava waste management include ploughing (Scenario A) and burning (Scenario B) at 22% and 66%, respectively. These two methods are mostly preferred because they are inexpensive and efficient. Typically, tractors are used to crush cassava waste before ploughing it into the soil (Scenario A) to return the fields to their pre-cultivation state. This study assumed that for Scenario A, cassava fields were ploughed and disked once. According to the burning method (Scenario B), cassava waste is manually gathered and burned on the field. However, during the stem cutting process, cassava waste is generally piled in several locations. The introduction of the new cassava waste collection practice (Scenario C), could be applied in this case. Under this scenario, waste would manually be collected and loaded into a tractor or truck for transport to bioethanol plants.

3.2.9 Transportation

In Thailand, cassava root is sold either by weight or its starch content and is transported to buyers by using small tractors or trucks. Both of these vehicles can accommodate approximately 5 and 12 tonnes of cassava, respectively. This study assumes the use of trucks with a 5 and 12-tonne capacity to transport cassava waste within an approximately 15 km radius from the farm to the plant. When calculating diesel fuel consumption for this study, the specific make of tractor was not considered. Small tractors and trucks are the most common vehicles employed for this purpose, which are both manufactured in Thailand [24].

3.3 Other data required for cassava waste production

3.3.1 Diesel consumption

The primary cassava farming practices that require diesel fuel are fieldwork, land preparation including transportation of fertiliser and herbicide inputs, harvesting practices and waste management and transportation. The assumed fuel consumption values for each operation outlined in Table 3 are based on a fuel consumption rate per hectare (litre/ha). It is important to note that most of these practices are performed once annually during the cassava cultivation rotation. Diesel consumption data were collected through interviews with the Thai cassava farmers and from the literature [2, 25, 26]. In Thailand, small agricultural tractors consume approximately 15 litres/100km of diesel fuel for fieldwork and transportation; fully loaded small trucks (12 tonnes per trip) consumes about 25 litres/100km travelled. Diesel emissions figures for field work and transportation are listed in Table 3.

3.4 Environmental impacts of cassava waste production

The ecological impacts assessment process involves identifying all the environmental flows associated with cassava waste production. This includes the complete range of chemicals, fertilisers, herbicides and diesel fuel consumed in cassava agricultural processes and their associated emissions, as well as the manufacturing and processing inputs used for the three scenarios outlined above. Each scenario features a distinct cassava waste management method that reflects different input quantities. As discussed above, these include Scenario A (ploughing), Scenario B (burning) and Scenario C (collection). To calculate the total associated emissions, these upstream environmental flows were combined with the flows associated with the actual cassava cultivation, harvesting and transportation. As a result, for each unit of cassava waste produced, several types of emissions were released to the air and soil. However, this study focuses only on

Table 3 Fertilizer, herbicides, diesel fuel for cassava crops

	Scenario A	Scenario B	Scenario C
Applied fertilizer	(kg/tonne cassava waste)		
N	10.238	10.238	24.047
P_2O_5	8.334	8.334	18.453
K_2O	12.857	12.857	29.286
Applied herbicides	(kg/tonne cassava waste)		
Paraquat	0.429	0.214	0.214
Glyphosate	0.714	0.500	0.500
Total	1.143	0.714	0.714
Diesel	(litre/tonne cassava waste)		
Land preparation	8.571	6.429	12.857
Harvesting	4.286	4.286	4.286
Waste management	4.286	2.143	4.286
Fertilizer transport	0.429	0.429	0.429
Cassava waste transport	-	-	3.571
Total	17.571	11.143	25.429

Notes :

1) In Scenario C, chicken manure was combined with N0.5%, P_2O_5 0.25% and K_2O 0.5% fertilizer
2) Cassava waste yield = 4.375 tonne/ha
   The distance between farms to plants is 15 km (average)

atmospheric emissions, so emissions captured by soil are not included in the analysis. The atmospheric emissions considered for the three scenarios include CO_2, CH_4, N_2O, SO_2, NO_x, HCl, HF, CO, NMVOC, H_2S and NH_3. These emissions were classified to examine the potential environmental impacts: Global Warming Potential (GWP), Acidification Potential (AP) and Tropospheric Ozone Precursor Potential (TOPP). The detailed environmental impact potentials for the cassava waste management practices for all three scenarios are presented in Table 4.

3.4.1 Global warming potential

The GHGs relevant to this study are Carbon Dioxide (CO_2), Nitrous Oxide (N_2O), and Methane (CH_4). Based on an IPCC 100-year scenario [27], global warming potential values (GWP) are 1, 23 and 296 for CO_2, CH_4, and N_2O, respectively. GHG emissions were calculated for cassava waste production under three different scenarios, including the production of materials and energy used. Also, results show that Scenario B (open burning) would produce fewer GHG emissions than Scenarios A and C. GHG emission results

Table 4 Atmospheric emissions of as received (wet) cassava waste management scenarios

Scenarios	Sources of emissions SO_2		Emissions (kg /kg cassava waste)											
			NO_x	HCl	HF	Particulates	CO	NMVOC	H_2S	NH_3	CH_4	N_2O	CO_2	
Scenario A: ploughing the waste to the soil	1. Chemical fertilisers	N	4.78E-05	1.67E-04	7.49E-07	1.05E-08	2.51E-05	3.42E-05	5.79E-06	2.71E-10	6.85E-05	7.07E-05	1.55E-04	3.02E-02
		P_2O_5	9.89E-05	8.20E-05	1.70E-07	9.58E-09	1.44E-05	1.61E-05	4.65E-06	4.12E-11	1.04E-07	1.47E-05	4.88E-07	9.94E-03
		K_2O	5.04E-06	2.43E-05	9.96E-07	9.13E-09	1.70E-05	1.07E-05	2.47E-06	1.31E-10	2.34E-08	3.47E-05	8.01E-07	1.44E-02
	2. Herbicides		2.84E-05	1.97E-05	4.56E-07	1.59E-08	2.17E-06	7.99E-06	2.93E-06	8.51E-11	1.85E-07	3.01E-05	1.98E-06	1.27E-02
	3. Diesel	Field work	2.43E-04	6.71E-04	5.34E-07	6.63E-08	9.02E-05	1.49E-04	2.15E-05	1.64E-13	1.89E-11	1.46E-05	2.41E-06	7.42E-02
		Transport	6.07E-06	1.68E-05	1.33E-08	1.66E-09	2.25E-06	3.72E-06	5.38E-07	3.58E-15	4.43E-13	3.62E-07	6.01E-08	1.85E-03
	Total		4.29E-04	9.80E-04	2.92E-06	1.13E-07	1.51E-04	2.22E-04	3.79E-05	5.29E-10	6.88E-05	1.65E-04	1.61E-04	1.43E-01
Scenario B: burning the waste in the field	1. Chemical fertilizers	N	4.78E-05	1.67E-04	7.49E-07	1.05E-08	2.51E-05	3.42E-05	5.79E-06	2.71E-10	6.85E-05	7.07E-05	1.55E-04	3.02E-02
		P_2O_5	9.89E-05	8.20E-05	1.70E-07	9.58E-09	1.44E-05	1.61E-05	4.65E-06	4.12E-11	1.04E-07	1.47E-05	4.88E-07	9.94E-03
		K_2O	5.04E-06	2.43E-05	9.96E-07	9.13E-09	1.70E-05	1.07E-05	2.47E-06	1.31E-10	2.34E-08	3.47E-05	8.01E-07	1.44E-02
	2. Herbicides		1.77E-05	1.23E-05	2.85E-07	9.93E-09	1.36E-06	4.99E-06	1.83E-06	5.32E-11	1.16E-07	1.88E-05	1.24E-06	7.96E-03
	3. Diesel	Field work	1.82E-04	5.03E-04	4.00E-07	4.97E-08	6.76E-05	1.12E-04	1.61E-05	1.10E-13	1.41E-11	1.09E-05	1.80E-06	5.57E-02
		Transport	6.07E-06	1.68E-05	1.33E-08	1.66E-09	2.25E-06	3.72E-06	5.38E-07	3.58E-15	4.43E-13	3.62E-07	6.01E-08	1.85E-03
	Total		3.58E-04	8.05E-04	2.61E-06	9.06E-08	1.28E-04	1.81E-04	3.14E-05	4.97E-10	6.87E-05	1.50E-04	1.59E-04	1.20E-01
Scenario C: collecting and using the waste in cassava-based	1. Chemical fertilizers	- N	1.12E-04	3.92E-04	1.76E-06	2.48E-08	5.89E-05	8.03E-05	1.36E-05	6.38E-10	1.61E-04	1.66E-04	3.64E-04	7.09E-02
		- P_2O_5	2.19E-04	1.82E-04	3.77E-07	2.12E-08	3.19E-05	3.56E-05	1.03E-05	9.13E-11	2.29E-07	3.25E-05	1.08E-06	2.20E-02
		- K_2O	1.15E-05	5.52E-05	2.27E-06	2.08E-08	3.86E-05	2.43E-05	5.63E-06	2.99E-10	5.34E-08	7.92E-05	1.82E-06	3.29E-02
	2. Herbicides		1.77E-05	1.23E-05	2.85E-07	9.93E-09	1.36E-06	4.99E-06	1.83E-06	5.32E-11	1.16E-07	1.88E-05	1.24E-06	7.96E-03
	3. Diesel	Field work	3.04E-04	8.38E-04	6.67E-07	8.29E-08	1.13E-04	1.86E-04	2.69E-05	2.04E-13	2.36E-11	1.82E-05	3.01E-06	9.28E-02
		Transport	5.67E-05	1.56E-04	1.25E-07	1.55E-08	2.10E-05	3.48E-05	5.02E-06	3.39E-14	4.40E-12	3.40E-06	5.61E-07	1.73E-02
	Total		7.21E-04	1.64E-03	5.48E-06	1.75E-07	2.65E-04	3.66E-04	6.33E-05	1.08E-09	1.61E-04	3.18E-04	3.71E-04	2.44E-01

from field burning of cassava waste show the projected emissions of 0.072 kg CO_2 equivalent per kilogram of cassava waste. Table 5 lists the total greenhouse gas emissions produced for Scenarios A, B and C as 0.195, 0.243 and 0.361 kg CO_2-eq, respectively, for 1 kg of cassava waste generated. The GHG emissions associated with Scenario C is about 85% and 48% higher than Scenarios A and B respectively. Therefore, from a GHG emissions perspective, results show cassava waste collection (Scenario C) would produce the most significant adverse environmental impact.

3.4.2 Acidification Potential (AP)

The primary pollutants that contribute to acidification include Sulphur Dioxide (SO_2), Nitrogen Oxides (NO_x) and ammonia (NH_3) which have the equivalency factors of 1, 0.7 and 0.7, respectively [28]. Table 5 summarises the acidification potential of these pollutants for the three scenarios. Results show that Scenario C reflected the greatest acidification potential (AP) emissions of 2.17×10^{-3}kg SO_2-eq/kg cassava waste, or approximately 75% and 46% greater than the values for Scenarios A and B. Acidification potential from open burning (Scenario B) of cassava waste in the field is due to the emission of about 4.33×10^{-4}kg SO_2 equivalent per kilogram of cassava waste.

3.4.3 Tropospheric ozone precursor potential

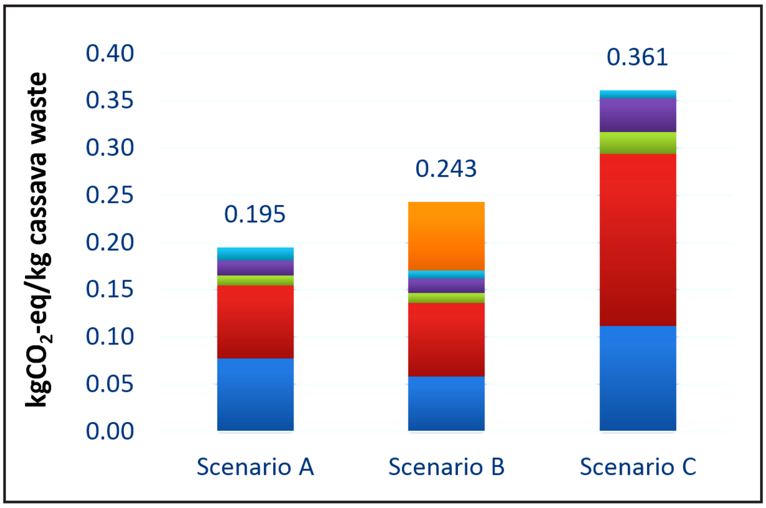
Emissions of total Non-Methane Volatile Organic Compounds (NMVOCs), Nitrogen Oxides (NO_x), Carbon <onoxide (CO) and Methane (CH_4) contribute to the formation of ground level (i.e. tropospheric) ozone [29]. Most tropospheric ozone formation results from fossil fuel combustion in the transport and energy supply sectors [30]. For this study, emissions of NMVOCs, NO_x, CO, and CH_4 were factor-weighted before aggregation to scale the respective Tropospheric Ozone Precursor Potentials (TOPP) of these compounds. The TOPP factor weight results are: NO_x (1.22), NMVOC (1), CO (0.11) and CH_4 (0.014) [29].

Table 5 illustrates that Scenario C produced the most significant quantity of TOPP emissions, followed by Scenarios A and B. This result is due to the large amounts of diesel fuel required for Scenario C compared to Scenarios A and B Tropospheric ozone emissions from open burning totalled approximately 4.18×10^{-4}kg TOPP equivalent per kilogram of cassava waste.

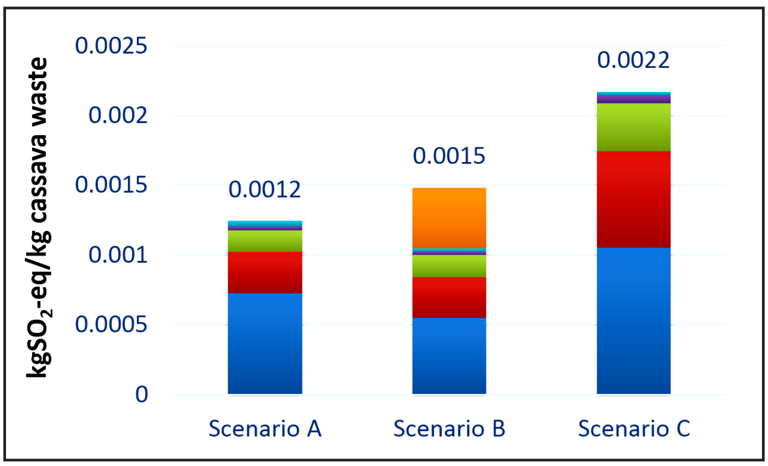
Table 5 GHG emissions, acidification potential and tropospheric ozone emissions associated with the production of cassava waste under three scenarios.

	Emissions	Emissions (kg) related to 1 kg cassava waste		
		Scenario A	Scenario B	Scenario C
GHG	CO_2 (note)	1.43E-01	1.20E-01	2.44E-01
	CH_4	1.65E-04	1.50E-04	3.18E-04
	N_2O	1.61E-04	1.59E-04	3.71E-04
	CO_2 equivalent	1.95E-01	1.71E-01	3.61E-01
	CO_2 equivalent related to open burning	-	0.72E-01	-
	Total CO_2 equivalent	1.95E-01	2.43E-01	3.61E-01
Acidification	NO_x	9.81E-04	8.06E-04	1.64E-03
	NH_3	6.88E-05	6.87E-05	1.61E-04
	SO_2(note)	4.29E-04	3.58E-04	7.21E-04
	SO_2 equivalent	1.24E-03	1.05E-03	2.17E-03
	SO_2 equivalent related to open burning	-	4.33E-04	-
	Total SO_2 equivalent	1.24E-03	1.48E-03	2.17E-03
TOPP	CO	2.22E-04	1.82E-04	3.67E-04
	CH_4	1.65E-04	1.50E-04	3.18E-04
	NO_x	9.81E-04	8.06E-04	1.64E-03
	NMVOC	3.81E-05	3.16E-05	6.38E-05
	TOPP equivalent	1.26E-03	1.04E-03	2.11E-03
	TOPP equivalent related to Open burning	-	4.18E-04	-
	Total TOPP equivalent	1.26E-03	1.46E-03	2.11E-03

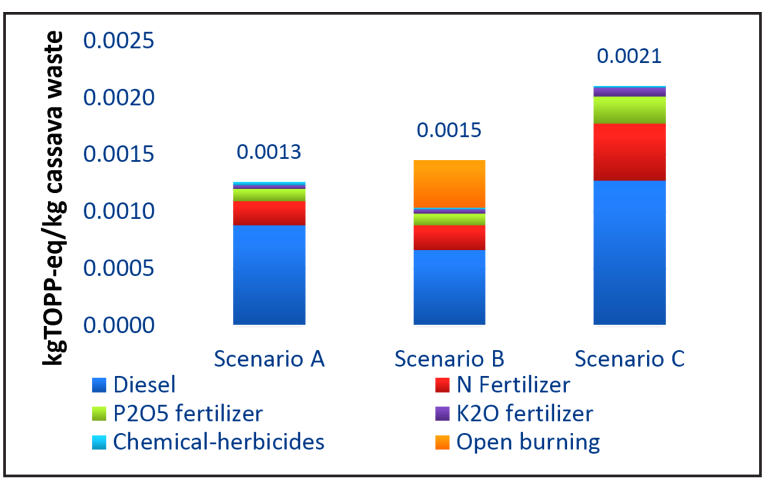
Note: CO_2 and SO_2 equivalent associated with open burring in scenario B is not included.



a) GHG emissions



b) Acidification potential



c) Tropospheric ozone precursor potential

Figure 2 The Breakdown of the a) GHG emissions, b) Acidification potential c) Tropospheric ozone precursor potential (TOPP) for scenarios.

4 Discussion

4.1 Greenhouse gas emissions associated with cassava waste management plans

As shown in Figure 2 Scenario C (cassava waste collection) would require the most fertilizer and diesel fuel inputs, and would result in significantly greater levels of GHG emissions compared to Scenarios A and B. For all the three scenarios, relatively small quantities of GHG emissions resulting from herbicide use were found in the environmental assessment of cassava production, because Thai cassava farmers typically do not apply large amounts of herbicides. The GHG emissions associated with herbicide production and use for the three scenarios were 0.014, 0.01 and 0.01 kgCO_2-eq/kg cassava waste, respectively. Nitrogen fertiliser production and application is the main source for GHG emissions within the life cycle of cassava waste production. For each scenario, the values for N-fertilizer were 0.078, 0.078 and 0.182 kgCO_2-eq/kg cassava waste production, respectively. In contrast, the values for the three scenarios for P_2O_5 fertilizer were 0.01, 0.01 and 0.02 kgCO_2-eq/kg, and those for K_2O-fertilizer were 0.02, 0.02 and 0.04 kgCO_2/kg, respectively. These findings show that no significant difference exists for GHG emissions attributable to fertiliser use between Scenarios A and B, because their respective cassava waste disposal practices do not require additional fertiliser inputs. In contrast, Scenario C would require fertiliser and chicken manure inputs to replenish the soil nutrients removed along with the cassava waste.

Diesel fuel consumption is the second largest source of GHG emissions for all three scenarios, totalling 0.08, 0.06 and 0.11 kgCO_2-eq/kg cassava waste, respectively. Scenario C showed the highest GHG emission values, primarily because the field collection of cassava waste requires greater fuel inputs for collection and transport rather than ploughing (Scenario A).

4.2 Acidification Potential (AP)

Figure 2 illustrates the acidification potential for the three scenarios. Results show that diesel fuel consumption produced the most significant quantity of AP emissions for Scenario A (7.28×10^{-4} kgSO_2-eq), B (5.51×10^{-4}kgSO_2-eq) and C (1.05×10^{-3}kgSO_2-eq). The second and third greatest sources for acidification potential emissions were the use of N-fertilizer and herbicides. The figures for AP potential of N-fertilizer production and consumption for all three scenarios are 2.93×10^{-4}, 2.93×10^{-4}, and 6.89×10^{-4} kgSO_2-eq/kg cassava waste, respectively. Contrary, less than 3% of total AP is emitted as a result of herbicide use per 1kg cassava waste production. The amount of AP from diesel fuel consumed in Scenario C is approximately 30% and 47% greater than Scenarios A and B, respectively. Also, balanced rates of N, P and K fertilisers and application of manure can also reduce soil acidification in agricultural fields [31].

4.3 Tropospheric ozone precursor potential

In Scenario C as shown in Figure 2 (cassava waste collection) exhibited the highest tropospheric ozone precursor and acidification potentials and the greatest quantities of GHG emissions. However, for all three scenarios, the emissions associated with diesel fuel consumption comprise more than 50% of total TOPP (Scenario A at 8.74×10-4, Scenario B at 6.64×10-4and Scenario C at 1.27×10^{-3}kgTOPP-eq/kg cassava waste produced). In terms of fertiliser inputs, the use of N-fertilizer produced the greatest quantities of TOPP emissions, followed by K-fertilizer and P-fertilizer (2.14×10^{-4}, 2.14×10^{-4} and 5.02×10^{-4} kgTOPP-eq/kg cassava waste generated). The results for P2O5-fertilizer were 1.07×10^{-4}, $1.07\times10^{-4}$and 2.36×10^{-4} kgTOPP-eq/kg cassava waste produced, and those for K2O-fertilizer were 3.37×10^{-5}, $3.37\times10^{-5}$and 7.68×10^{-5}kgTOPP-eq/kg cassava waste produced.

As discussed, Scenario C results in a significant contribution to tropospheric ozone precursor potential. The transport of cassava waste would also significantly contribute to TOPP emissions, mostly due to the NO_x released by diesel fuel combustion. In terms of AP emissions, NO_x emissions vary by vehicle type, age, engine, emission control system and the atmospheric conditions in which the vehicle operates [32]. TOPP emissions could be reduced by reducing the unnecessary use of agricultural equipment and vehicles and by using newer vehicles that typically release fewer relative quantities of NO_x emissions due to complete combustion. These measures could improve the environmental impact of this process.

5 Conclusions

This paper assessed the environmental impacts associated with three cassava waste management practices (ploughing, burning and collection) in Thailand. Results show that all three methods require energy inputs that generate GHG emissions of 0.195, 0.243 and 0.361 kg CO_2-eq/kg cassava waste, respectively. Of the three scenarios, field ploughing of cassava waste (Scenario A) emits the lowest levels of equivalent CO_2 emissions. Among the studied waste management scenarios, cassava waste collection, Scenario C, exhibits the highest environmental impact by emitting 85% more GHGs than Scenario A (ploughing) and 48% more than Scenario B (burning). Scenario C would emit the most substantial amounts of GHGs because collecting cassava waste on site would require more energy input (diesel fuel) than ploughing and burning. In this scenario, due to the removal of cassava waste from the field, greater amounts of fertiliser and diesel fuel is needed to restore soil quality, which would increase the environmental impacts associated with this cassava waste management scenario. However, it should be noted that, in Scenario C, cassava waste removed from the field is typically cofired with coal in cassava-based bioethanol plants which consequently reduces the amount of coal used in the process and its associated emissions.

Also, it is found that transporting cassava waste is a key contributing factor to GHG emissions, acidification and tropospheric ozone precursor emissions associated with all three scenarios. However, the environmental impacts of transportation of cassava waste could be the offset in Scenario C due to the potential for co-firing of the cassava waste and consequently reducing the emissions associated with transportation of the coal. Further work needs to be conducted to assess the reduction in emissions through this process especially considering different types of co-firing technologies.

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