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Life cycle assessment of a biogas system for cassava processing in Brazil to close the loop in the water-waste-energy-food nexus

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Abstract

Biogas, generated from anaerobic digester (AD), has been one of the promising sources of renewable energy. To manage the organic waste from small cassava industry in Brazil, a waste-water-energy-food nexus (WWEF) system is proposed, combining AD and co-generation or combined heat and power (CHP) plants. However, the environmental impacts and benefits of this system are yet not known. By using Life Cycle Assessment (LCA) method, environmental impacts of three scenarios are assessed, i.e. business-as-usual (base), improved business-as-usual and WWEF closed-loop scenarios. Functional unit (FU) in this study is defined as generating 1 kg cassava starch/flour. Global warming potential (GWP), cumulative energy demand (CED), freshwater eutrophication potential (FEP), terrestrial acidification potential (TAP) and water depletion potential (WDP) are selected. Landfilling cassava waste, power use for cassava starch and flour production, and emissions from fertilizer application are identified as environmental hotspots for business-as-usual case, suggesting making decisions on these aspects when dealing with environmental impacts. By using cassava waste to recover energy and nutrients for Brazilian rural family farming, the WWEF system is identified as the best environment-friendly scenario with lowest environmental impacts for selected impact categories. The impact savings of the closed-loop scenario for GWP are over 90%, while over 50% of emissions for other selected impact categories, except FEP (lower than 10%), are saved compared to the business-as-usual and improved scenarios. Sensitivity analysis reinforces the results. Overall, this study provides a view on the potential of using cassava waste for the WWEF closed-loop system in Brazil, suggesting that the proposed WWEF closed-loop system is feasible and beneficial for small industries from

the environmental perspective.

Keywords: Yuca; Manioc; Starch; LCA; Anaerobic Digestion; Environmental impacts.

Abbreviations

AD	Anaerobic Digester
ADP	Abiotic Depletion
ADP elements	Abiotic Depletion Potential of Elements
ADP fossil	Abiotic Depletion Potential of Fossil Fuels
ALO	Agricultural Land Occupation
AP	Acidification Potential
CC	Climate Change
CED	Cumulative energy demand
CHP	Co-generation or combined heat and power
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
FEP	Freshwater eutrophication potential
FU	Functional unit
FWAE	Fresh Water Aquatic Ecotox.
GWP	Global warming potential
HTP	Human Toxicity Potential
LCA	Life cycle assessment
LCI	Life cycle inventory
MAE	Marine Aquatic Ecotoxicity
MAETP	Marine Aquatic Ecotoxicity Potential
NER	Net Energy Ratio
ODP	Ozone Layer Depletion Potential
PED	Primary Energy Demand
PO	Photochemical Oxidation
POCP	Photochemical Ozone Creation Potential
SR	Sensitivity ratio
TAP	Terrestrial acidification potential
TE	Terrestrial Ecotoxicity
TETP	terrestrial ecotoxicity potential
TS	Total solids
VS	Volatile solids
WDP	Water depletion potential
WWEF	Waste-water-energy-food

1. Introduction

Renewable energy is advised as a strong alternative for fossil fuels, contributing to lower climate change and other environmental impacts. Biogas offers a source of renewable energy, since methane can be utilized in generation of heat and power and used as vehicle fuels (Weiland, 2010). As a promising energy source, biogas can be obtained by the digestion of several organic wastes e.g., agricultural residues and food wastes in the absence of oxygen. Although the biogas use in Brazil is limited to some bio-digestion plants, there is an opportunity for increasing its production (Salomon and Silva Lora, 2009). This could support the expansion of basic services such as electricity, water and sanitation which require amplification of energy supply in Brazil (Pereira et al., 2012). Meanwhile, anaerobic digester (AD) systems, are best explored for rural and peri-urban areas because they have appropriate spaces and constant sources of feedstocks (Tilley et al., 2008). Small-scale AD option has been identified as a choice for organic agriculture waste management in Brazil for closing the loop of the water-waste-food-energy nexus (WWEF) (van der Velden et al., 2021).

The organic agriculture is considered as a solution for rural regions of developing countries since it can lead to socio-economic and ecologically sustainable development. The Brazilian government has highlighted the organic agriculture since 1999 (Candiotto, 2018), and the Federal Government of Brazil enforced the Brazilian Federal Law of the Family Agriculture to encourage the development of family agriculture in 2006. During a decade of considerable expansion of agriculture in Brazil, the share of family agriculture in the total production stays approximately at the same level, illustrating that this production mode is becoming an unchallengeable part of the Brazilian productive agribusiness chain (Guanziroli et al., 2013). Meanwhile, Brazil, as the second largest producers of cassava worldwide, generates 49% of cassava products in the northeast region where the cassava is the major food crop due to its environmental conditions (Pires De Matos et al., 1997). Furthermore, with 1.38 Gt GHG emissions in 2016, agriculture and energy sectors contributed around 68% (500 Mt and 450 Mt) in Brazil (CAIT Climate Data Explorer, 2019). Therefore, to manage organic agriculture waste in Brazil, a small-scale AD and CHP system for cassava cultivation, cassava starch and flour production seems an attractive option for closing the loop of the WWEF. However, its environmental performance must be examined before implementation.

Life cycle assessment (LCA) is a widely accepted tool to assess the environmental impacts of products or services from cradle to grave, i.e. the whole life cycle. Several studies have explored the environmental impacts of biogas production from anaerobic digesters (AD). Among LCA studies on AD, biogas leakage was identified as one of main contributors for climate change impact category (Papong et al., 2014). Combining AD with different technologies also affected the environmental impacts of the AD process. For example, in a pyrolysis system for biochar production from digestate, using biogas and pyrolysis gas reduced the environmental impacts, while processes of dewatering and drying emitted the largest number of environmental emissions (Mohammadi et al., 2019). The biochar was used into the soil, as the greatest GHG emission mitigator, reducing 40% and 36% of the total in the scenarios of Sweden and Brazil, respectively. Apart from climate change, non-methane volatile organic compound (NMVOC) emissions from CHP plants were identified as key cause for some impact categories, e.g. photochemical ozone potentials, which made the AD and CHP plant worse than incineration waste treatment (Evangelisti et al., 2014). Different allocation methods also affected the climate emissions of AD process, which were reduced when applied economic or mass allocation for digestate (co-products) (Timonen et al., 2019).

Table 1 summarizes the LCA studies conducted for AD or considering AD processes as a target scenario. Functional units are presented in terms of energy production or waste treatment because these reviewed studies had different research objectives. Impact categories that have been widely studied are global warming (e.g. Ingrao et al. (2015)), acidification (e.g. Evangelisti et al. (2014)), eutrophication (e.g. Fusi et al. (2016)), water (e.g. Pacetti et al. (2015)), and energy (e.g. Shimako et al. (2016). Various feedstocks for AD process have also been explored in different regions to generate biogas under these LCA studies. However, these studies were focusing on European and Asian areas, and studies on cassava waste are limited. Similar trends are found in a review study by Bacenetti et al. (2016) that states among 105 LCA studies on AD published between 2000 and 2015, most studies were conducted in Europe, some in China and limited number in South and North America. Furthermore, waste from cassava starch/ flour production was not considered, especially in Brazil.

Therefore, this study aims to conduct LCA of a small-scale WWEF system built for Brazilian rural areas and identify the environmental hotspots to provide evidence-based information to support decision making in treating cassava waste processes for cassava starch and flour industry. The LCA study will then compare a business-as-usual (base) case to understand the trade-offs of environmental impacts in introducing cassava waste treatment. To the authors’ knowledge this is the first investigation of this kind applied to a Brazilian case study.

Table 1. Summary of reviewed LCA studies for AD.

Reference	Region	Functional unit	Feedstock	Type of LCI data	Impact (LCIA method)
Evangelisti et al. (2014)	UK	35,574 tons/year of the organic fraction of municipal solid waste (OFMSW)	Organic fraction of municipal solid waste (OFMSW)	Secondary	GWP; AP; POCP (CML)
Fusi et al. (2016)	Italy	Generation of 1 MWh of electricity to be fed into the grid	Maize silage, slurry, and tomato waste	Primary and secondary	ADP elements, ADP fossil, AP, EP, FAETP, GWP, HTP, MAETP, ODP, POCP, TETP. (CML 2001 method)
Ingrao et al. (2015)	Italy	1 kWh_e produced from biogas	An average of animal effluents, energy-crops and milling co-products	Primary and secondary	GWP
Mohammadi et al. (2019)	Sweden, Brazil, and China	1 t (ton) of dry matter sludge	Pulp and paper wastewater sludge	Primary and secondary	ADP, ADP fossil, CC, ODP, AP, EP, PO, TETP, HTP, FWAE, MAETP (CML-IA method)
Pacetti et al. (2015)	Italy	Production of 1 GJ of energy content	Maize, Sorghum and Wheat	Secondary	All 18 indicators assessed but CC, ALO, FE, TE and WDP were discussed (ReCiPe 2008)
Papong et al. (2014)	Thailand	1 MJ of biomethane and 1 km of vehicle driven.	Cassava starch wastewater	Primary and secondary	GWP, HTP, AP, EP (CML baseline 2000 method) and NER

Rana et al. (2016)	Italy	1 MJ purified biogas (PB)	Energy crops, Durum Wheat (DW) by-products from grain mills and Animal effluents.	Primary and secondary	Climate impacts
Rehl et al. (2012)	Germany	1 MJ of electricity supplied to the electricity network	Manure, Maize Ensilage, Grass ensilage and Grain	Primary and secondary	GWP, EP, AP, POCP (CML method) and PED
Shimako et al. (2016)	Global	1 MJ of produced energy	Microalgae	Secondary	All 18 impact categories (ReCiPe 2008), and CED
Slorach et al. (2019)	UK	Treatment of 1 ton of household food waste and Generation of 1 MWh of net electricity	Household food waste	Primary and secondary	All 18 impact categories (ReCiPe 2008), and PED
Timonen et al. (2019)	Finland	1 MJ energy and 1 kg nitrogen	Pig slurry and co-feedstock (grass and food industry side streams)	Primary and secondary	Climate impacts

Note: Global Warming Potential (GWP), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Abiotic Depletion Potential of Elements (ADP elements), Abiotic Depletion Potential of Fossil Fuels (ADP fossil), Eutrophication Potential (EP), Freshwater Aquatic Ecotoxicity Potential (FAETP); Human Toxicity Potential (HTP), Marine Aquatic Ecotoxicity Potential (MAETP), Ozone Layer Depletion Potential (ODP), terrestrial ecotoxicity potential (TETP), Abiotic Depletion (ADP), Climate Change (CC), Photochemical Oxidation (PO), Fresh Water Aquatic Ecotox. (FWAE), Agricultural Land Occupation (ALO), Freshwater Eutrophication Potential (FEP), Terrestrial Ecotoxicity (TE), Water Depletion Potential (WDP), Net Energy Ratio (NER), Primary Energy Demand (PED), Cumulative Energy Demand (CED)...

2. Material and methods

This section describes three scenarios for cassava industry in Brazil and LCA methods following the ISO 14044 (ISO, 2006), including the definition of goal and scope, life cycle inventory, life cycle impact assessment, and interpretation.

2.1. Goal and scope of the study

The goal of this study is to assess and compare the environmental impacts of the three scenarios for Brazilian cassava industry. The scope of this study includes the cassava cultivating process, cassava starch and flour process, AD process and CHP process. The functional unit (FU) for this study is the generation of 1 kg cassava products (starch/flour). The study considers three operational scenarios: the business-as-usual, improved business-as-usual, and WWEF closed loop.

2.2. Description of scenarios and system boundaries

This study focuses on a closed-loop system that integrates the nexus of water, waste, energy, and food in a small cassava industry. This closed-loop system is designed to recover energy and nutrients from cassava waste generated from the Brazilian cassava processing industry. The WWEF system is created by combining current cassava cultivation, cassava product (starch and flour) production in Brazil, small-scale AD with small-scale cogeneration or combined heat and power (CHP) plants (see Fig. 1). To lower the cost, each process is designed as closest as possible, and transport between different processes are unnecessary. The business-as-usual scenario, as a base case, is generated based on an industry that produces manioc products in the State of Goias, Brazil. To recover energy, an improved business-as-usual scenario is created. Meanwhile, a WWEF closed-loop scenario is established to further recover nutrients by utilizing digestate in crop production.

As demonstrated in Fig. 1 (yellow boundary), the business-as-usual scenario includes the cassava cultivating process, cassava producing process and landfill of cassava waste. The cassava cultivation requires cassava steams, chicken manures as organic fertilizers, fuel use for crop machines, pesticide, and herbicide. In this process, the direct emissions of applying organic fertilizers are assessed. The cassava producing process consumes water for washing and processing, electricity from national grid, and drying heat from wood stove. The outputs include cassava products (starch and flour) and cassava wastes. In this scenario, the wastes including wastewater and cassava pulp are directly landfilled, which is phasing out in many developed areas, but it is still a common practice in many regions due to easy operation and low operational cost (Ma and Liu, 2019), hence emissions from landfilling cassava waste are assessed.

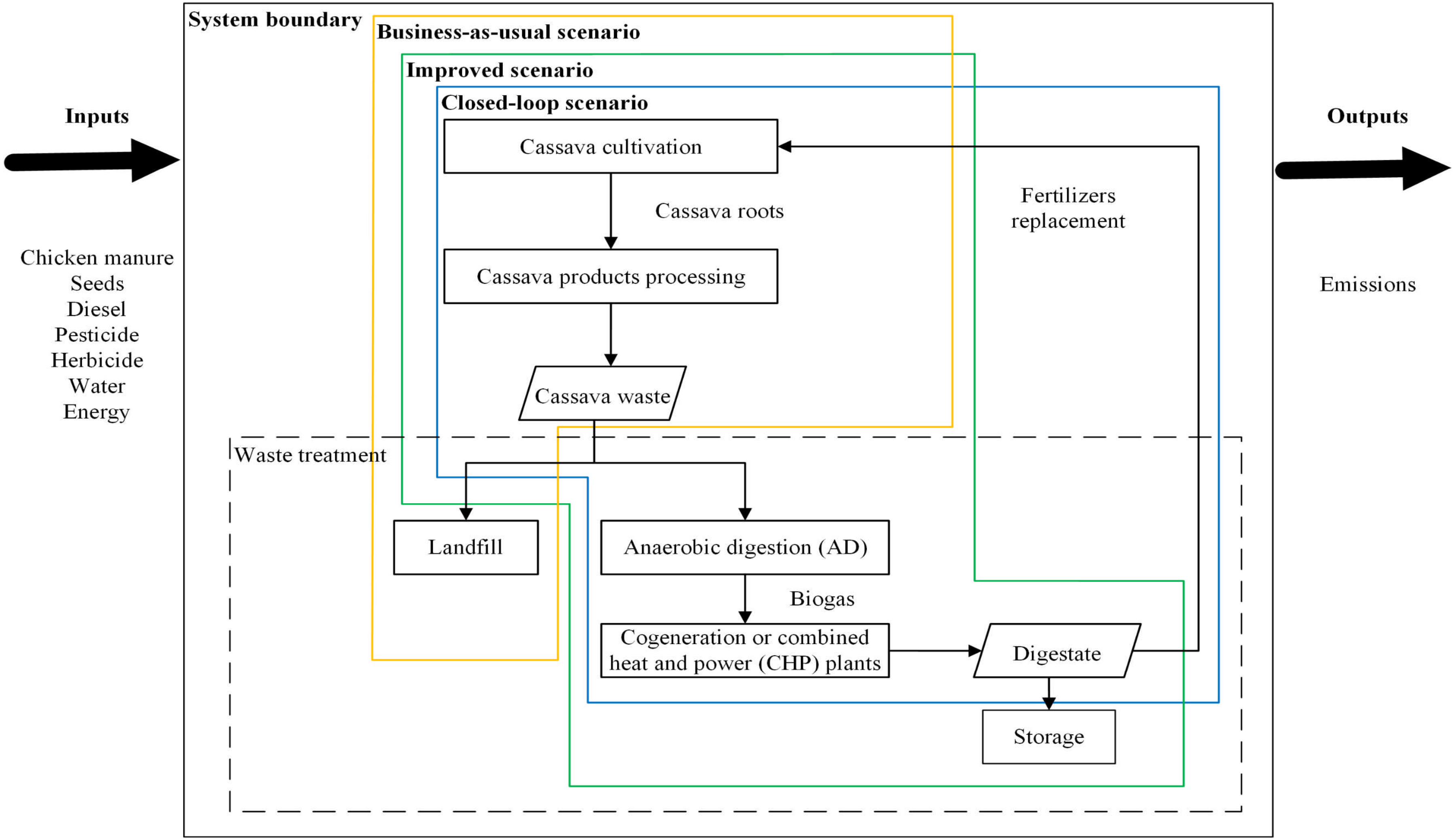


Fig. 1. System boundary of the WWEF system for the cassava industry. Functional unit: the generation of 1 kg cassava products (starch/flour)

Based on the business-as-usual scenario, an improved scenario (Fig. 1, green boundary) is proposed. This scenario adopts AD and CHP plant to prevent cassava waste from landfilling. The processes in this scenario are partly the same as those in the business-as-usual scenario, and some new processes are added. Landfill of cassava waste is removed, and the added processes include AD, CHP plant, and storage of digestate. Digestate is assumed to be stored near the farmland when the crop does not require fertilizer in the growth stage. AD and CHP plant are set up closely, and no external energy is consumed due to the use of recovered energy. Direct emissions from the operation of AD and CHP plant are included in this scenario. Digestate from the AD process is stored in tanks for a period of 3-6 months (Styles et al., 2018), and a post-treatment, e.g., biofertilizer production, is not included in this scenario. Emissions from the storage of digestate are also included. The surplus energy after satisfying the needs of the system is not exported to the electricity grid since there are some extra requirements to further process electricity from CHP plants (Coimbra-Araújo et al., 2014), Hence, there is no energy output from the WWEF system.

To further close the loop of the supply chain, digestate application is considered in the closed-loop scenario (Fig. 1, blue boundary). Digestate can replace mineral fertilizer to provide nutrients for crop growth. The rate of substitution can be 50 to 100% depending on the soil, the dose used, type of application and plant involved (Styles et al., 2018). Digested after AD process can be applied directly to crops with remarkable economic and environmental results (Nicoloso, 2014; Vivan et al. 2010). Thus, in this study, the AD digestate is assumed to be directly applied to crop production, replacing 50% of the fertilizer's use. Emissions from digestate used in cassava cultivating process are also assessed. Similar to the improved scenario, resources consumption and direct emissions from applying chicken manure, AD and CHP plant are considered as outputs for this closed-loop scenario.

2.3. Specification of life cycle inventory

Based on the scenarios above, the data from the industry in the State of Goias, Brazil and literature are collected. Table 2 presents the number of inputs and outputs for the three scenarios based on the functional unit (FU), i.e. generating 1 kg cassava starch/flour. Details of the raw data for the life cycle inventory (LCI) are presented in Table A 1 (Appendix A).

The cassava cultivating process contains the crop production in Brazil for obtaining raw cassava roots. For 1-hectare crop production, it requires 4.2 ton of chicken manure, which is indicated as the most efficient value for cassava production (Biratu et al., 2018). The local industry provides the specification of chicken manure with the value of 3.1%, 2.85% and 0.88% of N, P and K, respectively. Hence, to cultivate 1-hectare cassava roots requires 130 kg N, 120 kg P and 37 kg K. Emissions from the organic fertilizers' application, including ammonia, N_2O, NO_x, nitrate and phosphate, are assessed in this study. According to Prudêncio da Silva et al. (2014), ammonia emission factor is 0.26 while 70% of N contents contribute to ammonia emissions. They also provide nitrate emissions for maize and soybean in Brazilian tillage system as on average 20 kg/ha. This value is adopted for cassava production in this study due to the lack of data. Methods from Prudêncio Da Silva et al. (2014) are adopted to calculate the N_2O emissions, including N_2O emissions associated with volatilization, leaching and runoff of N inputs to managed soils. Meanwhile, the NO_x emissions are calculated based on N_2O emissions multiplying the factor of 0.21 (ibid). Also, Prudêncio Da Silva et al. (2014) stated that phosphate emissions are related to the quantity of soil eroded, hence an average value of soil eroded in Brazil for maize and soybean tillage system (i.e. 9 ton/ha per year) is used. The calculation method for phosphate emissions follows the study conducted by Nemecek and Schnetzer (2011). Furthermore, the amount of cassava stems consumed is 7000 stems/ha, which equals to 680 kg/ha (Jarvis et al., 2005). Crop machines in the fields consume 21L of diesel per hectare (Pingmuanglek et al., 2017). With net calorific value of 42.7 MJ/kg and density of 0.83 kg/L, the energy inputs for crop machines are 744 MJ/ha. For the consumption of pesticide and herbicide in cassava production, 1 kg yield cassava roots require 0.000077 kg fungicide/insecticide and 0.00015 kg glyphosate (Botero Agudelo et al., 2011). FAO (2013) stated that cassava can be cultivated in the areas where the rainfall achieves 400 mm, although 1700 mm rainfall could maximize the yield. Due to the moderate rainfall (100-1500 mm) in Brazil, no extra water is assumed to be consumed for cassava growth in Brazilian rural areas in this study. The yield of raw cassava roots for 1-hectare land reaches 22,500 kg (Pingmuanglek et al., 2017). Meanwhile, the land use change and embedded emissions of infrastructure are excluded in this study, which is in line with literature (Cahyani et al., 2019; Fantin et al., 2015; Fusi et al., 2016; Ingrao et al., 2015; Rana et al., 2016; Rehl et al., 2012). CO_2 absorption by the crops was neglected in this study due to the agreement that almost all carbon absorbed by crops will be released to the atmosphere within 1-2 years under static condition (Williams et al., 2006).

Table. 2. Life cycle inventory of the WWEF system

Stage	Activity	Inputs/ Output	Unit	Amount: Business-as-usual scenario	Improved scenario	Closed-loop scenario	Ref
Cassava cultivating process	Organic fertilizers	Chicken manure (N)	kg/FU	9.64x10^{-3}	9.64x10^{-3}	4.82x10^{-3}	Provided by the industry
		Chicken manure (P)	kg/FU	8.87x10^{-3}	8.87x10^{-3}	4.43x10^{-3}	Provided by the industry
		Chicken manure (K)	kg/FU	2.74x10^{-3}	2.74x10^{-3}	1.37x10^{-3}	Provided by the industry
	Stems	Cassava stems	kg/FU	5.04x10^{-2}	5.04x10^{-2}	5.04x10^{-2}	Jarvis et al. (2005)
	Fuel use for crop machine	Diesel	MJ/FU	5.51x10^{-2}	5.51x10^{-2}	5.51x10^{-2}	Pingmuanglek et al. (2017)
	Pesticide	Fungicide - Insecticide	kg/FU	1.28x10^{-4}	1.28x10^{-4}	1.28x10^{-4}	Botero Agudelo et al. (2011)
	Herbicide	Glyphosate	kg/FU	2.50x10^{-4}	2.50x10^{-4}	2.50x10^{-4}	Botero Agudelo et al. (2011)
	Fertilizers' appliance	Ammonia (NH3)	kg/FU	1.76x10^{-3}	1.76x10^{-3}	8.78x10^{-4}	Prudêncio da Silva et al. (2014)
		N2O	kg/FU	1.82x10^{-4}	1.82x10^{-4}	9.09x10^{-5}	Prudêncio da Silva et al. (2014)
		NOx	kg/FU	3.82x10^{-5}	3.82x10^{-5}	1.91x10^{-5}	Prudêncio da Silva et al. (2014)
		Nitrate	kg/FU	1.48x10^{-3}	1.48x10^{-3}	7.41x10^{-4}	Prudêncio da Silva et al. (2014)
		Phosphate	kg/FU	2.69x10^{-4}	2.69x10^{-4}	2.61x10^{-4}	Nemecek and Schnetzer (2011) Prudêncio da Silva et al. (2014)
	Digestate's application	NH3	kg/FU	-	-	1.11x10^{-4}	Yoshida et al. (2016)
		N2O	kg/FU	-	-	2.33x10^{-5}	Yoshida et al. (2016)

		NOx	kg/FU	-	-	$1.07x10^{-7}$	Prudêncio da Silva et al. (2014)
		Nitrate	kg/FU	-	-	$4.57x10^{0}$	Prudêncio da Silva et al. (2014)
Cassava starch and flour production	Process	water	kg/FU	$4.57x10^{0}$	$4.57x10^{0}$	$4.57x10^{0}$	Provided by the industry
		Electricity	kWh/FU	$3.89x10^{-2}$	-	-	Provided by the industry
		Heat	MJ/FU	$5.08x10^{-1}$	-	-	Pingmuanglek et al. (2017)
	Cassava waste emissions	Methane	kg/FU	$8.67x10^{-2}$	-	-	Panichnumsin et al. (2010) Scharff and Jacobs (2006) Tampio et al. (2016); Achi et al. (2020)
		N2O	kg/FU	$4.62x10^{-5}$	-	-	Panichnumsin et al. (2010); Pardo et al. (2015); Achi et al. (2020)
		NH3	kg/FU	$4.41x10^{-4}$	-	-	Panichnumsin et al. (2010); Pardo et al. (2015); Achi et al. (2020)
		Nitrate	kg/FU	$9.58x10^{-6}$	-	-	Obueh and Odesiri-Eruteyan (2016)
		Phosphate	kg/FU	$2.36x10^{-6}$	-	-	Obueh and Odesiri-Eruteyan (2016)
AD process	Biogas leakage	CO2	kg/FU	-	$9.10x10^{-4}$	$9.10x10^{-4}$	Evangelisti et al. (2014); Tampio et al. (2016)
		Methane (CH4)	kg/FU	-	$5.02x10^{-4}$	$5.02x10^{-4}$	Evangelisti et al. (2014); Tampio et al. (2016)
	Digestate storage emissions	Methane (CH4)	kg/FU	-	$2.62x10^{-3}$	-	Panichnumsin et al. (2010); Styles et al. (2018)

		NH3	kg/FU	-	1.32×10^{-7}	-	Panichnumsin et al. (2010); Styles et al., (2018)
CHP process	CHP operation	CO	kg/FU	-	1.50×10^{-4}	1.50×10^{-4}	Evangelisti et al. (2014)
		NOx	kg/FU	-	1.94×10^{-4}	1.94×10^{-4}	Evangelisti et al. (2014)
		CH4	kg/FU	-	4.23×10^{-4}	4.23×10^{-4}	Evangelisti et al. (2014)
		NMVOC	kg/FU	-	1.37×10^{-4}	1.37×10^{-4}	Evangelisti et al. (2014)

In the cassava starch and flour process, the total processed amount of cassava roots reaches 9.12ton/day based on the local industry. To obtain cassava products, the cultivated cassava roots from the farmlands are washed, two-step peeled, grinded and finally processed and heated to starch and flour. The local industry also states that 60% of the cassava roots can be processed into cassava products (starch and flour), and the whole process consumes 2.74 kg of water (from a deep well) and 0.023 kWh electricity for processing 1 kg cassava roots. The heat consumed for this process is 0.3 MJ/kg cassava roots (Pingmuanglek et al., 2017). For energy consumption, the business-as-usual scenario obtains electricity from the national grid and heat from wood stove while in the other two scenarios energy is provided by CHP plant integrated in the system. Furthermore, the business-as-usual scenario directly landfills cassava waste on the farmlands. The emissions from the landfilling cassava waste include nitrate, phosphate, methane (CH_4), N_2O and NH_3. According to Obueh and Odesiri-Eruteyan (2016), emission factors of nitrate and phosphate for fresh cassava waste are estimated as 1.83×10^{-6} kg/kg and 4.50×10^{-7} kg/kg, respectively. Additionally, methane (CH_4), N_2O and NH_3 emissions are estimated based on literature (Achi et al., 2020; Panichnumsin et al., 2010; Pardo et al., 2015; Scharff and Jacobs, 2006; Tabesh et al., 2019; Tampio et al., 2016). CO_2 emissions from landfilling organic waste is considered as biogenic carbon content, which is a part of the natural atmospheric cycle, hence it is not considered as a GHG emission (Kong et al., 2012), For that, CO_2 emissions caused by organic waste in landfills are excluded in this study.

The AD process is adopted for the improved scenario and closed-loop scenario. This process consumes electricity (3.5% of energy outputs) and heat (22% of energy outputs) for biogas generation (Kimming et al., 2011). Energy inputs are supplied by the CHP plant thus no external energy sources are required. The yield biogas from AD plants is estimated based on the features of cassava pulp, wastewater and biogas. The total solids (TS) and the volatile solids (VS) of cassava pulp is 0.305 kg/kg and 984 g/kg, respectively, while cassava wastewater's TS and VS are 17.8g/kg and 97.2%, respectively. The yield rate of biogas from cassava pulp and wastewater is 0.208 L/g VS (Panichnumsin et al., 2010). Furthermore, due to data availability, this study adopts general data of the net calorific value for biogas with 23 MJ/Nm^3 (Evangelisti et al., 2014). The biogas leakages are evaluated, letting out 2% of produced biogas (ibid), while the characterization of biogas is 60% methane and 40% CO_2 (Tampio et al., 2016). The outputs of digestate are calculated based on mass balance, i.e. the total mass input for the biogas process should be equal to the mass of outputs. The digestate is assumed to be stored in the improved scenario while directly applied for cassava growth in the closed-loop scenario. The emissions from storing digestate include methane (CH_4) and ammonia (NH_3), while N_2O emissions from the storage are negligible. The calculation method for storage emissions follows Styles et al. (2018). The closed-loop scenario directly applies digestate to the farmland, emissions of which are ammonia (NH_3), N_2O NO_x and nitrate. The average emission factors for ammonia (NH_3) and N_2O are, respectively, 0.016 kg/ kg N_{added} and 0.023 kg/ kg N_{added} (Yoshida et al., 2016). NO_x and nitrate emissions follow the calculation rules of emissions from fertilizers' applications (Prudêncio da Silva et al., 2014).

The energy process (CHP) is also employed for both the improved and WWEF closed-loop scenarios. Energy consumption in this process requires electricity for the operation of CHP plants with 4.5% of generated energy from CHP plants (Mohammadi et al., 2019). The emissions from CHP plants include CO, NO_x, CH_4 and NWVOC (Evangelisti et al., 2014). The electricity and heat generation from CHP plants are determined by the efficiency of the plants, i.e. 32% for electricity and 50% for heat (Patterson et al., 2011). The total heat and electricity generated from the CHP are calculated as 0.65 MJ/FU heat and 0.12 kWh/FU electricity, respectively.

2.4. Impact categories and factors

The impact categories, including global warming potential (GWP), cumulative energy demand (CED), freshwater eutrophication potential (FEP), terrestrial acidification potential (TAP) and water depletion potential (WDP) are selected based on the literature review (Table 1) and their relevance to the WWEF system. The characterization factors are collected for inputs and outputs of the system for each scenario (see Table A 2). These factors are sourced from the Ecoinvent v3.5 (Goedkoop et al., 2009) and the ReCiPe v1.13 (Wernet et al., 2016).

2.5. Sensitivity ratio (SR)

To assess the robustness of results in this study, sensitivity analysis is conducted. The sensitivity ratio (SR) is adopted to measure the sensitivity of parameters, which is calculated through equation 1.

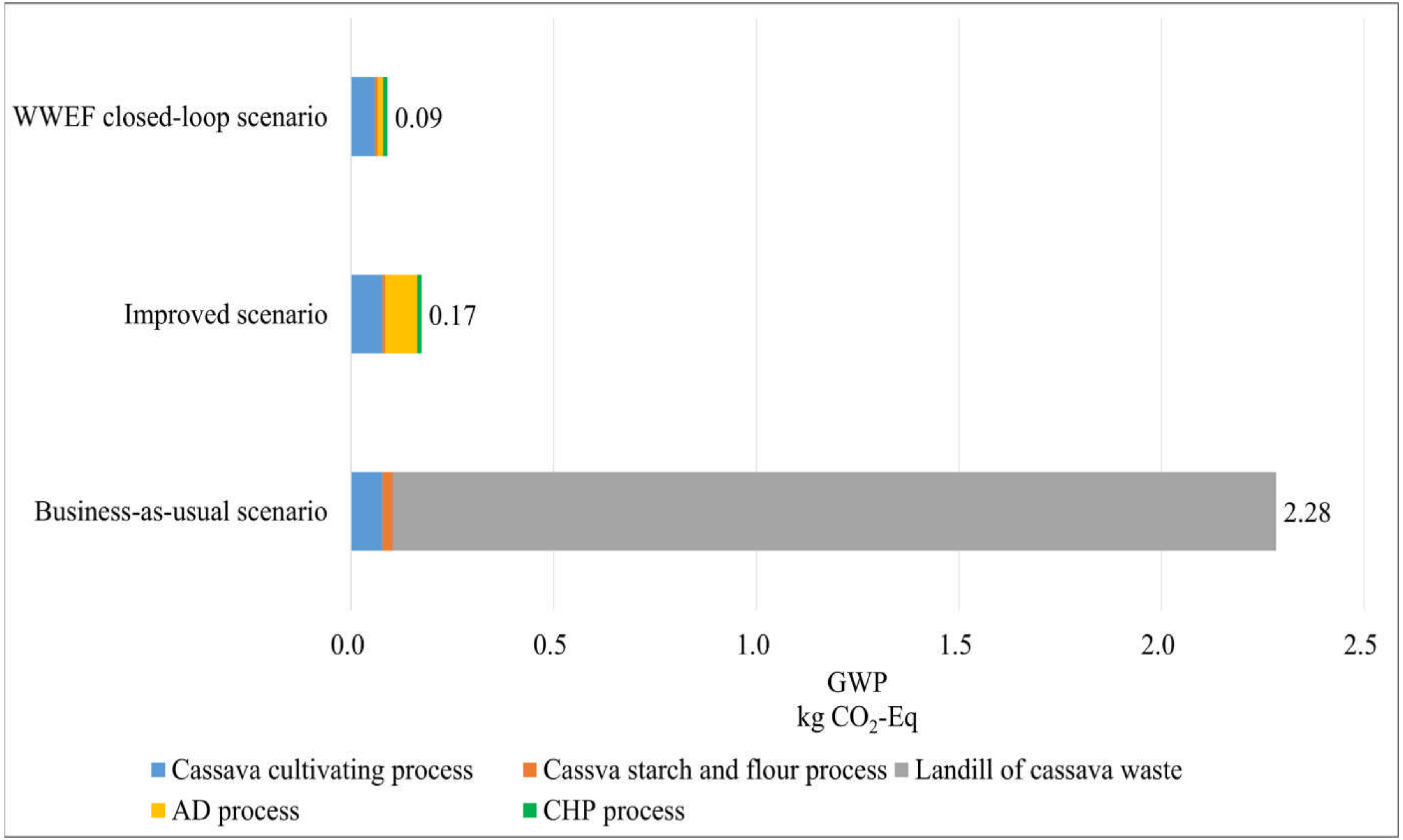
$$SR = \frac{\frac{\Delta Result}{Inital\ result}}{\frac{\Delta Parameter}{Initial\ parameter}} \quad \text{---}(1)$$

$\frac{\Delta Result}{Inital\ result}$ and $\frac{\Delta Parameter}{Initial\ parameter}$ represent the relative change of results and parameters. The SR shows the relative changes of results alongside the changes of parameters. This study conducts sensitivity analysis for parameters that contribute over 10% of impacts for selected impact categories in all three scenarios, supporting the robustness of the results.

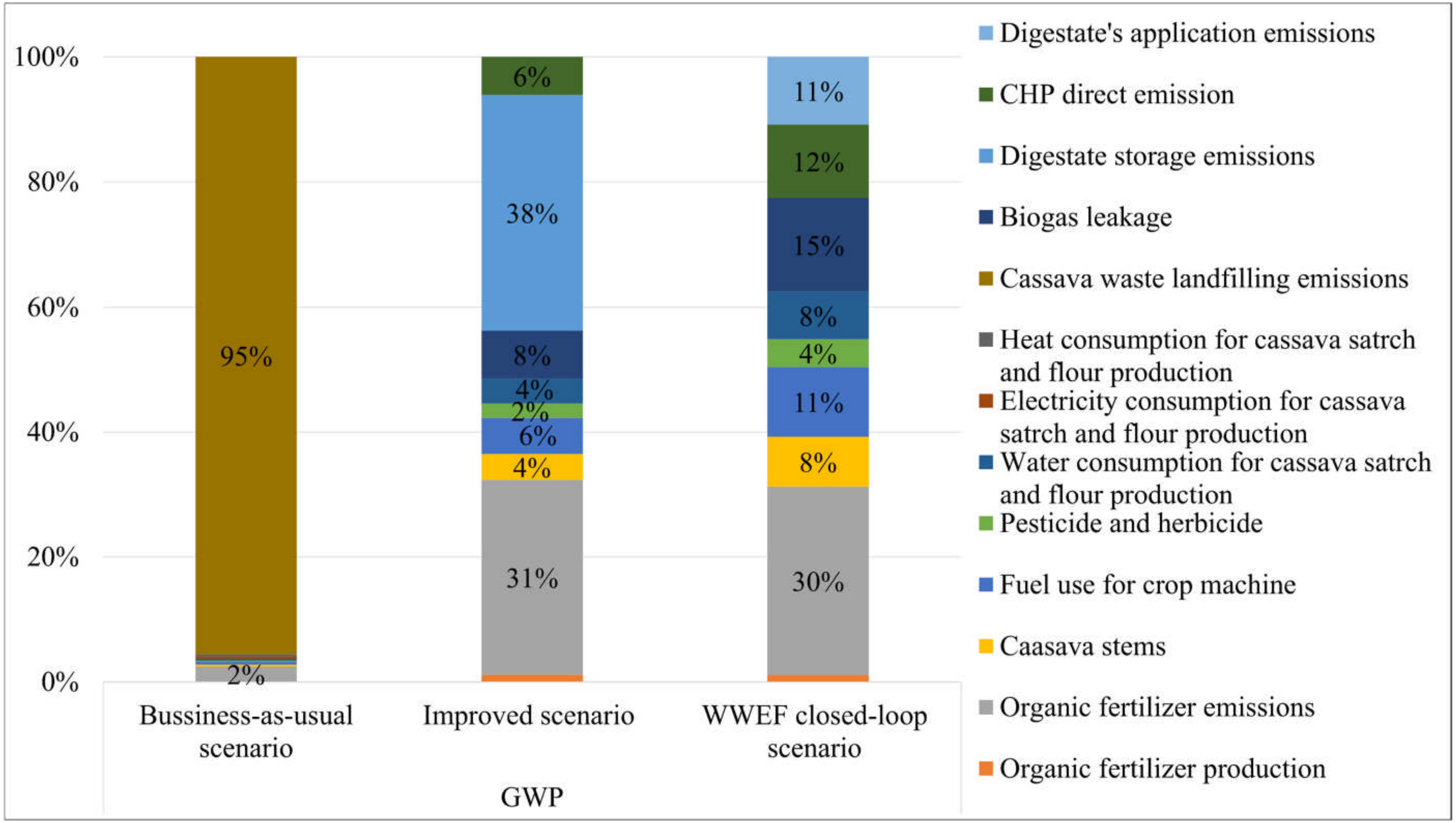
3. Results and discussion

3.1. Global Warming Potential

Fig. 2a presents the total global warming potential (GWP) impacts of the three scenarios, demonstrating that the WWEF closed-loop scenario has the best environmental performance while the business-as-usual scenario has the worst. The landfill of cassava waste is the major impact contributor (95% of the total) for the business-as-usual scenario. The cassava cultivating process and AD process contribute 90% in total of the GHG emissions in the improved scenario. In the closed-loop scenario, the cassava cultivating process dominates the GHG emissions, leading to 66%, while other processes such as biogas process emits maximum 15% of the total GHG emissions. Comparing to the business-as-usual and improved scenarios, the WWEF closed-loop scenario saves GHG emissions by 96% and 48%. The improved scenario emits only 8% of GHG emissions of business-as-usual scenario. Fig. 2b illustrates contributions of the inputs and outputs from each process in the three scenarios for the GWP impacts. For the business-as-usual scenario, methane (CH4) emissions from landfilling cassava waste are the main cause for climate change impacts (95% of the total), while organic fertilizers' application, as a second contributor, emit 2% of the total. With different feedstocks for AD plants, e.g., domestic sewage sludge, existing studies indicated similar findings of contributions of methane emissions in sludge landfilling or application (Cherubini et al., 2009; Wang et al., 2019). Furthermore, emissions from organic fertilizers' application cause around 70% and 50% GHG emissions for cassava cultivating process, which is in line with Lansche et al. (2020). These emissions also lead to around 30% of total emissions for both improved and closed-loop scenarios. Additionally, emissions from digestate storage in the improved scenario leads to around 38% of GWP impacts, while other inputs and emissions' contributions are negligible (up to 6%). Similarly, other inputs and emissions from fertilizers' application cause maximum 15% of GHG emissions in the closed-loop scenario. Therefore, as shown in Fig. 2b, adopting AD and CHP plant shows environmental advantages for the GWP impact category, which is in accordance with Lansche et al. (2020) for cassava waste.


WWEF closed-loop scenario
Improved scenario
Business-as-usual scenario
0.09
0.17
2.28
0.0
0.5
1.0
1.5
2.0
2.5
GWP
kg CO2-Eq
Cassava cultivating process
Cassva starch and flour process
Landill of cassava waste
AD process
CHP process

2 a)



2 b)

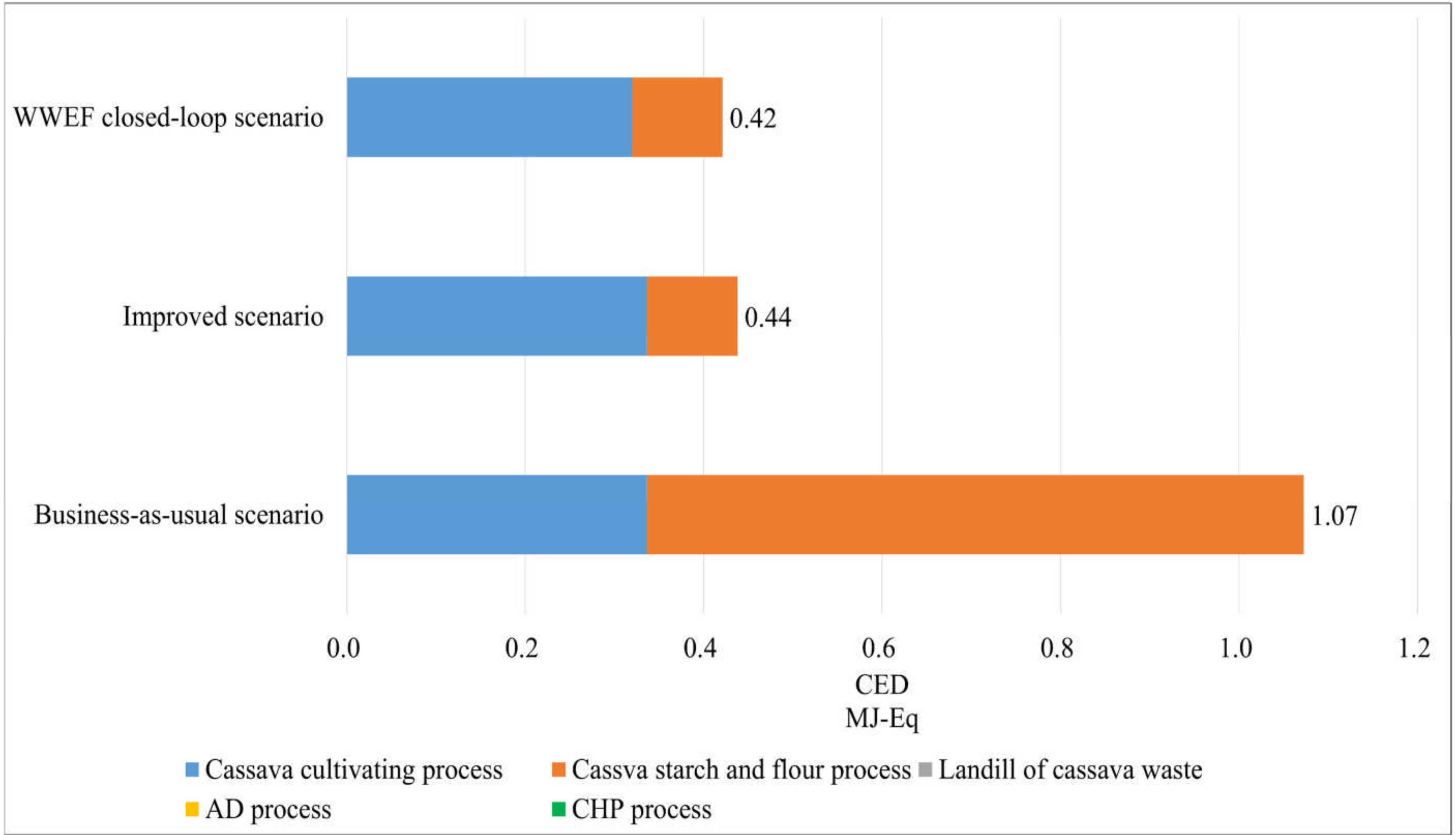
Fig. 2. a) contributions from stages and b) contributions from inputs and outputs for Global Warming Potential (GWP) for each scenario.

Based on functional unit (FU), i.e. generating 1 kg cassava product (starch/flour), Lansche et al. (2020) show GWP value of 1.02 kg CO_2-Eq/kg cassava starch produced for a Malaysia case study with the use of cassava waste for power generation. This is higher than the results of the WWEF closed-loop scenario with 0.09 kg CO_2-Eq/kg cassava starch/flour produced. The reason for this could be the use of different fertilizers, i.e. mineral and organic fertilizers.

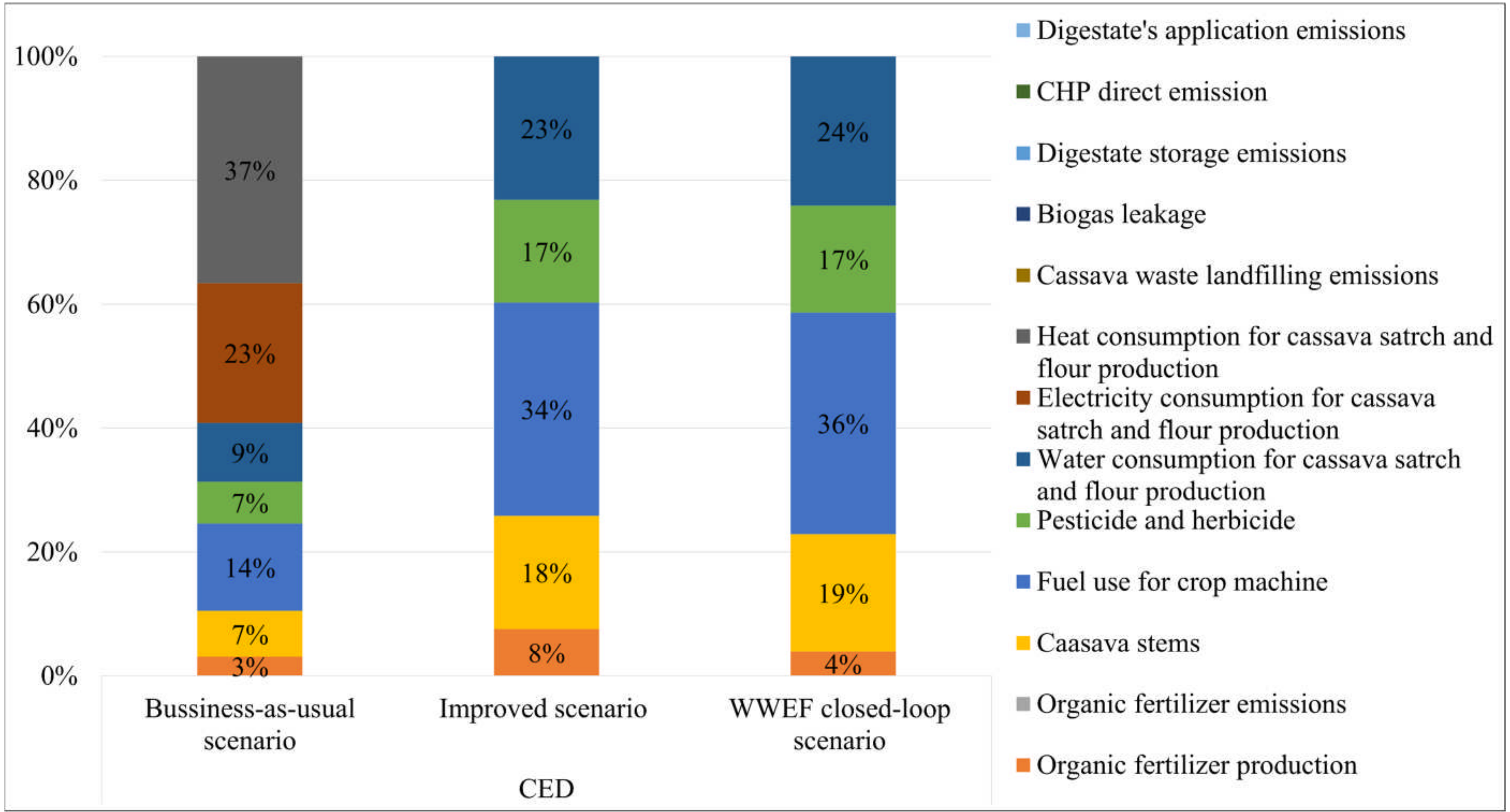
Based on the electricity generation in the energy process, the GHG emissions of the closed-loop scenario are calculated as 0.30 kg CO_2-Eq/kWh. Studies with similar results are found in existing literature (Fantin et al., 2015; Fusi et al., 2016; Rana et al., 2016; Rehl et al., 2012), which cite GHG emissions ranging from 0.209 to 0.408 kg CO_2-Eq/kWh from various feedstocks such as maize and animal slurry. This shows that the potential of GHG-emission contribution for generating electricity from cassava waste is comparable to other feedstocks. Furthermore, negative GHG emissions per kWh electricity in some studies are observed (Fusi et al., 2016; Lijó et al., 2014; Van Stappen et al., 2016), and this could be because these studies took the consequential LCA methods and created credits for electricity and other co-products. However, with consequential LCA, the GHG emissions can be overestimated, especially when it comes to bioenergy generation (Tsalidis and Korevaar, 2020).

3.2. Cumulative Energy Demand

The results of the three scenarios for the cumulative energy demand (CED) are presented in Fig. 3, illustrating that the WWEF closed-loop scenario emits the least CED impacts, followed by the improved and business-as-usual scenarios. With the recovery energy, the AD and CHP processes only generate air emissions while no energy and materials are consumed. Thus, these two processes have no contributions for the CED impacts. The cassava product (starch and flour) process in the business-as-usual scenario has contributed 69% for the CED impacts. However, for the improved and WWEF closed-loop scenarios, the cassava cultivating process contributes approximately 80% of the CED impacts. As it can be seen from Fig. 3b, which presents the proportion of CED impacts from inputs and outputs, in business-as-usual scenario, energy consumption (electricity and heat) contributes to the majority of the CED impacts with 60% of the total impacts. And this is the cause for the dominance of the cassava starch and flour process for the CED impacts. However, with energy recovery, the improved business-as-usual and WWEF closed -loop scenarios offset the impacts from energy consumption with 59% and 61% reduction, respectively. For both improved and closed-loop scenarios, water consumption for cassava starch and flour process, fuel use for crop machine and pesticide and herbicide application totally contribute to around 80% of the CED impacts. Although the direct application of digestate in the closed-loop scenario reduces the amount of organic fertilizer used, the reduction of the CED impacts is limited, with 4% impact mitigations compared to the improved scenario. For the generation of 1 kg cassava starch, Lansche et al. (2020) show higher CED impacts for Malaysia case with 9.48 MJ-Eq/kg cassava starch produced compared to 0.42 MJ-Eq/kg in this study. This is due to the large amount of power required to recover nitrogen and phosphate in their study. Same as GWP, the CED impacts of the closed-loop scenario are calculated as 1.4 MJ-Eq/kWh power generated. This shows significant improvement compared to the electricity from the national grid in Brazil (6.23 MJ-Eq/kWh) (Wernet et al., 2016). Although Shimako et al. (2016) investigated different feedstocks and regions, they stated that electricity from AD and CHP systems had better performance than the national grid electricity for CED impacts.


WWEF closed-loop scenario
Improved scenario
Business-as-usual scenario
0.42
0.44
1.07
0.0
0.2
0.4
0.6
0.8
1.0
1.2
CED
MJ-Eq
Cassava cultivating process
Cassva starch and flour process
Landill of cassava waste
AD process
CHP process

3 a)



3 b)

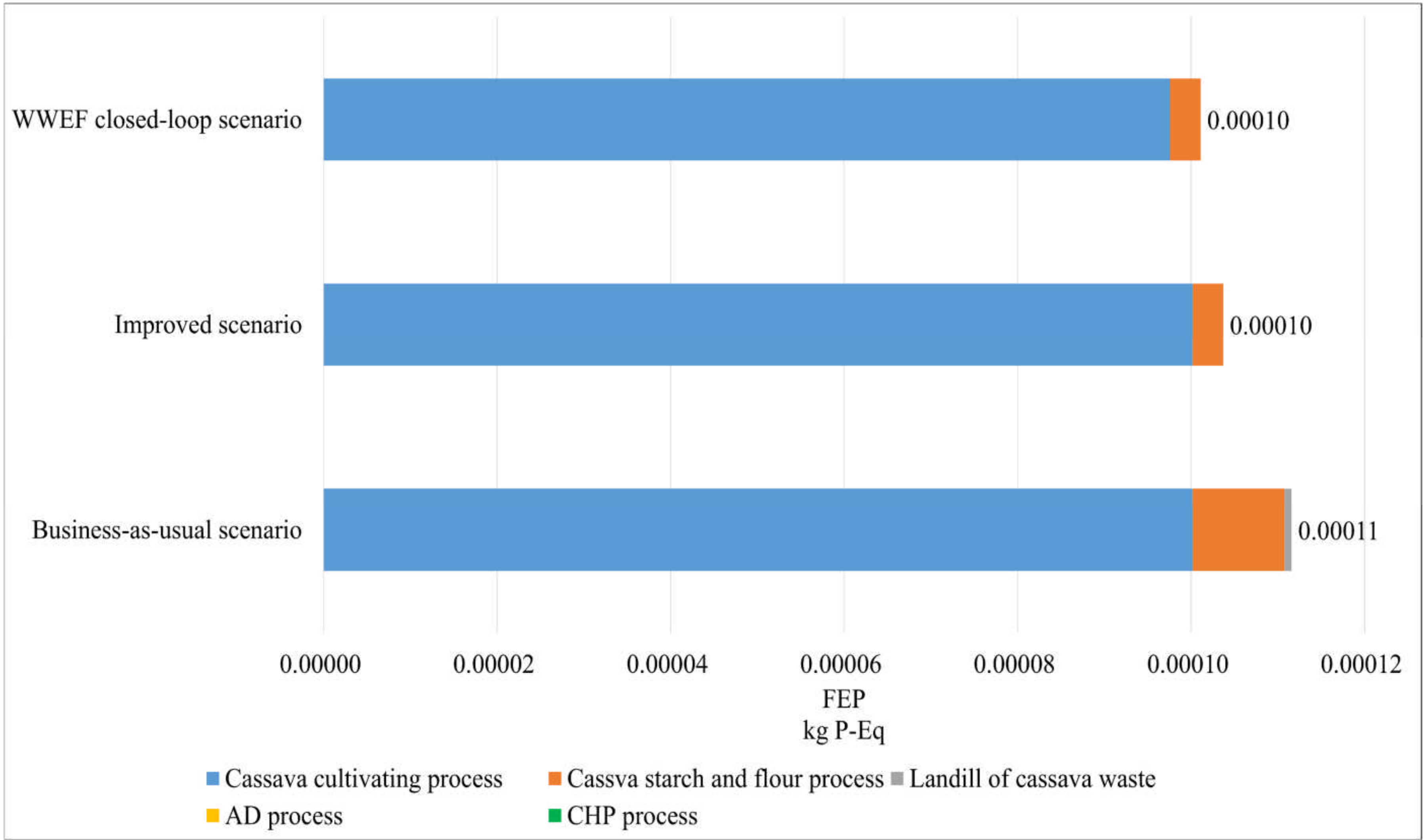
Fig. 3. a) contributions from stages and b) contributions from inputs and outputs for Cumulative Energy Demand (CED).

3.3. Freshwater eutrophication

For freshwater eutrophication (FEP) impacts, the general results of total P-Eq emissions for the three scenarios are similar to the previous two impact categories, i.e. the business-as-usual scenario is the worst one with highest FEP impacts, followed by the improved and closed-loop scenarios (see Fig. 4). The cassava cultivating process results in 90% of the FEP impacts for the business-as-usual scenario. In the improved and WWEF closed-loop scenarios, the emissions from AD and CHP plant have no effects on FEP impacts. Therefore, only the cassava cultivation and cassava starch and flour process emit P-Eq emissions. Both processes in these two scenarios contribute to the same percentage of P-Eq emissions, i.e. 97% from the cassava cultivating process and 3% from the cassava starch and flour process. Compared to the business-as-usual and the improved scenarios, the WWEF closed-loop scenario reduces P-Eq emissions by 9% and 3%, respectively. Fig. 4b demonstrates the contributions from each input and output for all three scenarios. The impacts from fertilizers' emissions dominate the FEP impacts in all three scenarios with contribution of around 80% of the total P-Eq emissions. Pesticide and herbicide, as the second contributor, contributes to approximately 5% of emissions in all three scenarios. The phosphate emissions from fertilizers' application are the major contributor, which is in line with the findings from Fantin et al. (2015). Meanwhile, in this study the phosphate emissions are strongly related to the quantity of soil erosion in Brazil, which is 9 ton/ha per year for all three scenarios. This is the reason why similar FEP impacts are emitted by all three scenarios. Although there are different feedstocks, Pacetti et al. (2015) stated that cultivating stage is the main contributor for FEP impacts with around 95% in an AD case. The improved scenario recovers theenergy from the system, but energy consumption contributes to insignificant emissions for the FEP impacts, i.e. around 7% of the total emissions in the business-as-usual scenario.

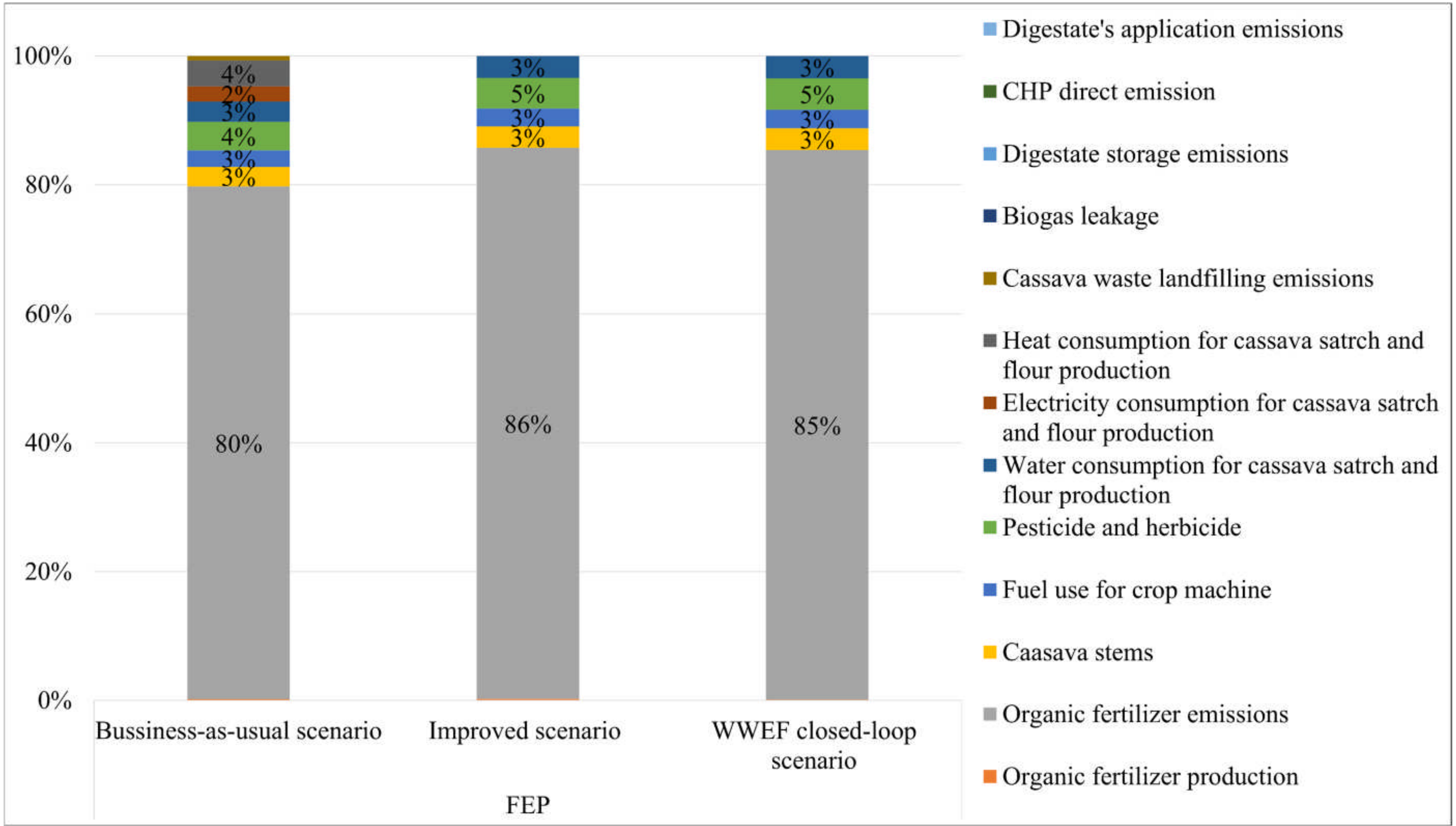
Similar to the previous impact categories, the results of FEP in this study are transformed into per kWh electricity generated in the WWEF system, i.e. 3.39x 10^{-4} kg P-Eq/kWh power for the closed-loop scenario. Similar results are found in Pacetti et al. (2015), although different feedstocks for AD units were assessed. Nevertheless, the consideration of credits from co-products based on consequential LCA also led to negative value of FEP impacts in the literature (Bacenetti and Fiala, 2015).

392



WWEF closed-loop scenario
Improved scenario
Business-as-usual scenario
0.00010
0.00010
0.00011
0.00000
0.00002
0.00004
0.00006
0.00008
0.00010
0.00012
FEP
kg P-Eq
Cassava cultivating process
Cassva starch and flour process
Landill of cassava waste
AD process
CHP process

393 4 a)



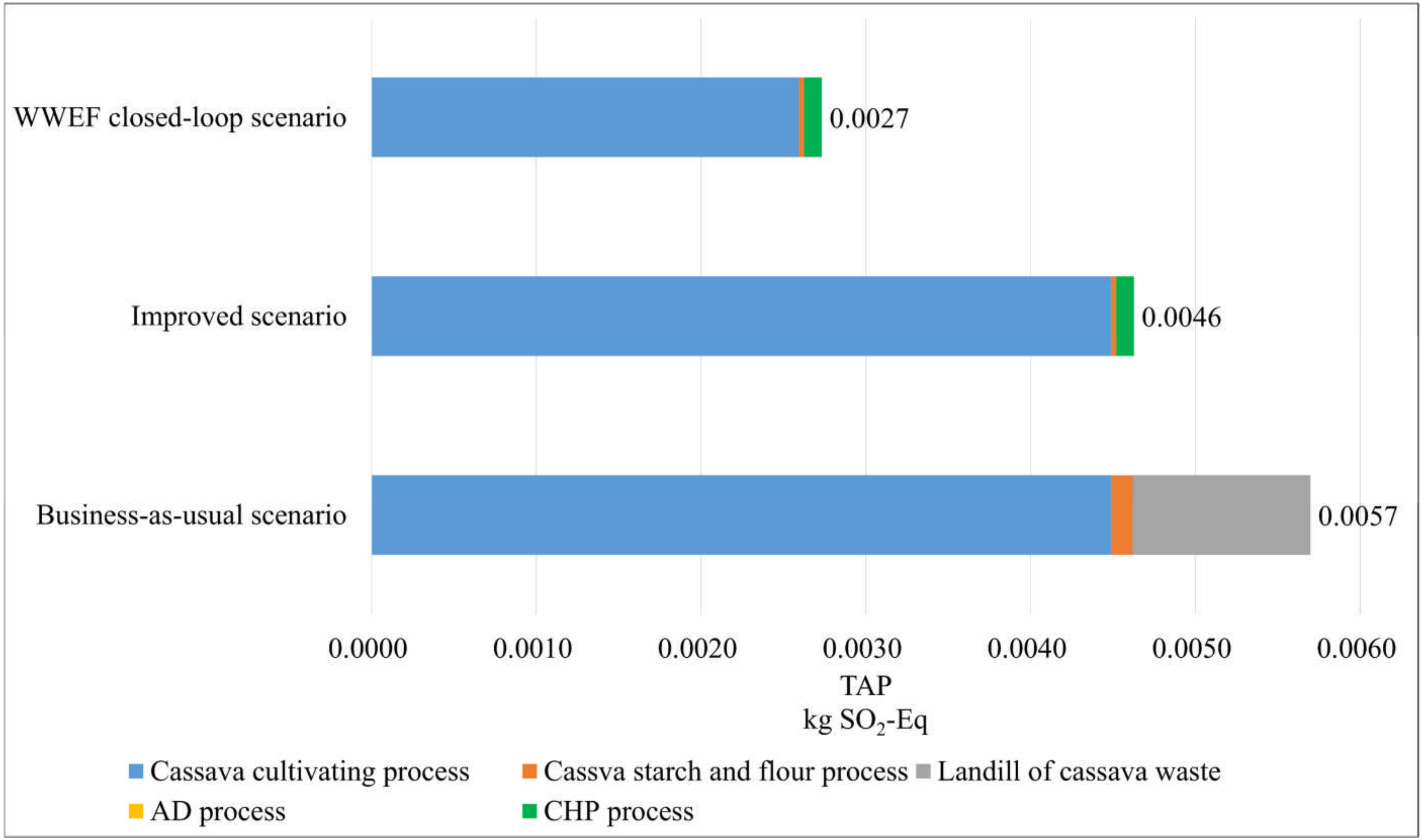
4 b)

Fig. 4. a) contributions from stages and b) contributions from inputs and outputs for Freshwater eutrophication (FEP).

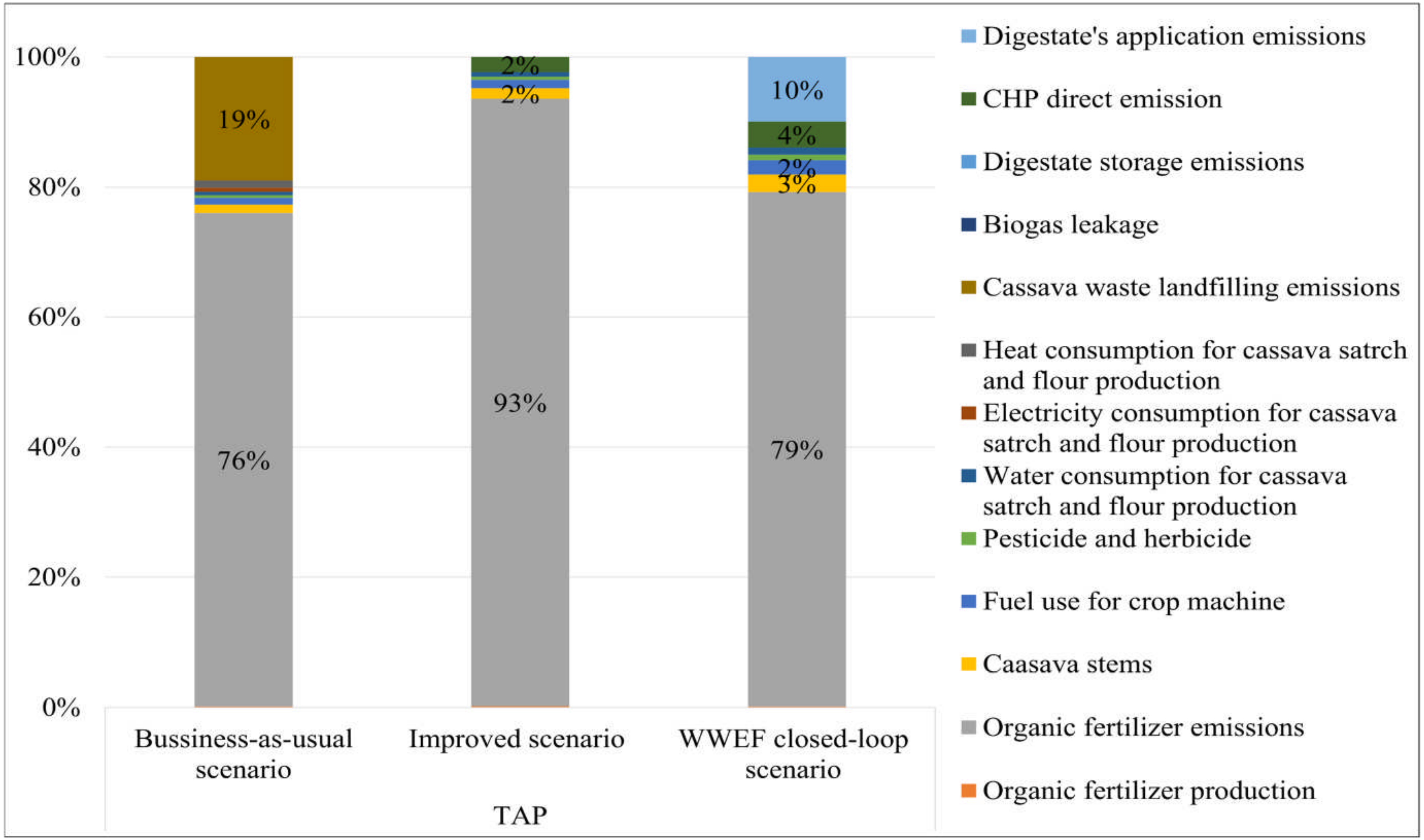
3.4. Terrestrial acidification

In Fig. 5, the WWEF closed-loop scenario is still the best scenario that emits the lowest value of SO_2-Eq emissions. The reduction of terrestrial acidification potential (TAP) impacts by the closed-loop scenario is 57% and 47% compared to the business-as-usual and improved scenarios, respectively. The cassava cultivating process and landfill of cassava waste contribute, respectively, to 79% and 19% of TAP impacts for the business-as-usual scenario. As it can be seen from Fig. 5b, in the business-as-usual scenario, the TAP impacts from emissions of organic fertilizers are 76% of the total, while emissions from landfilling of cassava waste contributes about 19% of TAP impacts. In the improved scenario, the cassava cultivating process causes the most significant TAP impacts with 93% of total impacts, followed by the CHP process (2%). In the closed-loop scenario, the cassava cultivating process and CHP process provide around 89% of the TAP impacts while the cassava cultivating process contributes 79% of the total emissions. Ammonia (NH_3) emissions from organic fertilizers' application are the major cause of the TAP impacts in all three scenarios (75%, 93% and 79% in the business-as-usual, improved and closed-loop scenarios, respectively), while NH_3 emissions from landfilling cassava waste (19%) and digestate application (10%) are the second contributors for the business-as-usual and closed-loop scenarios, respectively. Similar results are found in the study conducted by Fantin et al. (2015). The importance of NH_3 emissions to atmosphere for the TAP impacts has been acknowledged by Bacenetti et al. (2016) and Fantin et al. (2015). Due to the adoption of AD and CHP plant, the improved and closed-loop scenarios reduce the TAP impacts compared to the business-as-usual scenario by avoiding the landfilling of cassava waste.

Based on 1 kWh electricity generation, the TAP impacts are transformed into $9.17x10^{-3}$ kg SO_2-Eq for the closed-loop scenario. Existing literature shows similar results, ranging from $2.60x10^{-3}$ to $5.50x10^{-3}$ kg SO_2-Eq/ kWh power generated (Fusi et al., 2016). However, co-products contribute to credits (i.e. avoided burden) in some LCA studies, leading to a negative value of total emissions (Bacenetti et al., 2016; Pacetti et al., 2015)


WWEF closed-loop scenario
Improved scenario
Business-as-usual scenario
0.0027
0.0046
0.0057
0.0000
0.0010
0.0020
0.0030
0.0040
0.0050
0.0060
TAP
kg SO_2-Eq
Cassava cultivating process
Cassva starch and flour process
Landill of cassava waste
AD process
CHP process

5 a)



5 b)

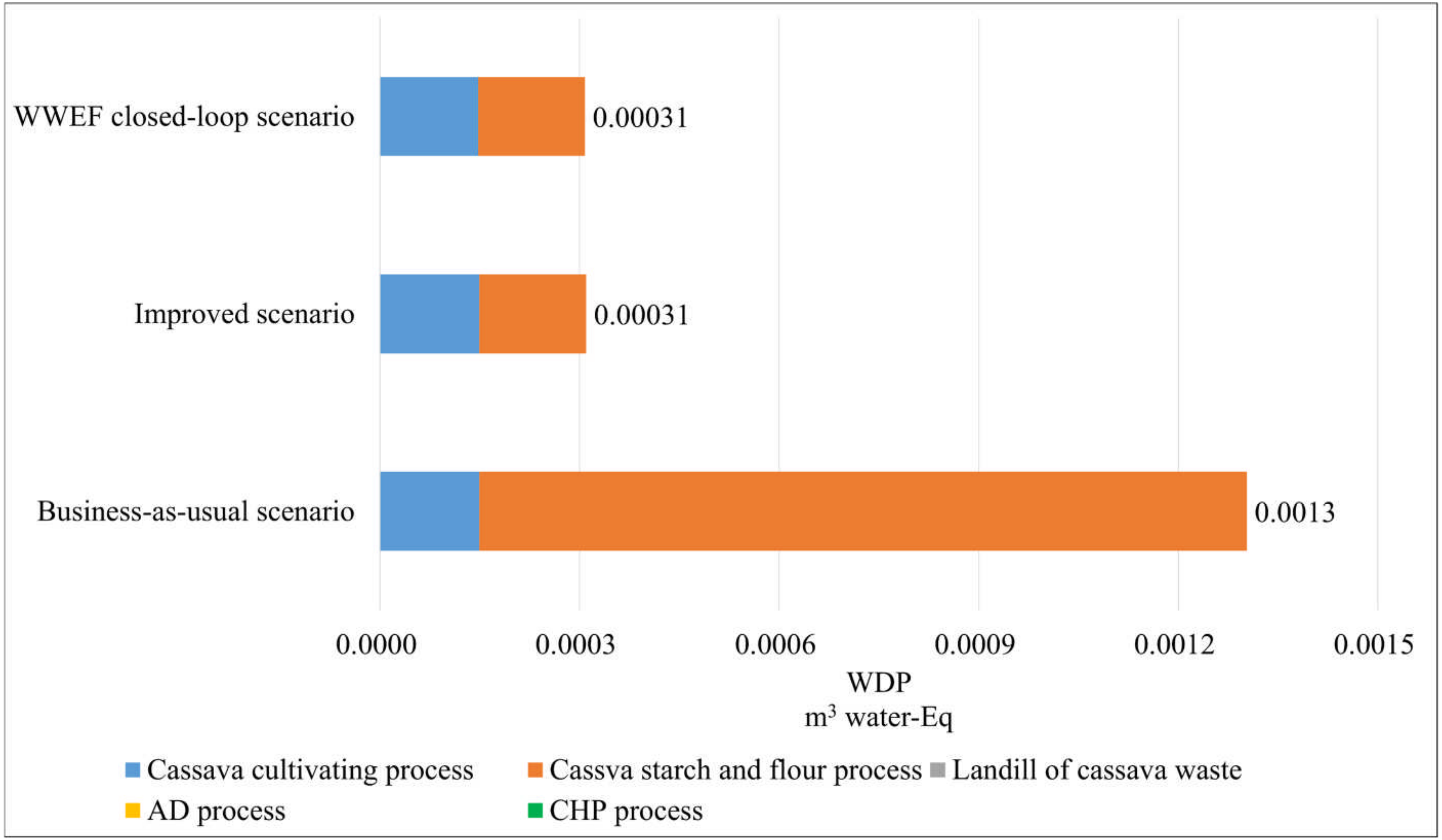
Fig. 5. a) contributions from stages and b) contributions from inputs and outputs for Terrestrial acidification (TAP).

3.5. Water depletion

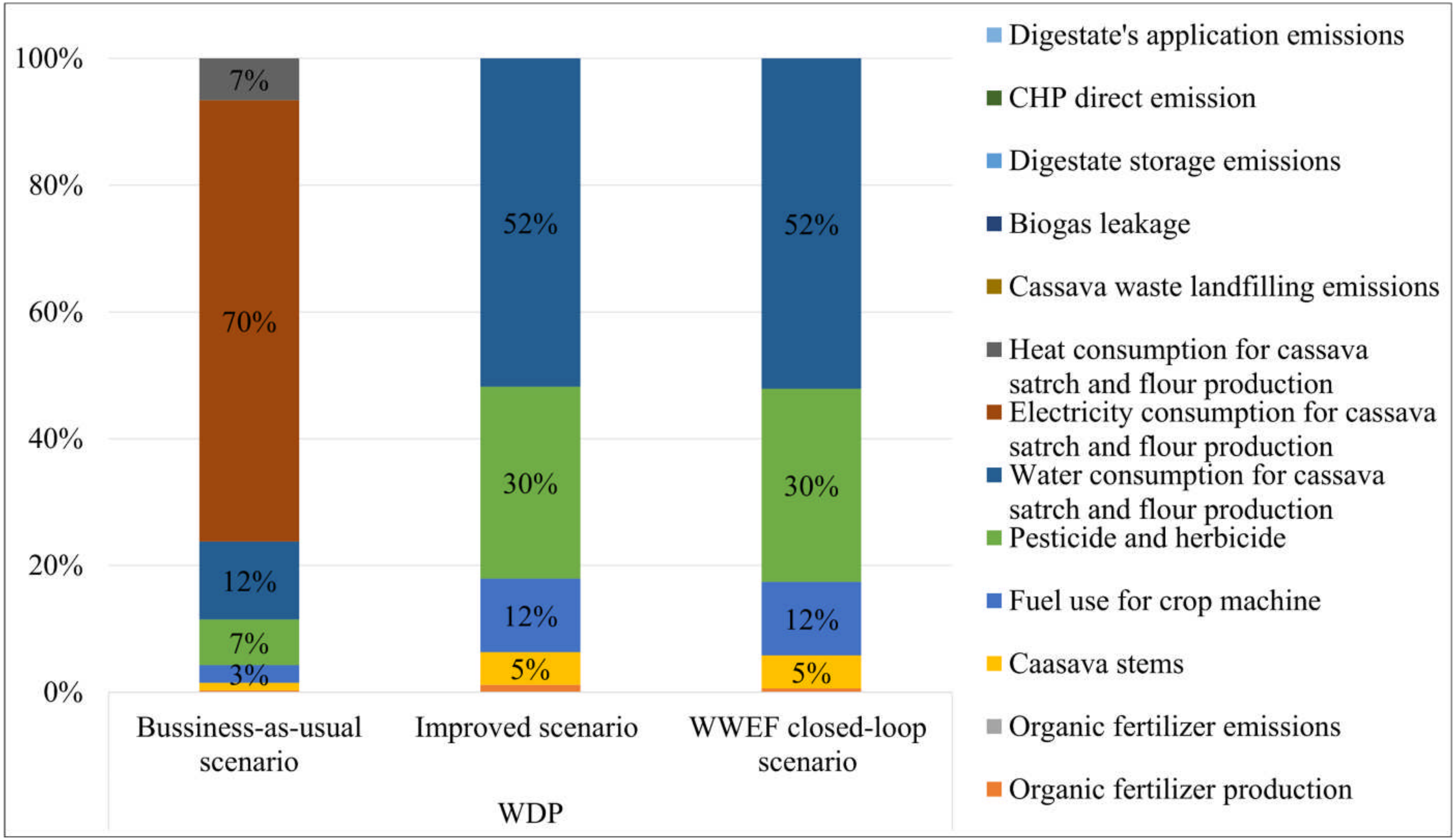
Compared to the business-as-usual scenario, both the improved and WWEF closed-loop scenarios reduced around 76% of impacts for water depletion potential (WDP). There is insignificant difference between the improved and the WWEF closed-loop scenarios, see Fig. 6. Among all three scenarios, AD and CHP processes have no contribution to the WDP impacts. The cassava product (starch/flour) process is the main WDP impacts emitter in the business-as-usual scenario (89% of the total), while in the other two scenarios cassava cultivating process contributes to similar impacts from the cassava product process (around 50% for each). As shown in Fig. 6b, electricity consumption from the national grid contributes 70% of the total WDP impacts for the business-as-usual scenario due to high contributions from hydro electricity production for electricity mix in Brazil. With the use of recovered electricity and avoidance of electricity use from national grid, water depletion impacts are avoided. Meanwhile, water consumption and pesticide and herbicide respectively provide around 10% of the total WDP impacts for the busines-as-usual scenario. With energy recovery in both improved and closed-loop scenarios, water consumption and pesticide and herbicide production dominate the WDP emissions with around 82% of the total emissions. Similar to CED, the energy recovery supports the improved and closed-loop scenarios to emit less impacts than the business-as-usual scenario. Meanwhile, insignificant amount of the WDP impacts is saved by nutrient recovery in the closed-loop scenario.

When compared to the electricity from the national grid (0.023 m^3 water-Eq/kWh) (Wernet et al., 2016), the closed-loop scenario presents a better performance (0.001 m^3 water-Eq/kWh).

Hence, further use of power from the WWEF system would mitigate the WDP impacts, which can also be observed from the comparison between the business-as-usual scenario and the other two scenarios, i.e. energy recovery avoids WDP impacts. With irrigation for feedstock cultivation, Pacetti et al. (2015) presented higher WDP impacts for electricity generation from AD units, ranging from 0.025 to 0.15 m^3 water-Eq/kWh. However, negative values for WDP impacts are also presented due to credits created by co-products (Slorach et al., 2019).

455

WWEF closed-loop scenario
0.00031
Improved scenario
0.00031
Business-as-usual scenario
0.0013
0.0000
0.0003
0.0006
0.0009
0.0012
0.0015
WDP
m3 water-Eq
Cassava cultivating process
Cassva starch and flour process
Landill of cassava waste
AD process
CHP process

456 6 a)

457


458 6 b)

459 Fig. 6. a) contributions from stages and b) contributions from inputs and outputs for Water depletion (WDP).

3.6. Sensitivity analysis

This study conducts the sensitivity analysis of the parameters that cause over 10% of environmental impacts for the five impact categories above. All three scenarios are assessed under the sensitivity analysis to identify the robustness of the results. As shown previously, for the business-as-usual scenario, the methane (CH_4) emissions from the landfilling cassava waste are the major contributor for the GWP impacts, while energy consumption (electricity and heat) strongly contributes to the CED and WDP impacts. Ammonia (NH_3) emissions from the organic fertilizers' application and landfilling cassava waste, and phosphate emissions from the organic fertilizer's application are identified as environmental hotspots for the TAP and FEP impacts in the business-as-usual scenario. Meanwhile, water consumption for cassava starch and flour process and fuel use for crop machines also provide over 10% of emissions for the WDP and CED impacts, hence they are included in the analysis. For the improved and closed-loop scenarios, N_2O emissions from fertilizers' application are environmental hotspot for the GWP impacts, while methane (CH4) emissions from digestate storage also contribute significant GHG emissions in the improved scenario. Meanwhile, fuel use for crop machines, biogas leakage and CHP plant emissions also provide around 12% of the GWP impacts in the closed-loop scenario. Furthermore, cassava stems, pesticide and herbicide consumption, fuel use for crop machine and water consumption are key parameters for the CED impacts in both improved and closed-loop scenarios. Similar to the business-as-usual scenario, phosphate emissions from cassava cultivating process are the biggest environmental hotspots for the FEP impacts as described above in both improved and closed-loop scenarios. Ammonia (NH_3) emissions from fertilizers' application are significant for the TAP impacts in both scenarios while emissions from digestate application contribute around 10% of the TAP impacts in the closed-loop scenario. Furthermore, the major WDP impact contributors in both improved and closed-loop scenarios are water consumption for cassava starch and flour process, fuel use for crop machines and pesticide and herbicide use. In this study, the sensitivity analysis assumes a 20% decrease of these inputs or emissions to identify the robustness of the results.

Table. 3 shows the results of the sensitivity analysis for the selected parameters. In business-as-usual scenario, methane emissions from cassava waste (0.95), heat consumptions (0.37), phosphate emissions (0.80), ammonia emissions from fertilizers' application (0.75) and electricity consumptions (0.70) are, respectively, the most sensitive for the GWP, CED, FEP, TAP and WDP impact categories. Meanwhile, fuel use for crop machines and electricity consumption are relatively sensitive for the CED impacts (0.14 and 0.23, respectively) while ammonia emissions from landfilling cassava waste (0.19) and water consumption (0.12) also affect the TAP and WDP impacts. In the improved scenario, N_2O emissions from fertilizers' application and methane (CH4) emissions from digestate storage are sensitive for the GWP impacts with the ratio of over 0.30, while fuel use for crop machine, cassava stems, water consumption and pesticide and herbicide use are considered sensitive for the CED impacts. Meanwhile, phosphate emissions and ammonia emissions from fertilizers' application are most sensitive for the FEP and TAP impacts in the improved scenario. For WDP, fuel use for crop machine, water consumption, and pesticide and herbicide are strongly sensitive parameters. Afterwards, similarly phosphate emissions and ammonia emissions from fertilizers' application are the most sensitive parameters for the FEP and TAP impacts in the WWEF closed-loop scenario, while 0.10 of sensitivity ratio are observed for digestate application emissions for TAP. Fuel use for crop machine, water consumption and pesticide and herbicide are sensitive to WDP and CED, while cassava stems are also considered a sensitive parameter for CED with the ratio of 0.19. For the GWP impacts in the closed-loop scenario, N_2O emissions from fertilizers' application are the most sensitive (0.30), followed by biogas leakage (0.15), CHP plant emissions (0.12), fuel use for crop machine and emissions from digestate application (0.11 for each). Therefore, the sensitivity analysis demonstrates the robustness of the results from this study.

Table. 3. Sensitivity analysis for selected parameters.

Scenario	Sensitivity parameter	Sensitivity ratio				
		GWP	CED	FEP	TAP	WDP
Business-as-usual scenario	Methane emissions from cassava waste -20%	0.95	N	N	N	N
	Fuel use for crop machine -20%	N	0.14	0.03	0.01	0.03
	Heat consumption for cassava starch and flour process -20%	N	0.37	0.04	0.01	0.07
	Electricity consumption for cassava starch and flour process -20%	N	0.23	0.02	0.01	0.70
	Phosphate leaching from organic fertilizers' application -20%	N	N	0.80	N	N
	Ammonia (NH3) emissions from organic fertilizers' application -20%	N	N	N	0.75	N
	Ammonia (NH3) emissions from landfilling cassava waste -20%	N	N	N	0.19	N
	Water consumption for cassava starch and flour process -20%	N	0.09	0.03	0.01	0.12
Improved scenario	N2O emissions from fertilizers' application-20%	0.31	N	N	N	N
	Methane (CH4) emissions from digestate storage -20%	0.38	N	N	N	N
	Cassava stems -20%	0.04	0.18	0.03	0.02	0.05
	Fuel use for crop machine -20%	0.06	0.34	0.03	0.01	0.12
	Water consumption for cassava starch and flour process -20%	0.04	0.23	0.03	0.01	0.52
	Phosphate leaching from organic fertilizers' application -20%	N	N	0.86	N	N
	Ammonia (NH3) emissions from organic fertilizers' application -20%	N	N	0.00	0.93	N
	Pesticide and herbicide -20%	0.02	0.17	0.05	N	0.30
WWEF closed-loop scenario	N2O emissions from fertilizers' application -20%	0.30	N	N	N	N
	Cassava stems -20%	0.08	0.19	0.03	0.03	0.05
	Fuel use for crop machine-20%	0.11	0.36	0.03	0.02	0.12
	Biogas leakage -20%	0.15	N	N	N	N
	CHP direct emissions -20%	0.12	N	N	0.04	N
	Emissions from digestate application -20%	0.11	N	N	0.10	N
	Water consumption for cassava starch and flour process -20%	0.08	0.24	0.03	0.01	0.52

	Phosphate leaching from organic fertilizers' application -20%	N	N	0.85	N	N
	Ammonia (NH3) emissions from organic fertilizers' application -20%	N	N	N	0.79	N
	Pesticide and herbicide -20%	0.04	0.17	0.05	0.01	0.30

Note: N: no effect.

3.7. Lessons learned

Results in this study reveal that business-as-usual Brazilian cassava starch/flour industry should pay more attention to avoid landfilling cassava waste, especially when reducing GHG emissions. Power consumption, e.g. electricity use, needs to be reduced in terms of CED and WDP impacts. Meanwhile, cultivation of cassava shows high impacts for the FEP and TAP impact categories due to organic fertilizer application. Compared to the business-as-usual scenario, the improved scenario has better environmental performance in all 5 selected impact categories by avoiding landfilling waste and therefore recovering power and nutrients. Furthermore, the WWEF close-loop scenario, by recovering nutrients, is the best choice for the local industry to improve environmental performance. Hence, this study suggests the WWEF close-loop system as a promising solution for local cassava product industry to turn cassava waste to feedstock of AD and CHP plant (i.e. power and nutrient recovery) and therefore saving environmental impacts for all 5 selected impact categories.

Limitations of this study should be highlighted, as some of them sometimes are important for further investigations. Firstly, this study adopted primary and secondary data from local industry and published papers and reports for the life cycle inventory. This might leave some uncertainties for the results, which requires an uncertainty analysis to avoid overestimations of the significance of findings (Geisler et al., 2005). To overcome the data availability issue, sensitivity analysis has been conducted while efforts on primary data collection for the whole supply chain are suggested for future work. Secondly, the scope of this study is limited to the AD and CHP technologies for the WWEF system. However, more nutrient and power recovery technologies should be included concerning to further improve efficiency of recovery. For example, more power and full nutrients can be recovered by an enzymatic technology for food waste (Ma et al., 2020). This might further improve the environmental performance of the WWEF system, but this requires more investigation. Finally, when compared to literature, consequential LCA methods are acknowledged to affect results. Hence, a consequential LCA study for the WWEF system is suggested to see how consequence of WWEF systems influences the current system.

4. Conclusions

To the authors' best knowledge, this study is first done for assessing environmental impacts of the current model and proposed WWEF system for the Brazilian cassava product industry. Findings can be used to support the case study of the cassava industry in Goias state (Brazil). This work adopts environmental LCA method and compared the business-as-usual scenario, the improved scenario and the WWEF closed-loop scenario. Landfilling cassava waste, electricity use and organic fertilizer application are identified as key contributors for the 5 selected impact categories in the business-as-usual scenario, suggesting the need for improving the environmental performance from these activities for the local industry. With power and nutrient recovery, the WWEF closed-loop system shows promising potential to improve the local cassava product industry in Brazil. Sensitivity analysis reinforces the robustness of the results. Meanwhile, to further improve this study methodologically, uncertainty analysis, considering more advanced technologies, and conducting consequential LCA study are recommended.

Acknowledgements

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CRediT author statement

Haodong Lin: Methodology, Formal Analyses, Investigation, Writing Original-Draft, Visualization; **Aiduan Borrion**: Conceptualization, Methodology, Supervision, Writing - Review & Editing; **Warde Antonieta da Fonseca-Zang**: Conceptualization, Resources, Writing - Review & Editing, Funding acquisition; **Joachim Werner Zang**: Conceptualization, Writing - Review & Editing; **Wilson Mozena Leandro**: Conceptualization, Writing - Review & Editing; **Luiza Cintra Campos**: Conceptualization, Supervision, Writing - Review & Editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Table A. 1. Summary of raw data for life cycle inventory for the WWEF system

Process	Activity	Materials/energy	Amount	Unit	Source
Inputs for the system					
Cassava cultivating process	Fertilizer	Chicken manure	$4.20x10^{3}$	kg/ha	Biratu et al. (2018)
		Chicken manure (N)	$1.30x10^{2}$	kg/ha	Provided by the industry
		Chicken manure (P)	$1.20x10^{2}$	kg/ha	Provided by the industry
		Chicken manure (K)	3.70x10	kg/ha	Provided by the industry
	Stems	Cassava stems	$6.80x10^{2}$	stems/ha	Jarvis et al. (2005)
	Corp machine	Diesel	$7.44x10^{2}$	MJ/ha	Pingmuanglek et al. (2017)
	Pesticide	Fungicide -Insecticide	$7.70x10^{-5}$	kg/kg root	Botero Agudelo et al. (2011)
	Herbicide	Glyphosate	$1.50x10^{-4}$	kg/kg root	Botero Agudelo et al. (2011)
Cassava starch process	Processing	Water	$2.74x10^{0}$	kg/kg root	Provided by the industry
		Electricity	$2.33\ x10^{-2}$	kWh/kg root	Provided by the industry
		Heat	$3.05\ x10^{-1}$	MJ/kg root	Pingmuanglek et al. (2017)
Biogas process	AD	Electricity	$9.72\ x10^{-3}$	kWh/MJ output	Kimming et al. (2011)
		Heat	$2.20\ x10^{-1}$	MJ/MJ output	Kimming et al. (2011)
Energy process	CHP plants	Electricity	$1.25\ x10^{-2}$	kWh/MJ output	Mohammadi et al. (2019)
Yield products and emissions					
Cassava cultivating process	Fertilizers’ emissions	Ammonia (NH_3)	$2.37x10^{1}$	kg/ha	Prudêncio da Silva et al. (2014)
		N_2O	$2.46x10^{0}$	kg/ha	Prudêncio da Silva et al. (2014)
		NO_x	$5.16x10^{-1}$	kg/ha	Prudêncio da Silva et al. (2014)
		Nitrate	$2.00x10^{1}$	kg/ha	Prudêncio da Silva et al. (2014)

		Phosphate	$3.63x10^{0}$	kg/ha	Nemecek and Schnetzer (2011); Prudêncio da Silva et al. (2014)
Cassava product process	Processing	Cassava product	$6.00x10^{-1}$	kg/kg root	Provided by the industry
		Cassava pulp	$4.00x10^{-1}$	kg/kg root	Provided by the industry
		Wastewater	$2.74x10^{0}$	kg/kg root	Calculated by mass balance
	Cassava waste emissions	nitrate	$1.83x10^{-6}$	kg/kg cassava waste	Obueh and Odesiri-Eruteyan (2016)
		phosphate	$4.50x10^{-7}$	kg/kg cassava waste	Obueh and Odesiri-Eruteyan (2016)
		Methane (CH_4)	$8.20x10^{-2}$	kg/kg cassava pulp	Panichnumsin et al. (2010); Scharff and Jacobs (2006); Tampio et al. (2016)
			$7.00x10^{-3}$	kg/kg cassava wastewater	Achi et al. (2020); Scharff and Jacobs (2006); Tampio et al. (2016)
		N_2O	$1.27x10^{-5}$	kg/kg cassava pulp	Panichnumsin et al. (2010); Pardo et al. (2015)
			$8.25x10^{-6}$	kg/kg cassava wastewater	Achi et al. (2020); Pardo et al. (2015)
		Ammonia (NH_3)	$1.22x10^{-4}$	kg/kg cassava pulp	Panichnumsin et al. (2010); Pardo et al. (2015)
			$7.88x10^{-5}$	kg/kg cassava wastewater	Achi et al. (2020); Pardo et al. (2015)
AD process	Processing	Biogas	$1.44x10^{0}$	MJ/kg pulp	Evangelisti et al. (2014)
			$8.28x10^{-2}$	MJ/kg wastewater	Evangelisti et al. (2014)
		Digestate	$9.24x10^{-1}$	kg/kg pulp	Calculated by mass balance
			$9.96x10^{-1}$	kg/kg wastewater	Calculated by mass balance

	Biogas leakage	CO_2	1.57×10^{-2}	kg/m3 biogas yield	Evangelisti et al. (2014); Tampio et al. (2016)
		CH_4	8.64×10^{-3}	kg/m3 biogas yield	Evangelisti et al. (2014); Tampio et al. (2016)
	Digestate storage emissions	Methane (CH_4)	5.07×10^{-4}	kg/kg digestate	Panichnumsin et al. (2010); Styles et al. (2018)
		Ammonia (NH_3)	2.07×10^{-7}	kg/kg digestate	Panichnumsin et al. (2010); Styles et al. (2018)
	Emissions from the use of digestate	Ammonia (NH_3)	1.04×10^{0}	kg/ha	Yoshida et al. (2016)
		N_2O	1.50×10^{0}	kg/ha	Yoshida et al. (2016)
		NO_x	3.14×10^{-1}	kg/ha	Prudêncio da Silva et al. (2014)
		Nitrate	2.00×10^{1}	kg/ha	Prudêncio da Silva et al. (2014)
CHP process	Processing	Electricity	32%	efficiency	Patterson et al. (2011)
		Heat	50%	efficiency	Patterson et al. (2011)
	CHP plants' emissions	CO	1.15×10^{-1}	g/MJ biogas	Evangelisti et al. (2014)
		NO_x	1.48×10^{-1}	g/MJ biogas	Evangelisti et al. (2014)
		Methane (CH_4)	4.65×10^{-1}	g/MJ biogas	Evangelisti et al. (2014)
		NMVOC	1.05×10^{-1}	g/MJ biogas	Evangelisti et al. (2014)

Table A. 2. Characterization factor of inputs and outputs.

Impact category	GWP (kg CO2-Eq/unit)	FEP (kg P-Eq/ unit))	TAP (kg SO2-Eq/ unit)	WDP (m^3 water-Eq/ unit))	CED (MJ-Eq/ unit))	Source
Chicken manure (N)	1.34×10^{-1}	1.62×10^{-5}	6.48×10^{-4}	2.40×10^{-4}	2.19×10^{0}	Ecoinvent v3.5
Chicken manure (P)	6.81×10^{-2}	8.24×10^{-6}	3.30×10^{-4}	1.22×10^{-4}	1.12×10^{0}	Ecoinvent v3.5
Chicken manure (K)	5.31×10^{-2}	6.43×10^{-6}	2.58×10^{-4}	9.53×10^{-5}	8.71×10^{-1}	Ecoinvent v3.5
Cassava stems	1.43×10^{-1}	6.77×10^{-5}	1.46×10^{-3}	3.18×10^{-4}	1.58×10^{0}	Ecoinvent v3.5
Diesel	1.82×10^{-1}	5.28×10^{-5}	1.09×10^{-3}	6.50×10^{-4}	2.73×10^{0}	Ecoinvent v3.5
Fungicide - Insecticide	9.74×10^{0}	6.05×10^{-3}	8.31×10^{-2}	2.13×10^{-1}	1.80×10^{2}	Ecoinvent v3.5
Glyphosate	1.10×10^{1}	1.65×10^{-2}	4.89×10^{-2}	2.66×10^{-1}	1.98×10^{2}	Ecoinvent v3.5
water	1.50×10^{-3}	7.71×10^{-7}	6.67×10^{-6}	3.51×10^{-5}	2.22×10^{-2}	Ecoinvent v3.5
Electricity	2.45×10^{-1}	6.70×10^{-5}	9.21×10^{-4}	2.34×10^{-2}	6.23×10^{0}	Ecoinvent v3.5
Heat	1.79×10^{-2}	8.82×10^{-6}	1.25×10^{-4}	1.68×10^{-4}	7.73×10^{-1}	Ecoinvent v3.5
Ammonia (NH_3)	0.00×10^{0}	0.00×10^{0}	2.45×10^{0}	0.00×10^{0}	0.00×10^{0}	ReCiPe v1.13

N_2O	$2.98x10^{2}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13
NO_x	$2.45x10^{0}$	$0.00x10^{0}$	$5.60x10^{-1}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13
Nitrate	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13
Phosphate	$0.00x10^{0}$	$3.30x10^{-1}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13
Methane	$2.50x10^{1}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13
CO_2	$1.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13
CO	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13
NMVOC	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	$0.00x10^{0}$	ReCiPe v1.13

583 Note: Unit varies for different substance, but including kg for material and emissions, kWh for electricity and MJ for heat.

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