Implementing Circular Economy Concept by Converting Cassava Pulp and Wastewater to Biogas for Sustainable Production in Starch Industry

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Research

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Implementing Circular Economy Concept by Converting Cassava Pulp and Wastewater to Biogas for Sustainable Production in Starch Industry

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Highlights

- Converting cassava pulp and wastewater to biogas is one way to apply CE concept.
- 77% of GHG emission reduction comes from using cassava pulp and wastewater to biogas production.
- The advantages of CE concept adaption in cassava starch industry are increase energy security and resource efficiency.
- Regulatory and social responsibility are the key drivers for CE concept implementation in cassava starch industry.

Abstract

This research integrated the circular economy (CE) concept in the cassava starch industry in Thailand, and revealed the benefits of biogas generation from both the wastewater and waste cassava pulp with a focus on the identification and analysis of the key drivers and challenges to increase the efficiency of the biogas system. The research methodology applied the CE concept for scenarios of cassava pulp utilization for biogas production, compared to the no waste treatment and anaerobic wastewater treatment scenarios, in terms of an economic assessment, resource efficiency, water recovery, land use, and global warming potential. Proposed options mainly involved the conservation of energy, water, land use, and reduction

of greenhouse gases emissions. These included the reuse and recycling of water and use of biogas to substitute for fuel oil for burners and electricity in the cassava starch production process.

Keywords: anaerobic digestion, GHG emission, biogas, tapioca starch

1. Introduction

The circular economy (CE) concept, or simply circularity, is an increasingly popular concept in the effort to maximize resources and minimize waste. It is an economic system aimed at eliminating waste and continually using or recirculating resources. The CE concept involves the reuse, sharing, repairing, refurbishing, remanufacturing, and recycling of materials to create a closed-loop system. The advantages of the CE concept are reduced costs from the efficient use of energy and resources and waste management costs, increased income from waste utilization as a raw material in the process, and reduced emissions, pollution, and release of chemical substances to the environment via soil, water, and air (Geissdoerfer et al., 2017; Lieder and Rashid 2016; Murray et al., 2017; Morseletto, 2020).

Cassava is an economically important tuber crop in Thailand that is used in food, animal feed, pharmaceuticals, production of bioethanol, and other industries. In 2017, Thailand was the world's largest exporter of cassava starch with a 68% market share. Approximately 4.2 million tons (t) of native cassava starch were produced in Thailand and 75% of this was exported (Chuasuwan, 2018). The export value of native starch increased from US$ 1.2 billion in 2017 to US$ 1.5 Billion in 2018 (Thai Customs Department, 2019).

The cassava starch production process (CSPP) generally has eight steps, which are comprised of: receiving cassava roots from suppliers, screening out rocks and soil, washing the roots, rasping them into smaller pieces, extracting the starch granules from the cassava pulp, separating the impurity from the starch slurry, dewatering, and drying to obtain starch (Songkasiri et al., 2014a), as shown in Figure 1. One ton of starch is produced from approximately 4.4 t of cassava roots, using 10.9 m^3 of water, 207.8 kWh of electricity, 1,898.2 MJ of fuel for drying the starch, 0.9 kg of chemicals, and 93.1 m^3 of biogas for use in the boiler and to generate electricity. Wastes from the CSPP typically consist of 0.6 t rhizomes, 0.17 t sand, 0.1 t cassava peels, 2.5 t wet pulp, 8.4 m^3 wastewater, and 4.0 kg of low-grade starch (Trakulvichean et al., 2019).

The wastewater has a high chemical organic content, measured as an oxygen demand (COD) level (4,800 – 70,000 mg/L), high total volatile solids (1,200 – 39,000 mg/L), and a low pH (4.3 – 5.6) (Chavalparit and Ongwandee, 2009; Colin et al., 2007; Paixão et al., 2000;

Songkasiri et al., 2014b; Sun et al., 2012; Wang et al., 2011; Zhang et al., 2011). In 2014, Thailand produced biogas from the starch wastewater at a total amount of approximately 550 million Nm^3 from 122 biogas plants. The biogas was used to produce 127.5 MW of electricity and 181.5 ktoe of heat (DEDE, 2014).

The Thai 20-Year National Policy Plan (2017 – 2036) focuses on a bio-, circular, and green (BCG) economy approach as a step towards solving the natural resource problems and improving the environment and social sustainability of the country. The BCG economy in Thailand focuses on reducing raw materials and waste, improving production efficiency, upgrading technology, and creating innovation for a higher efficiency (NSTDA, 2018).

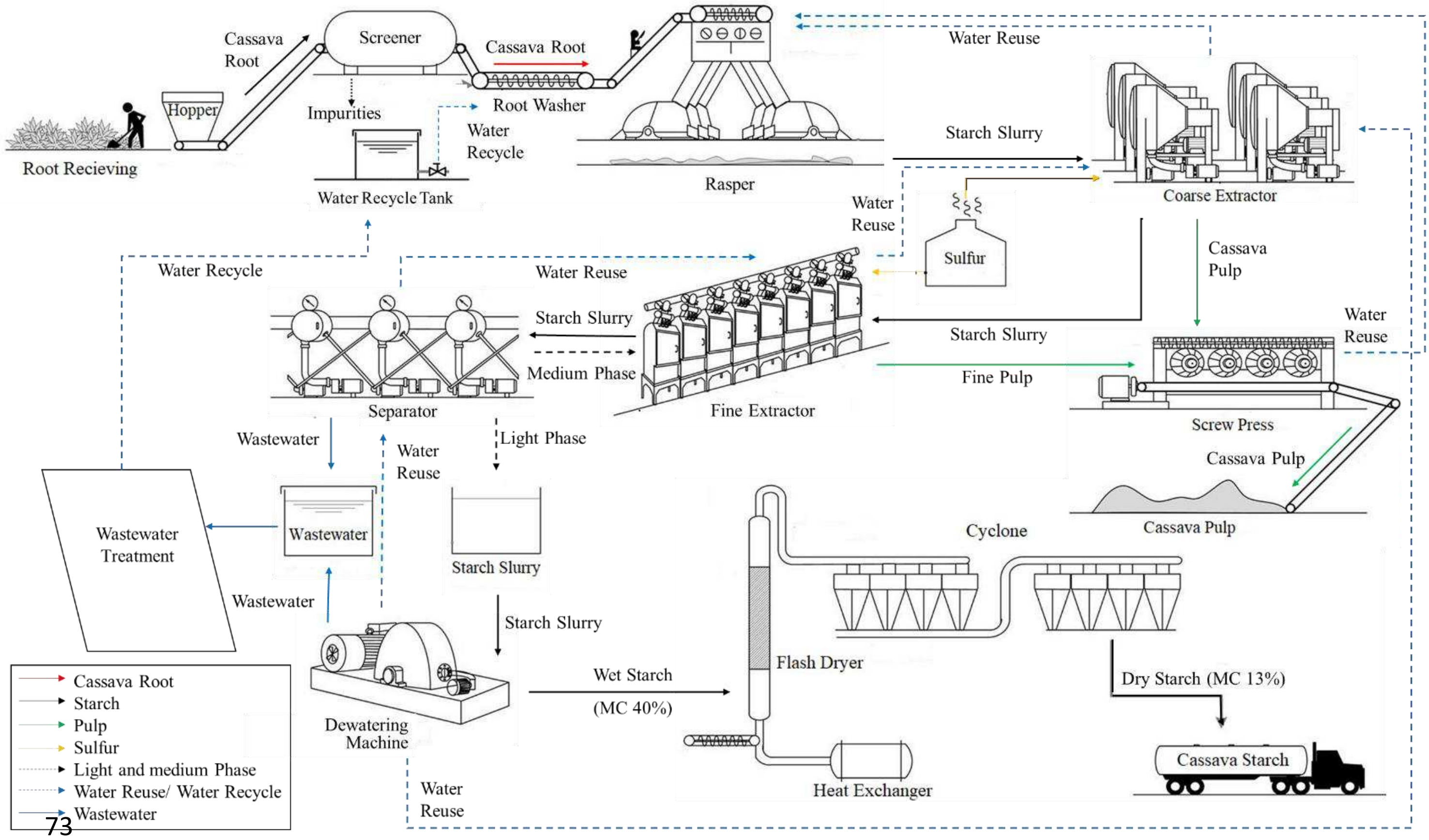

Fig. 1 Schematic diagram summarizing the CSPP (Songkasiri et al., 2014a)

The CE concept applied in the CSPP can lead to sustainable development, a higher economic profit, and a more efficient resource usage through waste minimization, as well as environmental benefits (Geissdoerfer et al., 2017; Lieder and Rashid 2016; Murray et al., 2017; Morseletto, 2020). Normally, the CSPP generates wastewater and solid waste. These cause environmental problems from the wastewater and solid waste discharge and emission release. Other than anaerobic wastewater treatment to generate biogas, the reuse and recycle methods can be applied to the CSPP to minimize the wastewater (Dakwala, 2011; Yesaswini and Saravanathamizhan, 2018).

The reuse of wastewater exiting CSPP is proposed as follows: (i) wastewater from coarse extraction and pulp dewatering unit are reused to chopping and rasping unit, (ii) wastewater from the fine extraction, separating, and dewatering units are reused to coarse extraction unit, (iii) wastewater from the separating unit reused to fine extraction unit, and (iv) wastewater from dewatering unit reused to separating unit. Accumulation of contaminants, i.e., protein and fiber is needed to be monitored (Songkasiri et al., 2014a).

For the water recycling, wastewater from the CSPP occurs in the separating unit (Chavalparit and Ongwandee, 2009; Songkasiri et al., 2014b). The effluent stream consists of starch, protein, fine fiber, and toxic chemicals and can be treated by both aerobic and anaerobic treatments. However, aerobic treatment produces a bad odor and requires a large area so most cassava starch factories use anaerobic treatment. The advantages of the anaerobic treatment are (i) reduce the cyanide toxicity, (ii) reduce bad odors, and (iii) remove the organic matter to produce biogas (Fukushima et al., 2016; Rajbhandari and Annachhatre, 2014; Oliveira, et al., 2001).

Wastewater from the CSPP is used to produce biogas, which in turn is used to generate heat and electricity for factories with surplus electricity being sold to the grid. According to the updated Thai Alternative Energy Development Plan (AEDP) in 2018 under the concept of energy security, there has been a tendency to increase strategies that promote biogas formation from waste and wastewater, and this is predicted to increase from the current 546 MW to 928 MW by 2037, which would increase the proportion of electricity produced from renewable energy (RE) in Thailand to 20% of the overall capacity in the country (DEDE, 2019).

Solid waste from the CSPP consists of pulp, peel, sand, and rhizomes. The adaptation of CE concept by using the solid waste as the raw material to produce value added products is an important option for the long-term sustainability of the CSPP. These valued added products can be divided in three sectors: biofuels, biochemical, and biobased products for agriculture.

Peel, sand, and rhizomes are usually used as a soil conditioner. Moreover, other options for peel utilization include to sell it as animal feed and to use to produce biofuel, such as biochar. (Lounglawan et al., 2011; Sivamani et al., 2018). Rhizome utilization options are its use as an adsorbant for metal ions from rivers (Jorgetto et al., 2014) and combusted to produce heat in form of fuel pellets, briquettes, biochar, and bio-oil (Torii et al., 2011; Sivamani et al., 2018).

However, most of the solid waste is cassava pulp, with currently around six million tons being produced annually in Thailand from the CSPP.

The current options for cassava pulp utilization are to sell it as raw material for animal feed, produce cassava pellets, use as raw material for mushroom growing media, or it is sometimes given to farmers for free (Trakulvichean et al., 2017; Sivamani et al., 2018). The retail prices of wet and dried cassava pulp are 5.98 and 83.11 US$/t, respectively. Nevertheless, disposing of the cassava pulp in these options lead to the problem of a strong odor from its fermentation, especially during the rainy season. Moreover, laws and regulations on waste management place limits on the transport of cassava pulp. Cassava pulp has high organic content that has the potential for use as a feedstock for biogas because it is mostly comprised of lignocellulose with (by weight in dry basis) 60 – 75% starch, 13 – 28% crude fiber, 4 – 15% cellulose, 4 – 5% hemicellulose, 1 – 3% lignin, 1 – 2% protein, 0.1 – 0.2% lipids, 2 – 12% ash, and 1 – 17% of other materials (Chavalparit and Ongwandee, 2009; Rattanachomsri et al., 2009; Sriroth et al., 2000; Virunanon et al., 2013; Yimmongkol and Jattupornpong, 2007) as well as an alternative for waste reduction and environmental improvement due to reducing greenhouse gas (GHG) emissions (Hansupalak et al., 2016). Dried cassava pulp is sold to pellet or fertilizer at 9.00 – 17.79 US$/t. The pulp can instead be used to produce biogas as LPG which can be sold to generate about 18.00 US$/t of pulp. By using the biogas instead of fuel oil to produce the heat and generate electricity, it can generate an equivalent value of 13.33 and 5.00 US$/t of cassava pulp, respectively.

However, the use of the lignocellulosic materials found in cassava pulp for biogas production is limited because these substrates are very difficult to digest and resist microbial hydrolysis in biogas production. Despite these limitations of the production biogas from cassava pulp at a commercial level are the pretreatment technology, conversion technology, and cost-effectiveness (Jeihanipour, 2011; DIW, 2010).

For resource efficiency, problems encountered in converting cassava pulp to biogas have to be overcome in order that starch factories can be accredited for adaption the CE concept that produces biogas from both the wastewater and cassava pulp for generation of heat and electricity. For the industrial process, three scenarios are considered as follows: **scenario 1** is without a biogas system in factory, **scenario 2** is with biogas generation from the wastewater only, and **scenario 3** is with biogas generation from both the wastewater and cassava pulp.

Since **scenarios 1** and **2** above are well documented, this study, focus on investigating the benefits of using **scenario 3**, that is using both the wastewater and cassava pulp for biogas production in the cassava starch industry in Thailand as summarized schematically in Figure

2. In addition, this research also highlights the main drivers and barriers to implementing the CE concept in the CSPP in Thailand.

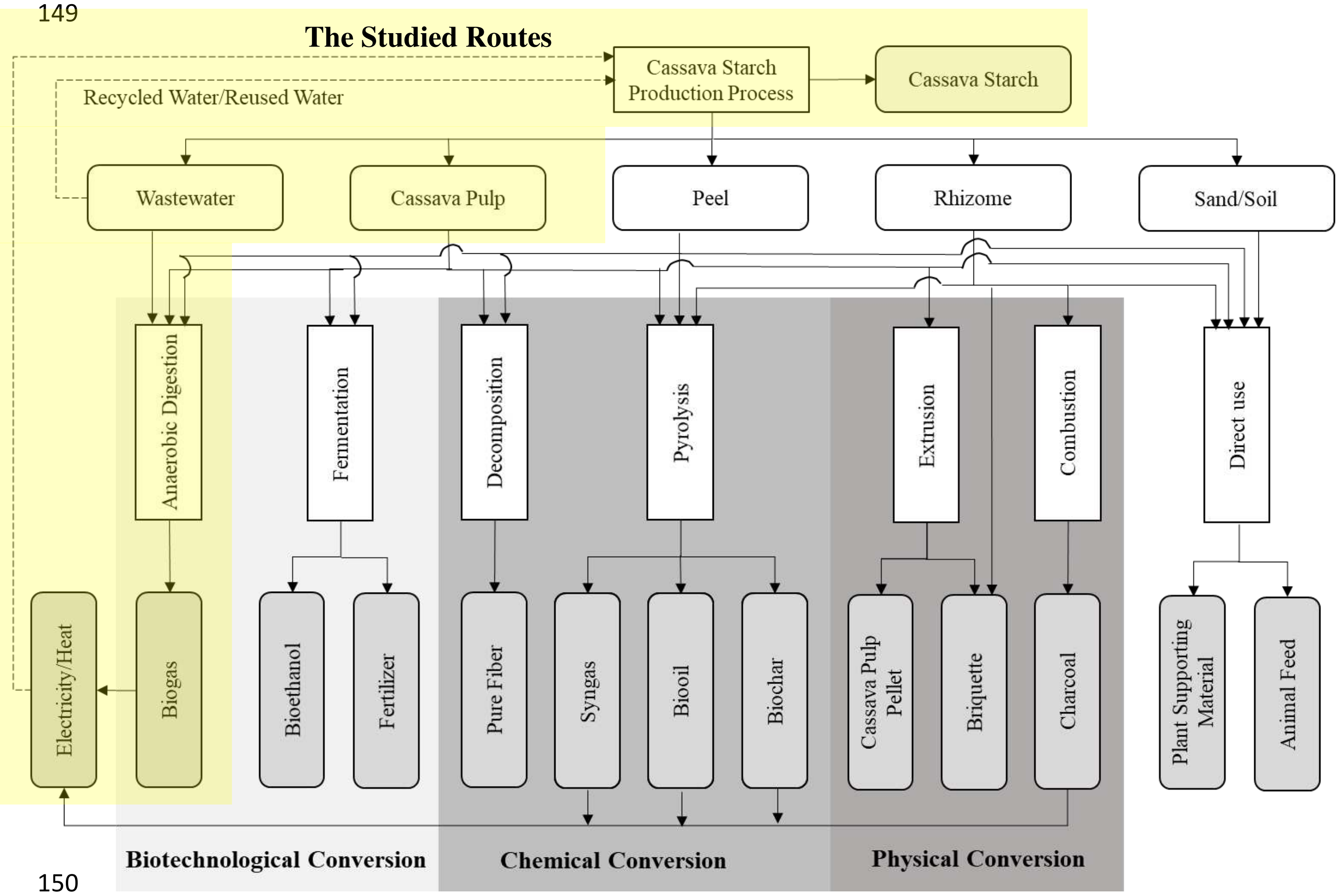

Fig. 2 Implementation of CE concept in the Thai cassava starch industry

2. Methodology

In 2020. Thailand has 112 cassava starch factories in operation and they generate a total of 10.5 million t/y of wet pulp, and 35.1 million m^3/y of wastewater from the production process (Trakulvichean et al., 2019). The number includes both native and modified starch factories. Sixty-two (55.4%) of these factories have biogas generation systems from the wastewater only, six (5.4%) factories have biogas systems from both the wastewater and pulp and two (1.8%) currently only have biogas systems from the wastewater but biogas systems from cassava pulp are under construction. Fifty of these factories are considered small with a production capacity of less than 100 t/d, and so these factories do not qualify for the investment necessary to build a biogas system from wastewater and cassava pulp. Unless their production capacity increases, the use of biogas from wastewater in those 62 factories will likely not increase.

Data was collected from a native cassava starch factory in Northeastern Thailand in the base period of January to December 2018. The starch production capacity was 500 t/d. A systematic methodology to use wastewater and cassava pulp for biogas production in the starch industry, in terms of the economics, resource efficiency, water recovery, reduction of the GHG emission, and land use.

2.1 Data collection of biogas production in the cassava starch factory

2.1.1 Data collection

Primary data was obtained from a native cassava starch factory in the Northeastern region of Thailand. The starch production capacity was 500 t/d with 196 working d/y. Wastewater from the starch production process was 1,135,944 m^3/y, while solid waste pulp generation from the process was approximately 450 t/d. Biogas conversion technology for wastewater comprised a covered lagoon with a wastewater receiving capacity of 165,970 m^3, while the biogas conversion technology of the solid cassava pulp used a thermophilic continuously stirred tank reactor (CSTR) at 55°C with pulp utilization capacity of 450 t/d.

2.1.2 Scope and system boundary

The system boundary of this study was scoped gate-to-gate to compare with the three studied scenarios (introduction). The economics, resource efficiency, water recovery, reduction of GHG emissions, and land use of these three scenarios were analyzed with a 10-y operational period base.

2.2 Resource efficiency and water recovery analysis

The study aims to minimize waste generation and emissions by incorporating resource use efficiency in a closed-loop product. Resource and water consumption input to the process was calculated using the life cycle inventory for the three studied scenarios (section 2.1.2), and the resource efficiency and water recovery analysis was undertaken and compared between the three studied scenarios.

As stated, one ton of starch is produced from approximately 4.4 t of cassava roots, using 16.7 m^3 of water, 197.8 kWh of electricity, 1,644.4 MJ of fuel for drying the starch, 0.4 kg of chemicals, and 59.3 m^3 of biogas for use in the boiler and to generate electricity. Waste from the production process consisted of 0.5, 0.4, 0.1, and 1.6 t dry basis of rhizomes, sand, peels, and dried pulp, respectively, and 7 kg dry basis of low-grade starch, plus 19.6 m^3 of wastewater. The low-grade starch is the large particles and defect color that occurs during the production process. The low-grade cassava starch is reprocessd to increase the production capacity by reducing the starch loss. Figure 3 presents a simplified input and output summary of the CSPP at the case study site in Thailand.

A case study was undertaken of a cassava factory that had a starch production capacity of 500 t/d and generated 6,560 m^3/d wastewater with a COD of 12,184 mg/L. The biogas production system was a covered lagoon for the wastewater treatment and a CSTR for biogas production from the cassava pulp. The covered lagoon was 165,970 m^3 in size with a retention time of 15 d. The system yielded a COD removal efficiency of 92%, achieving a COD at the outlet of 1,037 mg/L and produced 41,000 m^3 biogas/d with a CH_4 composition of 55% by volume.

In this same case study, the pulp was transported to the biogas plant in the starch factory, where the biogas production capacity from the pulp was 3.2 m^3 biogas/m^3 reactor • day using the thermophilic (55°C) CSTR technology with 15% (w/v) total solid (TS). The primary and secondary digesters were operated in series, with a buffer tank after the secondary digesters. The sediment from the buffer tank was recycled to the primary digesters, which contained the thermophilic anaerobic bacteria, to ensure the stable operation of the system and enhance the CH_4 content in the biogas. The average biogas production yield was 500 m^3/t TS under a hydraulic retention time of 16 d, and yielded 22,500 m^3 biogas/d.

2.3 Environmental and economic analysis

The benefits of applying the CE concept in the cassava starch industry were assessd in terms of an economic assessment, resource efficiency, water recovery, reduction in GHG emission and GHG emissions, and land use. The research framework is illustrated in Figure 3.

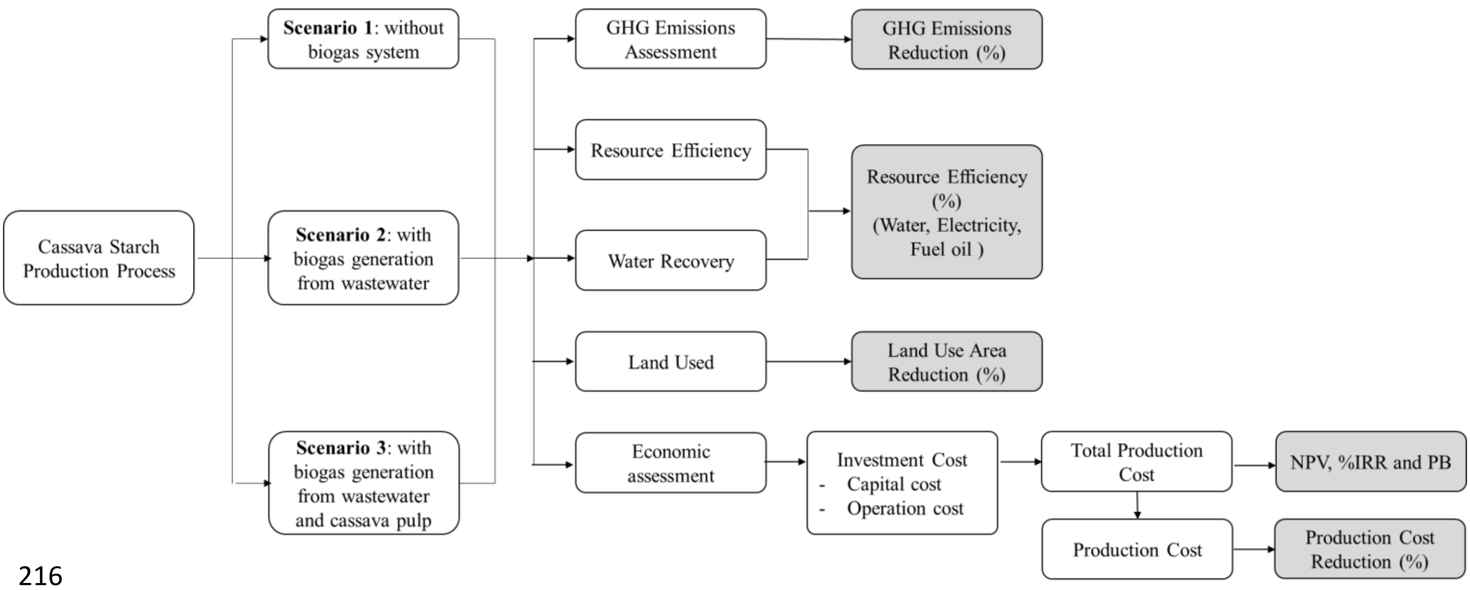

Fig. 3 Research framework

2.3.1 Environmental assessment

Environmental impact was calculated in terms of the GHG emission from the inputs of the resource usage and the outputs of the processed waste and wastewater, where the GHG emission was determined as the production of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emission factors used the data from the 2006 IPCC Guideline for National Greenhouse Gas Inventories and Thailand Greenhouse Gas Management Organization (Eggleston et al., 2006; Thailand Greenhouse Gas Management Organization, 2019). The CO_2 emissions from the wastewater and cassava pulp digestion in an anaerobic digestion system were not considered here as these are of biogenic origin. Assessment of the CH_4 and N_2O production potential was based on the concentration of degradable organic matter in the wastewater and cassava pulp. Further emissions released from the biogas combustion to produce heat and electricity, as well as emissions from resource usage were input to the process.

2.3.2 Economic impact

Key indicators utilized for the economic analysis were the net present value (NPV), internal rate of return (IRR), and payback period (PBP) (Jovanović, 1999). The calculations were based on a 10-y operation period with the capital and operating costs calculated as the total production cost. According to the scenario, the first year of operation included the major financial investment. The capital cost included buildings, machinery, and equipment. The operating costs consisted of materials, labor, social fund, tax fund, and depreciation. The material cost was calculated from the price of direct materials for manufacturing.

(i) Calculation of the NPV

The NPV was used to calculate the value of the future project in terms of the present value. A positive NPV from the investment will add value to the company and benefit the company shareholders. The NPV is the model for economic cost analysis, where decreasing the investment cost reduces the NPV by reducing the investment timing. The NPV of the investment project was calculated from Eq. (1);

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \quad (1),$$

where C_t is the net cash inflow during the period t, C_o is the total initial investment cost, r is the discount rate, and t is the number of time periods.

(ii) Calculation of the IRR

The IRR is used to evaluate the desirability of an investment or project. The higher the IRR on a project, the more desirable it is to undertake the project. Assuming all projects require the same amount of up-front investment, the project with the highest IRR would be considered the best and undertaken first. The IRR was calculated from Eq. (2),

$$0 = \sum_{t=1}^{T} \frac{C_t}{(1+\mathrm{IRR})^t} \qquad (2),$$

(iii) Calculation of the PBP

The PBP is the period of time required to recoup the funds expended in the investment, and was calculated from Eq. (3);

$$\mathrm{PBP} = \frac{\text{Cost of investment}}{\text{Annual cash inflow}} \qquad (3),$$

2.4 Drivers and barriers to applying the CE concept in the Thai CSPP

Data was collected from twelve cassava starch industries to determine the drivers and barriers to implementation of the CE concept. The information was collected using surveys, interviews, and questionnaires. Four of these factories applied biogas production from cassava pulp under the CE concept.

3. Results and Discussion

3.1 Resource efficiency analysis

3.1.1 Analysis of water consumption and waste generation

For each ton of cassava starch, the water consumption within the starch production process in **Scenario 1** used 16.7 m^3 of freshwater and generated 19.6 m^3 of effluent as show in table 1 and figure 4. The wastewater enters the open lagoon for evaporation. To minimize wastewater sources, starch factories should recycle the water in the production process. In the existing process, wastewater from the separating and dewatering units were reused to the extracting and separating unit. The used water from the dewatering unit contained protein impurities and so was not suitable to be reused in the other stages except for root washing. However, the used water from the extracting unit can be returned to the chopping and rasping unit because the water contained extracted starch (Sánchez et al., 2017).

For **Scenario 2**, the water consumption (per ton of cassava starch) was 15.1 m^3 of freshwater and 1.6 m^3 of recycled water, generating 19.6 m^3 of effluent. The wastewater entered the covered lagoon to generate 59.3 m^3 of biogas. For **Scenario 3,** the water consumption was 15.1 m^3 of freshwater and 1.6 m^3 of recycled water to generate 17.6 m^3 of effluent. The wastewater entered the covered lagoon to generate 357.8 m^3 biogas as show in figure 4. The biogas from **Scenario 2 and 3** used to producing heat and electricity in the CSPP. The treated wastewater was discharged into the open lagoon and then evaporated. Rather than evaporation, an alternative approach is to use the macronutrients dissolved within the effluent as liquid fertilizer (Sánchez et al., 2017; Songkasiri et al., 2014b).

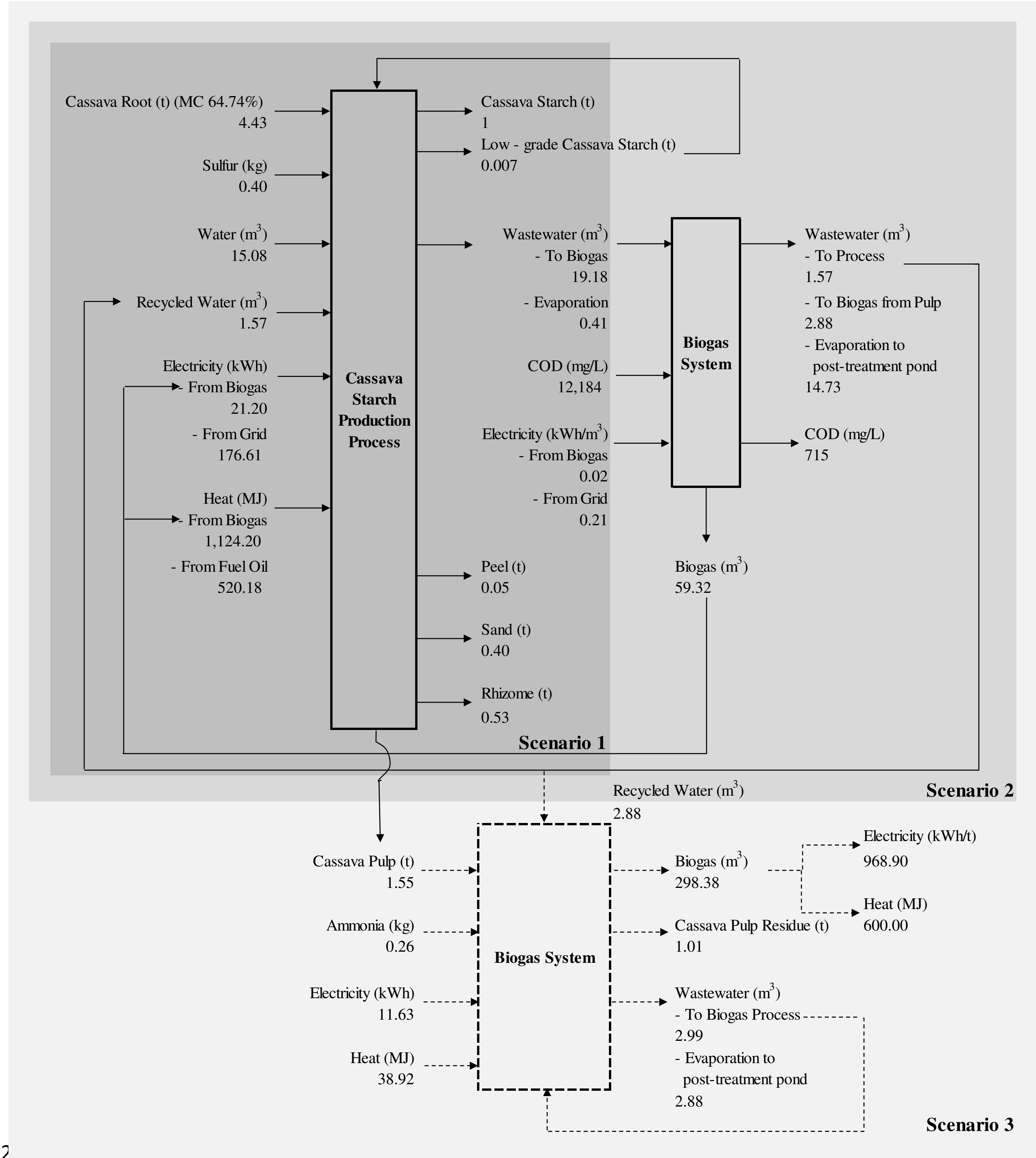

Fig. 4 Resource consumption and waste generation (per one ton of cassava starch produced) from CSPP. Three scenarios of starch production consist of (i) **scenario** 1, without biogas system in factory, (ii) **scenario 2**, with biogas generation from wastewater, and (iii) **scenario 3**, with biogas generation from wastewater and cassava pulp.

3.1.2 Analysis of energy consumptions

The electricity consumption of the CSPP was calculated as 197.8 kWh/t of cassava starch. For **Scenario 2**, 4.5 kWh/t cassava starch produced was required for the biogas system from wastewater, whereas in **Scenario 3** this was almost 2.6-fold higher at 11.6 kWh/t the CSPP as show in table 1. However, the biogas obtained from the wastewater produced 21.2 kWh of electricity or 2.54 US$/t of starch, while the biogas production from cassava pulp produced 968.9 kWh of electricity and then be used in the CSPP 176.6 kWh or 21.19 US$/t of starch. Therefore, a surplus of 738.4 kWh from **Scenario 3** was generated and could theoretically be sold to the electricity grid as 88.60 US$/t of starch as show in table 1 and figure 4.

The fuel oil used to supply process heat for the flash dryer was evaluated as 1,518.5 MJ. Biogas recovery from the wastewater treatment system has shown great potential for cassava starch factories. Since the price of fuel oil has increased significantly over the past decade, cassava starch factories have been using biogas to replace the fuel oil for the burners to generate hot air for drying the moist starch. The direct burning of the biogas obtained from the wastewater can supply 1,124.2 MJ of energy. Moreover, the biogas from **Scenario 3** is able to supply 1,724.2 MJ of energy as show in table 1. In conclusion, the fuel oil is unnecessary for thermal energy in the CSPP. The recovered biogas from the wastewater and cassava pulp was used to substitute fuel oil of 29.4 and 15.7 L/t of starch and this helped to reduce the fuel cost by approximately 16.49 and 8.80 US$/t of starch, respectively, based upon the cost of fuel oil at 0.56 US$/L as show in table 1 and figure 4.

3.1.3 Cost reduction

One of the starch factories that recently changed its pulp utilization options from dried cassava pulp to biogas production has shown a significant saving on the fuel oil and electricity used. However, the main production cost in the CSPP is the expenditure on purchasing cassava roots, which makes up to 83 – 91% of the total costs. The other costs are electricity (3 – 9%), fuel (4 – 5%), water (1%), chemicals (4%), and labor (2%) (Songkasiri et al., 2014b). The reduction in the fuel oil and electricity from biogas in **Scenarios 2** and **3** reduced the total costs by 4% and 11%, respectively as show in figure 5. A return to the government actively promoting investment through incentives, as well as easing of conditions for sale to the grid would see these figures improve dramatically through the additional income it would provide.

3.2 Environmental impact assessment

The CE concept focuses on reducing the landfill, GHG emission, and production energy consumption, while increasing the resource use efficiency and so enabling a new life-cycle for the otherwise end-of-life product. Regarding the minimization of the GHG emissions, the CO_2 equivalent from the three scenarios was considered in this study to analyze the GHG emission.

In this study, the GHG emission was related to the emissions from electricity consumption, energy consumption, cassava pulp utilization options, and water treatment methods. Under **Scenario 3**, the cassava starch industry applied the CE concept, including a covered lagoon for biogas generation from wastewater and a CSTR for biogas generation from the cassava pulp, reducing the GHG emission by 77% as show in figure 5. This result was achieved by the reduced electricity consumption from the electricity grid and the reduced GHG emission from wastewater treatment using anaerobic technology.

Table 1. The resource usage, waste generation, GHG emission, and land use of the Thai CSPP (per one ton of cassava starch produced)

	Scenario 1	**Scenario 2**	**Scenario 3**
Resource usage			
Cassava root (t dry basis)	1.56	1.56	1.56
Fresh water (m^3)	16.65	15.08	15.08
Chemical (kg)	0.26	0.26	0.66
Recycled water (m^3)	0.00	1.57	4.45
Biogas production (m^3)	0.00	59.32	357.70
Electricity from grid (kWh)	197.8	176.6	0.0
Electricity from biogas (kWh)	0.0	21.2	197.8 (Surplus:738.4)
Fuel oil consumption (L)	45.15	15.71	0.00
Biogas for drying (m^3)	0.00	64.45	98.84
Waste generation			
Wastewater to final open lagoons (m^3)	19.18	14.73	17.61
COD of wastewater to final open lagoons (mg/L)	12,184	715	715
Cassava pulp (t dry basis)	1.55	1.55	1.01
Peel (t dry basis)	0.05	0.05	0.05
Rhizome (t dry basis)	0.53	0.53	0.53
Sand/soil (t dry basis)	0.40	0.40	0.40
GHG emission (kg CO_{2eq})			

	Scenario 1	Scenario 2	Scenario 3
Wastewater	398.67	15.74	15.74
Cassava pulp fermentation	0.71	0.71	0.47
Electricity consumption in biogas system	-	0.15	19.93
Electricity consumption in cassava starch production	115.15	106.36	33.26
Thermal consumption in biogas system	-	-	0.00 (3×10^{-3})
Thermal consumption in cassava starch production	121.42	89.64	74.93
Total	635.95	212.62	144.33
Land use (ha)	59.22	47.18	18.90

3.3 Land use

The three scenarios were also examined for their effect on the land utilization. For a cassava starch factory with a process capacity of 500 t/ d, the land use options are the construction of a 1.6 ha starch production plant, 14.5 ha wastewater treatment (covered lagoon), 1.8 ha CSTR for biogas production from cassava pulp, and 44.3 ha for drying the cassava pulp. The total land use areas for **scenarios 1**, **2**, and **3** were 59.2, 47.2, and 18.9 ha, respectively as show in table 1. The land needs are significantly reduced for **scenario 3** due to the reduction of the cassava pulp drying area.

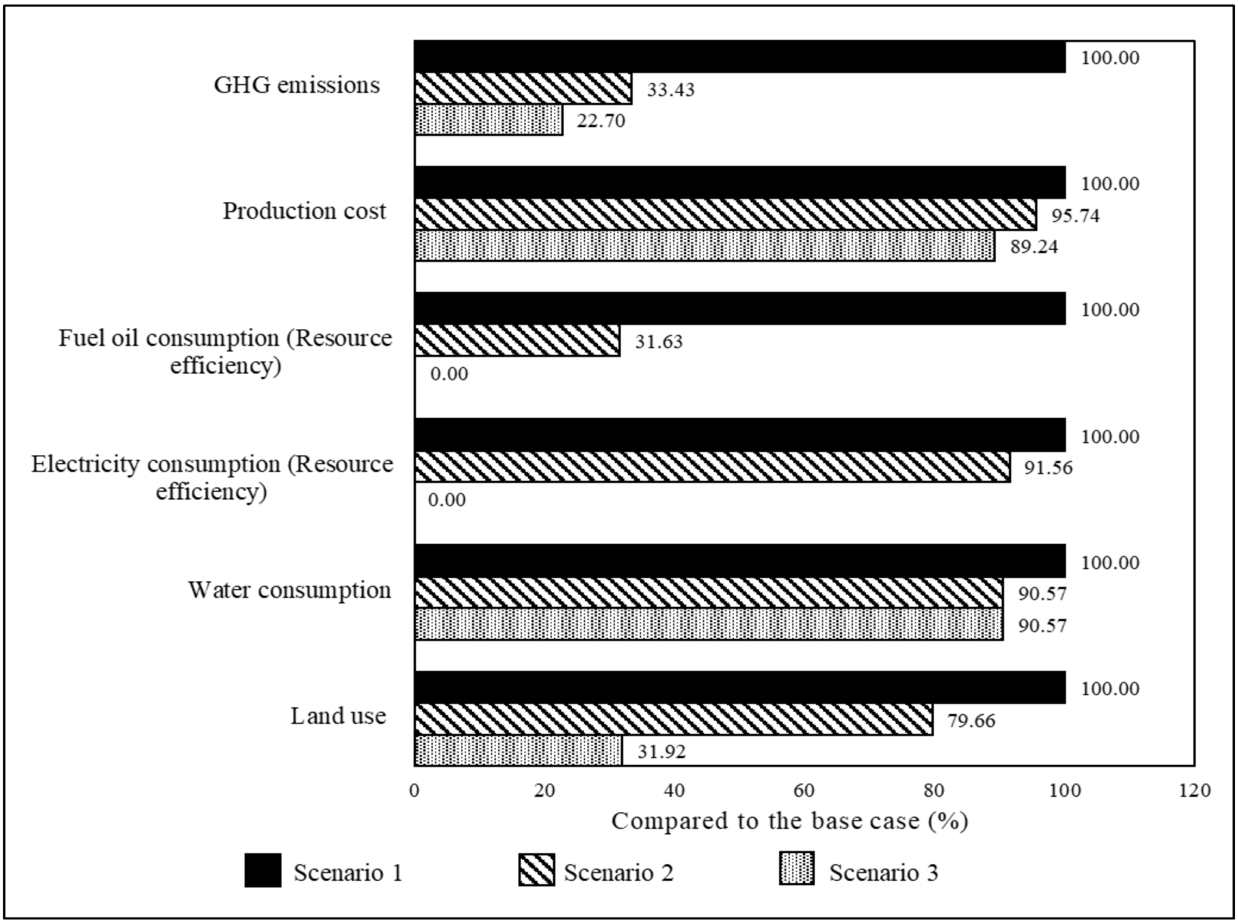

Fig. 5 Overall reduction of GHG emission, production cost, resource use, and land use from the three scenarios of starch production. **Scenario 1** is without a biogas system in factory, **Scenario 2** is with biogas generation from the wastewater, and **Scenario 3** is with biogas generation from both the wastewater and cassava pulp.

3.4 Economic impact

The economic viability and the IRR are the main factors of concern to any entrepreneur, and the first stage that entrepreneurs will calculate is total investment cost. The investment cost of a biogas system depends on type of feedstock and biogas conversion technology. The relationship between the investment time and biogas conversion technology provides a measurement of the corresponding effect in terms of investment timing. For this, the NPV is the economic analysis method that best assesses the investment cost of a biogas system.

As outlined already, cassava pulp can be utilized in many ways, such as the animal feed, and a carbon source in an alcohol fermentation process. However, the factories are not entirely satisfied with the current cassava pulp utilization and disposal options because the cassava pulp still has high starch content, which they view as a loss to them, even though odor is a constant problem. Biogas generation from cassava pulp is one option to solve these problems (Thai

Customs Department, 2019; Trakulvichean, 2017, 2019; Yimmongkol and Jattupornpong, 2007).

The investment cost varied with the size of reactor and the organic loading rate to the system (kg COD/m^3 of digester/d). The investment and operation costs of the CSTR technology were 180 – 267 US\$/m^3 biogas system and 0.07 – 0.17 US\$/m^3 wastewater, respectively, (DIW, 2010). In this study, the investment cost of the biogas production system consisted of land (10 – 25%), reactor system (18 – 35%), piping (5 – 13%), purification system (8 – 12%), generator (15 – 29%), and other (e.g. insulation and equipment installation). The key economic indicators for a biogas system from wastewater and cassava pulp are presented in Table 2. For the biogas generation from **scenarios 2** and **3**, the total investment cost was 2.24 and 8.65 million US\$, respectively. The PBP for biogas generation from **scenario 3** was the most economically attractive option due to the highest NPV of US\$ 6.15 million with a PBP of 4.37 y.

Table 2. Key indicators of different biogas technologies

Key indicator	Unit	Biogas from wastewater	Biogas from wastewater and cassava pulp
Discount rate	%	10	10
Investment cost (First year)	Million US\$	2.24	8.65
NPV	Million US\$	1.98	6.14
IRR	%	18	31
PBP	Year	5.03	4.37

3.5 Drivers and barriers of CE concept implementation for the CSPP

This study determined which four main factors that were technical, economic, regulatory, and social responsibility as a driver or a barrier for CE concept implementation in the CSPP. A driver was defined as a supporting factor and a barrier was defined as an inhibiting factor to implementation of the CE concept using the wastewater and cassava pulp to produce biogas for producing heat and electricity in factories.

The results showed that the main driver and barrier for CE concept implementation in the CSPP were technical concerning. These results corresponded to the previous study about the implementation of CE concept in industry. The regulatory factors were the most important concern to entrepreneurs (36%), followed closely by economic factors (35%) and then social responsibility and technical support at 21 and 8%, respectively. For the barriers to CE concept implementation technical problems were the most important factor that concerned entrepreneurs (35%), followed by regulatory, economic, and social at 23%, 22%, and 20%, respectively, (Sousa-Zomer et al., 2018; Vanner et al., 2014). The driver and barrier of CE concept implementation are as show in table 3.

3.5.1 Technology

The technical barrier are outlined in turn below.

(*i*) *Limitations of pretreatment technology*

The application of biogas production from cassava pulp still has technical and cost-effectiveness limitations. Technically, the cassava pulp has a high lignocelluloses so these are difficult to convert into biogas. It requires both a long substrate retention time inside the reactor and an equally large reactor size so the cassava pulp required the pretreatment process to increasing surface area of cassava pulp, increasing microorganism accessibility, increasing substrate digestibility, and increasing lignin and hemicellulose solubility. These are the reasons for the high investment cost of a biogas system (Wang et al., 2011; Cannemi et al., 2014). Currently, the total degradation time for the solid organic waste is approximately 30 d. Consequently, various pretreatment methods have been used to improve the rate of the hydrolysis of lignocelluloses for biogas production (Zhang et al., 2011; Zheng, 2014).

(*ii*) *Availability of cassava pulp*

The amount of energy produced from biogas varies with the volume of cassava pulp generated by the factory, making it difficult to manage the energy. Cassava pulp is an agricultural residue that is available only during the cassava root harvesting period (September to April), is difficult to store, and so it is sometimes left on the biogas generation site for mulching purposes (Cannemi et al., 2014). Biogas production systems that support a wide range of raw materials and substrates would enhance the investment opportunities for biogas production systems and satisfy the desire of the electricity utility for year-round generation. More work needs to be done on developing such systems.

(*iii*) *Lack of a successful model for biogas production from cassava pulp*

A modified covered lagoon is the most popular system chosen by investors for processing cassava pulp due to the stability of the system. Furthermore, the system is able to support the fluctuation/variance of wastewater/solid waste in each production season, does not have a very high investment cost and is relatively easy for operation and maintenance. However, most starch factories are not confident in the efficiency of the high technology for biogas system generation from cassava pulp, since the technology has not yet been established at the commercial scale, nor shown to be cost-effective. Too few models of success to establish the efficiency of this biogas technology are available to satisfy the doubts of potential investors.

3.5.2 Economic

Economic barriers to CE concept implementation for the CSPP are related to the cost-effectiveness, uncertain return and profit, and lack of incentive.

(*i*) *Financial barriers*

The biogas investment and operation cost was approximately 6.00 – 1000.00 US$/$m^3$ and 0.02 − 2.67 US$/$m^3$ of wastewater respectively, ranging from a simple lagoon to high technology biogas system with pretreatment technology. It can be seen that the more complex the technology, the higher the operating cost. The cost depends not only on the chosen technology, but also the type of feedstock (DIW, 2010; Zheng, 2014). Therefore, biogas production from the cassava pulp requires a pretreatment step to adjust the physical and chemical properties, which results in higher biogas production costs and investment costs.

Current benefit measures provided by the government, such as tax benefits and financial support, are too little to motivate entrepreneurs to invest more in building biogas systems. Added to this is the difficulty of paperwork when requesting funding for an extension of the support limit, for permits, and for licenses, which often involve different agencies. Thus, the associated beurocracy needs to be made easier.

(*ii*) *Lack of incentive*

Government policies, especially the announcement to stop accepting claims and proposals to sell electricity from very small power producers (VSPP) that generate electricity from RE, is causing a slowdown in investment and is of great concern to the entrepreneurs who have already invested in biogas power generation systems. In addition, the current electricity purchase price is close to the production cost, making the PBP longer, and so far less attractive for the private sector to invest in. This is because the Ministry of Energy estimates that current electricity reserves are about 30% (DEDE, 2019). The termination of financial assistance, especially for the cases of waste and wastewater without efficient technology, is a major obstacle causing the private sector to cancel or delay the decision to invest in biogas production systems. Although there is an overall policy to promote energy from renewable resources, the denial of new feed-in tariff (FiT) approvals is possibly the greatest barrier to investment. It not only denies an increase in the use of renewable resources, it runs counter to CE concept implementation.

3.5.3 Regulatory

Environmental regulations are one of the drivers of CE concept implementation for the CSPP related to the reduction of GHG emission. Since laws require expensive policing and civil actions, voluntary compliance under social responsibility would be preferable (Carbon Brief, 2018).

(*i*) *Agreement on GHG emissions in COP24*

From COP24, Thailand signed an agreement on the implementation of the guidelines of the Paris Agreement to reduce its GHG emission by 20% below the 2010 emission levels by 2030. Environmental policies have been set up, such as the Environmentally Sustainable Transport System Plan, a Waste Management Roadmap, FiT, and tax incentives, to promote investment in RE (DEDE, 2019).

(*ii*) *Laws on waste and wastewater treatment*

Hazardous Waste Management laws define cassava pulp as a hazardous waste so it is prohibited to transport it off-site. This results in the disturbing odors and the need for landfill for drying the cassava pulp.

In terms of barriers, the primary disincentives are the high initial investment costs, lack of a conducive legal system, limited government support, especially in power purchase and production of RE, as well as a conflict in the laws on waste management and product lifecycle management. These are outlined in turn below.

(*iii*) *Lack of a conducive legal system*

The government attaches great importance to the development of the country into the CE. However, this top down policy has not been integrated into the actual production stream with any unity. By way of example, investment in biogas systems still requires contacting several departments, either sub-district administration organizations, provincial industry authorities, Department of Industry, Department of Business Development, Department of Alternative Energy Development and Energy Conservation, local power authorities, local environment authorities, and the Energy Regulatory Office.

(*iv*) *Limited government support*

Policy/law/regulation in RE and the environment is unclear and highly changeable in biogas production systems. Thailand has the policies and strategies in place associated with a sustainable development, environment, and energy, including the implementation of the Sustainable Development Agenda B.E. 2030, (Sustainable Development Goals: SDGs), the AEDP was updated in 2018 to focus on BCG economy. However, the various promotional measures focus on the economic returns and determination of the purchase price of RE is mainly based on the lowest cost of energy.

(v) Conflict of laws on waste management on product lifecycle management

The Urban Planning Act stipulates that biogas projects are on a negative list and so cannot be co-located with raw material production sources (e.g., cassava starch factories and palm oil plants). Currently, the Ministry of Industry is in the process of listening to public opinion to solve this issue of the urban plan problem as it is also associated with the request for borrowing funds from the bank by the developer.

3.5.4 Social responsibility

Social responsibility is driven by CE concept implementation in the cassava starch industry related to the area of the industry. These are discussed below

(*i*) *Expansion of communities close to industry*

With the high demand for living space, communities are expanding closer to the cassava processing factories, which, when first established, were relatively isolated. This is largely due to a lack of proper zoning from the outset. Communities are of course concerned about the detrimental environmental effects of industry and are active in their surveillance and reporting to the government. This result in an important driving force for investment in the CE concept and minimization of emissions and waste.

The current barriers are associated with the lack of environmental concern from entrepreneurs.

(*ii*) *Lack of environmental concern*

Thailand's environmental laws have only been set for sewage measures. Therefore, entrepreneurs are not interested in investing in high-efficiency biogas production systems that require a high investment. This is in contrast to foreign countries, such as Germany and Italy, who have implemented measures to support/attract the use of more modern technology.

Therefore, Thailand should establish a network, including the enforcement of environmental laws, and improve related laws to be in the same direction. Environmental crime punishment, surveillance, and reporting are important driving forces for investment in biogas production systems. This would include the establishment of an organization to disseminate knowledge, including making policy recommendations that promote and support the construction of biogas production systems in accordance with space and industry limitations. In addition, for effective operations, the government needs to establish a mechanism for monitoring and disseminating biogas performance to the public.

Table 3. Drivers and barriers for the CE concept implementation of the Thai CSPP

	Technology	Economic	Regulatory	Social responsibility
Driver			- Agreement on COP24 for GHG emission reduction to 20% below the business as usual by 2030	Expansion of community close to industry
			- Laws on waste and wastewater treatment	
Barrier	- Limitations of pretreatment technology	- Financial barriers from investment cost effectiveness	- Conflict of laws on waste management and product lifecycle management	Lack of environmental concern
	- Availability of cassava pulp (technology for flexible substrate)	- Lack of incentive	- Lack of a conductive legal system	
	- Lack of a successful model for biogas production from cassava pulp		- Limited government support	

4. Conclusion

The purpose of this study was to apply the CE concept implementation for the CSPP by using cassava pulp and wastewater to biogas production. The advantages of these implementation attempt to increase energy security and resource efficiency and decrease the problems of waste management including reduce disturbing odor, the waste entering landfills, GHG emissions, and land use. However, the barriers to biogas production from cassava pulp are cost and technology for pretreatment of the cassava pulp. Supportive regulatory and financial support mechanisms are needed for an investor to progress from the early business-planning stages through to operations and commercial sustainability.

5. Declarations

5.1 Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request. The necessary data that generated and analyzed during this study are included in this published article and its supplementary information file.

5.2 Competing interests

The authors declare that they have no competing interests.

5.3 Funding

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5.4 Authors' contributions

Songkasiri, W. designed, directed, and coordinated for this research. Songkasiri, W. and Phalakornkule, C. provided conceptual and technical guidance for all aspect of the project. Lerdlattaporn, R. and Trakulvichean, S. performed and analyzed the data of economic assessment, resource efficiency, water recovery, land use, and global warming potential for using wastewater and cassava pulp for biogas production in the cassava starch industry in Thailand. Lerdlattaporn, R. wrote the manuscript. Songkasiri, W. and Phalakornkule, C. commented, reviewed, and edited for its completion.

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Figures

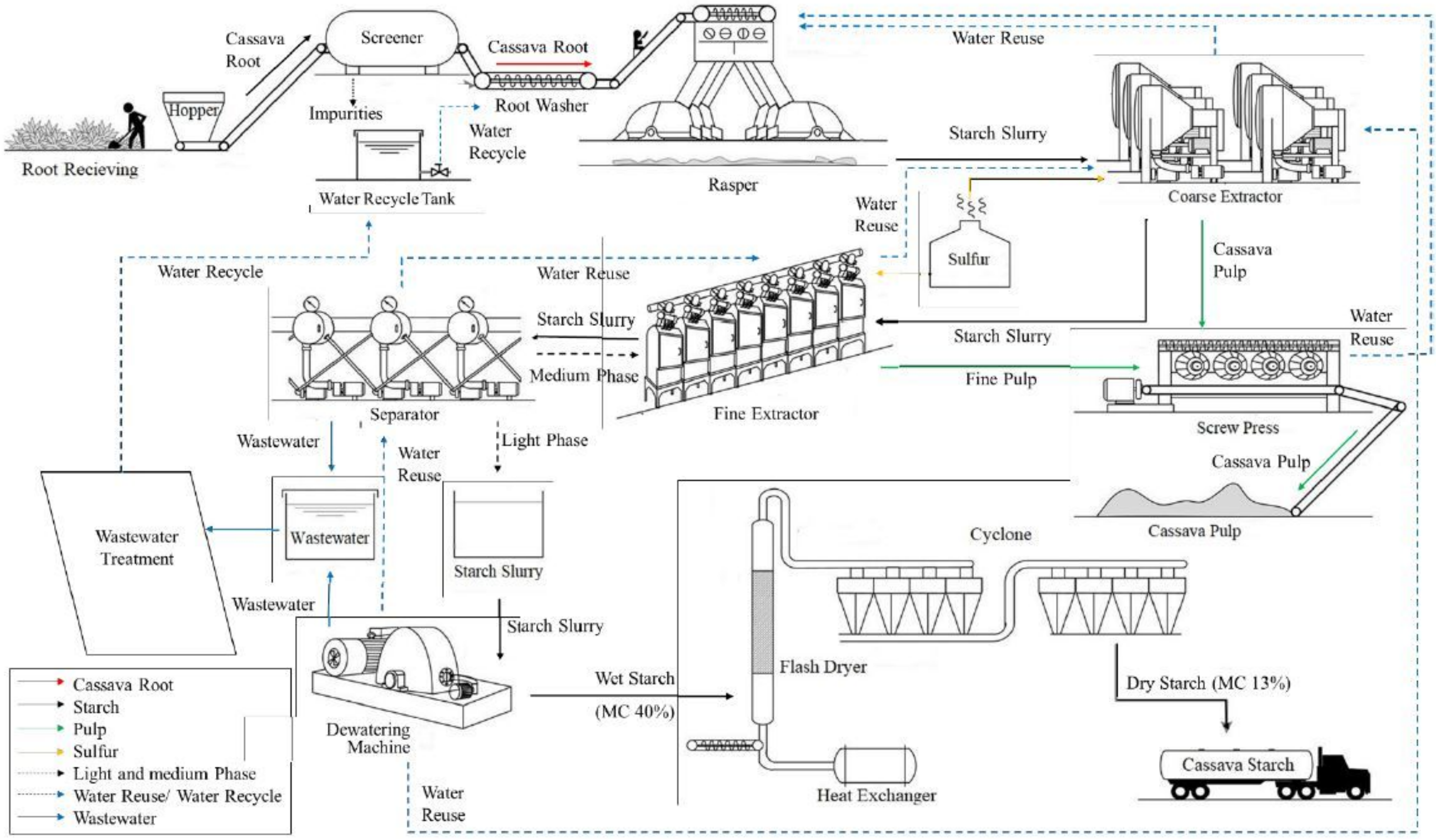

Figure 1

Schematic diagram summarizing the CSPP (Songkasiri et al., 2014a)

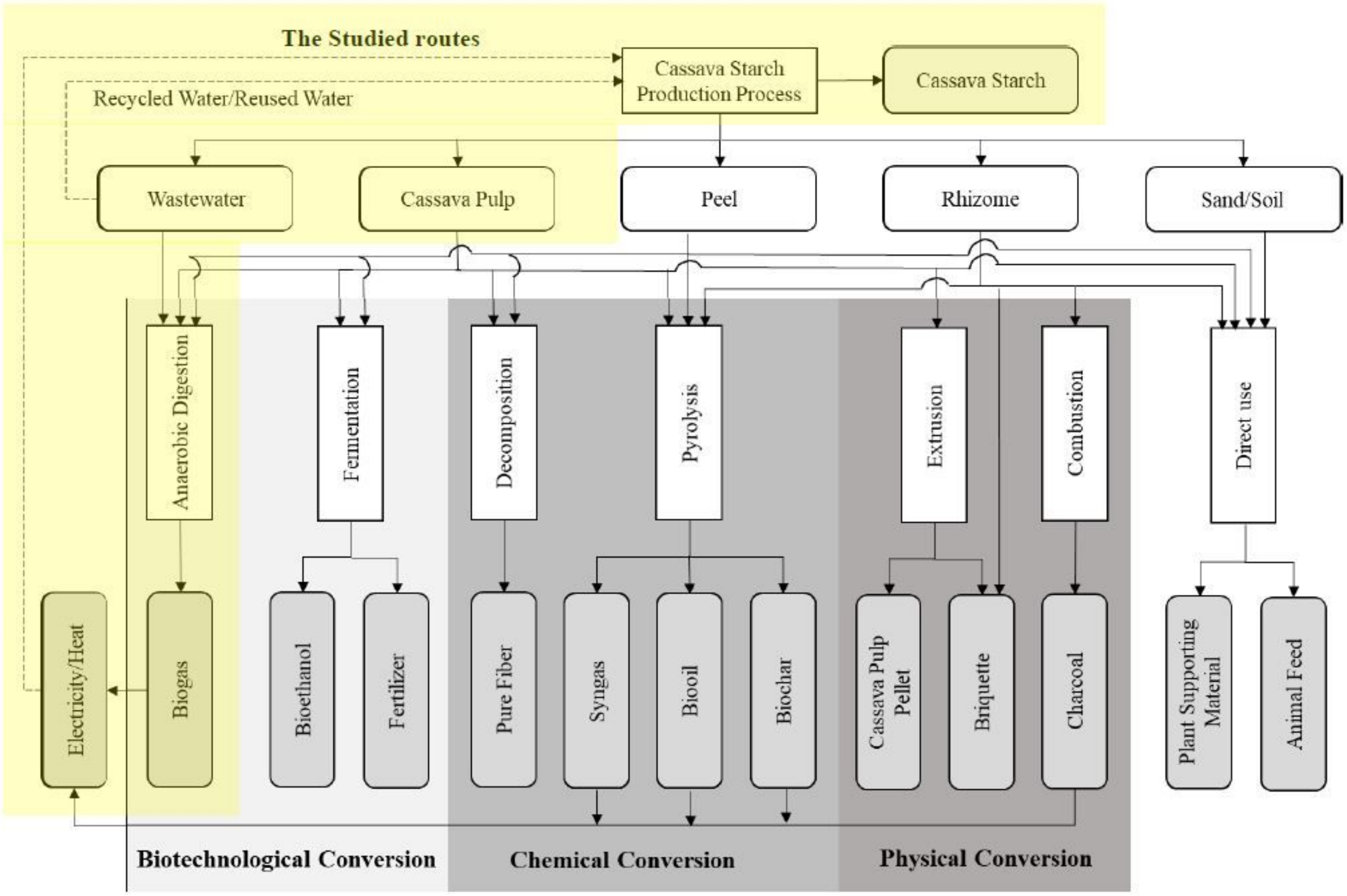

Figure 2

Implementation of CE concept in the Thai cassava starch industry

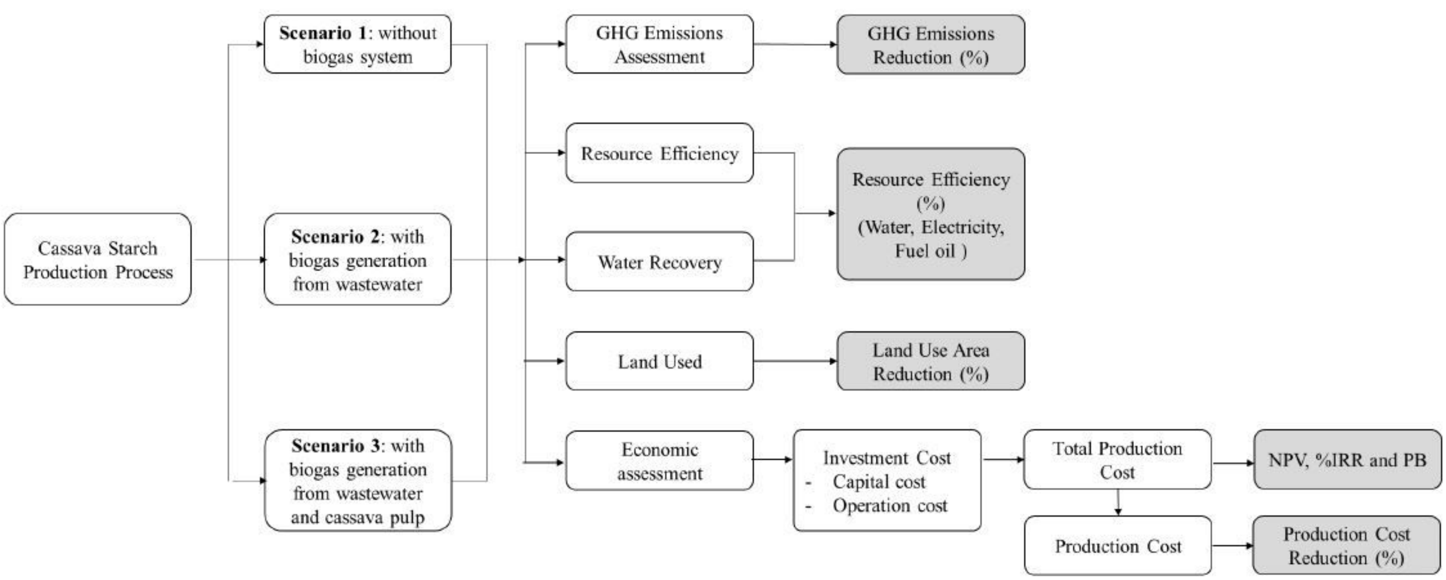

Figure 3

Research framework

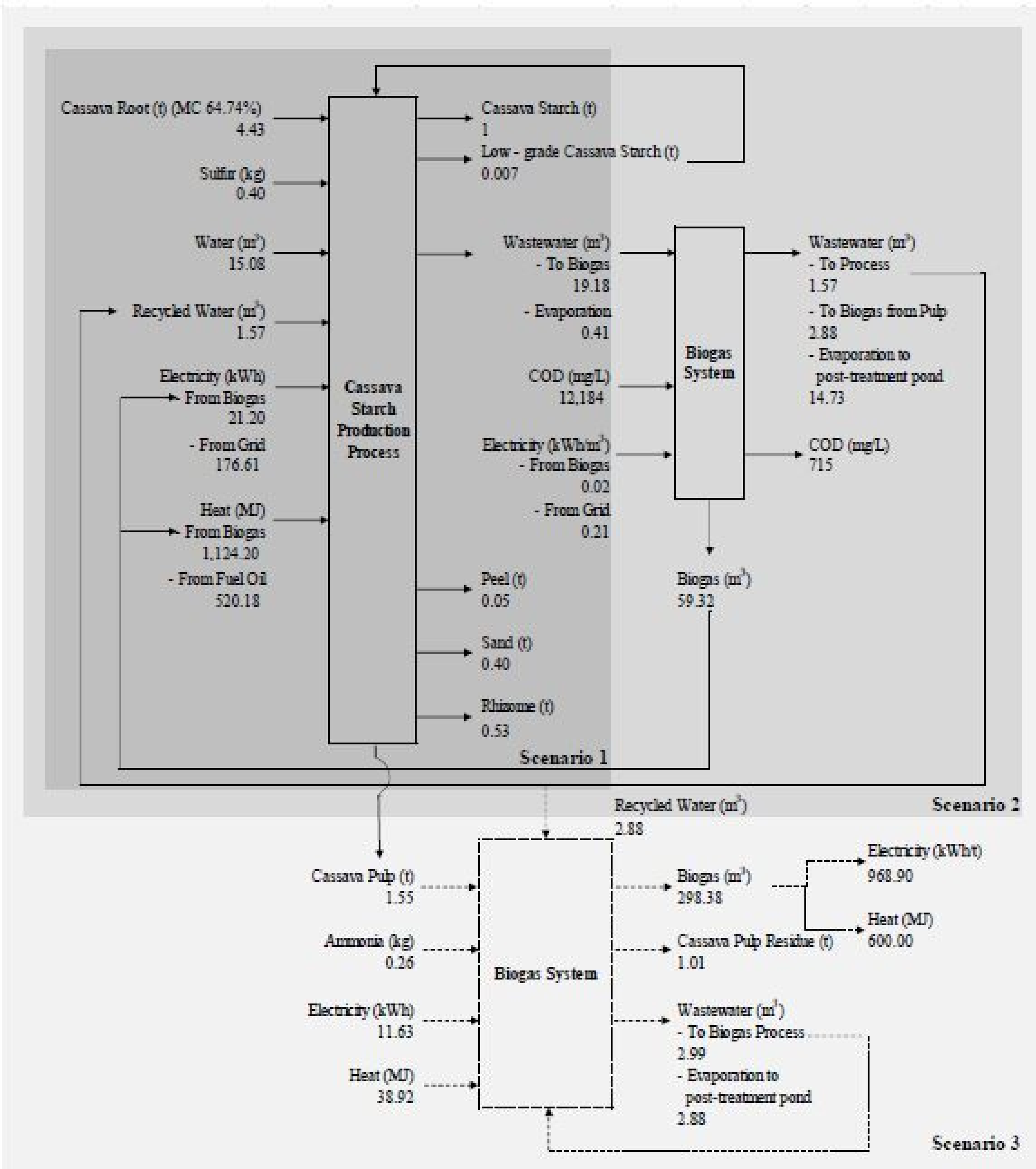

Figure 4

Resource consumption and waste generation (per one ton of cassava starch produced) from CSPP. Three scenarios of starch production consist of (i) scenario 1, without biogas system in factory, (ii) scenario 2, with biogas generation from wastewater, and (iii) scenario 3, with biogas generation from wastewater and cassava pulp.

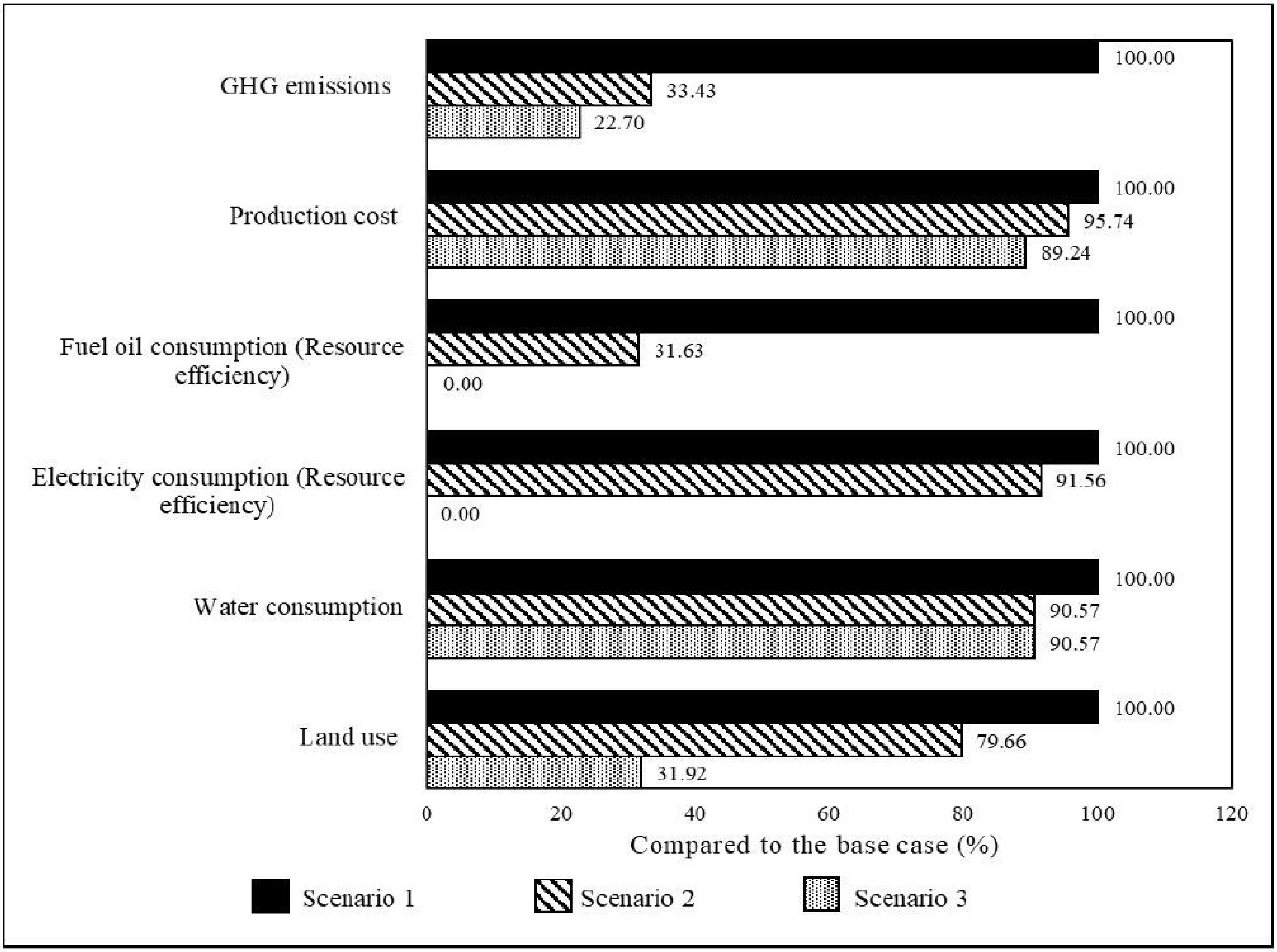

Figure 5

Overall reduction of GHG emission, production cost, resource use, and land use from the three scenarios of starch production. Scenario 1 is without a biogas system in factory, Scenario 2 is with biogas generation from the wastewater, and Scenario 3 is with biogas generation from both the wastewater and cassava pulp.