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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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Abstract

Adoption of the circular economy concept to utilize wastes and by-products from the cassava starch industry for biogas production has been considered a viable option. The annual generation of wastewater and cassava pulp in Thailand is reported to be approximately 21 million m^3 and 9.5 Mt, respectively. This research therefore aimed to analyze the key drivers and challenges in implementing the circular economy concept in the cassava starch industry in order to generate higher demand for biogas systems, increase the energy security and resource efficiency, and combat the environmental problems associated with cassava wastes. The following three scenarios were analyzed in this study: (1) a factory without integrated biogas system, (2) a factory with integrated biogas installation using wastewater as a raw material, and (3) a factory with biogas system using both wastewater and cassava pulp as raw materials. The assessment of economic feasibility, resource efficiency, water recovery, land use, and global warming potential was performed to compare different scenarios. This study found that Scenario 3 generated the highest net present value and the shortest payback period of 6.14 million USD and 4.37 yr, respectively, for the 10-yr operational period. Moreover, Scenario 3 had the highest resource efficiency and water recovery with the lowest land use (1.89×10^5 m^2 at 5×10^5 kg of starch d^{-1}) and the lowest global warming potential (0.14 kg CO_{2eq} kg^{-1} of starch).

Keywords: Anaerobic digestion, GHG emission, Biogas, Tapioca starch, Waste recovery, Thailand

Introduction

Application of the circular economy (CE) concept to wastes and by-products from the cassava starch production process (CSPP) can lead to sustainable development, higher economic profit and more efficient resource usage through waste minimization, as well as environmental benefits [1, 2]. Cassava, an economically important tuber crop in Thailand and other ASEAN countries, is widely used in food, animal feed, pharmaceuticals, bioethanol, and other industries. In 2019, Thailand was the world's largest cassava starch exporter, occupying 80% of the world's market share of native cassava starch export with 2.8 Mt and 30% of modified cassava starch export with over 1.0 Mt of tapioca starch [3]. The export value of native starch and modified starch was 2.1 billion USD in 2018 [4].

To produce 1000 kg of starch requires approximately 4400 kg of cassava roots, 10.9 m^3 of water, 207.8 kWh of electricity, 1898 MJ of heat for drying the starch, 0.9 kg of chemicals, and 93.1 m^3 of biogas necessary for heat and electricity generation. Wastes from the CSPP typically consist of 600 kg of rhizomes, 170 kg of sand, 100 kg

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of cassava peels, 2500 kg of wet pulp, 8.4 m^3 of wastewater, and 4.0 kg of low-grade starch [5].

To date, the CSPP industry in Thailand has adopted the CE concept by distributing rhizomes, sand, and peels to farmers so they can be used as soil conditioners. Recirculating systems and anaerobic digestion are also employed to minimize wastewater generated from the CSPP (Fig. 1) [6–8]. The remaining wastewater from the CSPP is then used to produce biogas to generate heat or electricity, which can be used in the manufacturing process with surplus electricity being sold to the grid. Wastewater generally has a high level of chemical oxygen demand or COD (4800–70,000 g m^{-3}), high total volatile solids (1200–39,000 g m^{-3}), and low pH (4.3–5.6) [9–13]. In 2019, Thailand produced approximately 260.7 million Nm^3 of biogas from native starch wastewater from 62 biogas plants [5].

Cassava pulp, a solid waste that has not yet been fully utilized, can potentially be used as a feedstock for biogas production. This also contributes to waste minimization, environmental improvement, and reduction of greenhouse gas (GHG) emissions [14]. However, less than 10% of starch factories in Thailand use cassava pulp to produce biogas due to its high lignocellulosic content. Cassava pulp consists of 60–75% starch, 4–15% of cellulose, 4–5% hemicellulose, 1–3% lignin, 1–2% protein, 0.1–0.2% lipids, 2–12% ash, and 1–17% other materials [9, 15, 16]. Cassava pulp is currently sold as a raw material for the production of animal feed, cassava pellets, and mushroom growing media. The remaining pulp is sometimes given or sold to farmers to be used as soil conditioners at the value of 0.00–0.02 USD kg^{-1} [5, 17]. However, the demand for cassava pulp fluctuates depending on the factory location, competition with other raw materials, and/or season of the year. Further, the sun drying of cassava pulp prior to sale is problematic due to strong odor from fermentation and wastewater runoff in the rainy season.

The comparison of cassava pulp utilization options between biogas, bioethanol, fermented animal feed, and mushroom growth media in terms of economic and environmental costs in Thailand showed that the biogas production option was the most economically attractive option with the lowest environmental cost [5, 18]. In terms of global warming potential, the CSPP industry has adopted biogas conversion technology for wastewater treatment in the past 20 years, and it was found that GHG emissions could be reduced by 0.49–0.75 kg CO_{2eq} kg^{-1} starch. Therefore, the reduction of 0.9–1.0 billion kg CO_{2eq} yr^{-1} was contributed from the CSPP industry as a whole in Thailand [14].

Cassava pulp with high lignocellulosic materials has not been extensively used for biogas production as it is difficult to digest, particularly at the hydrolysis step.

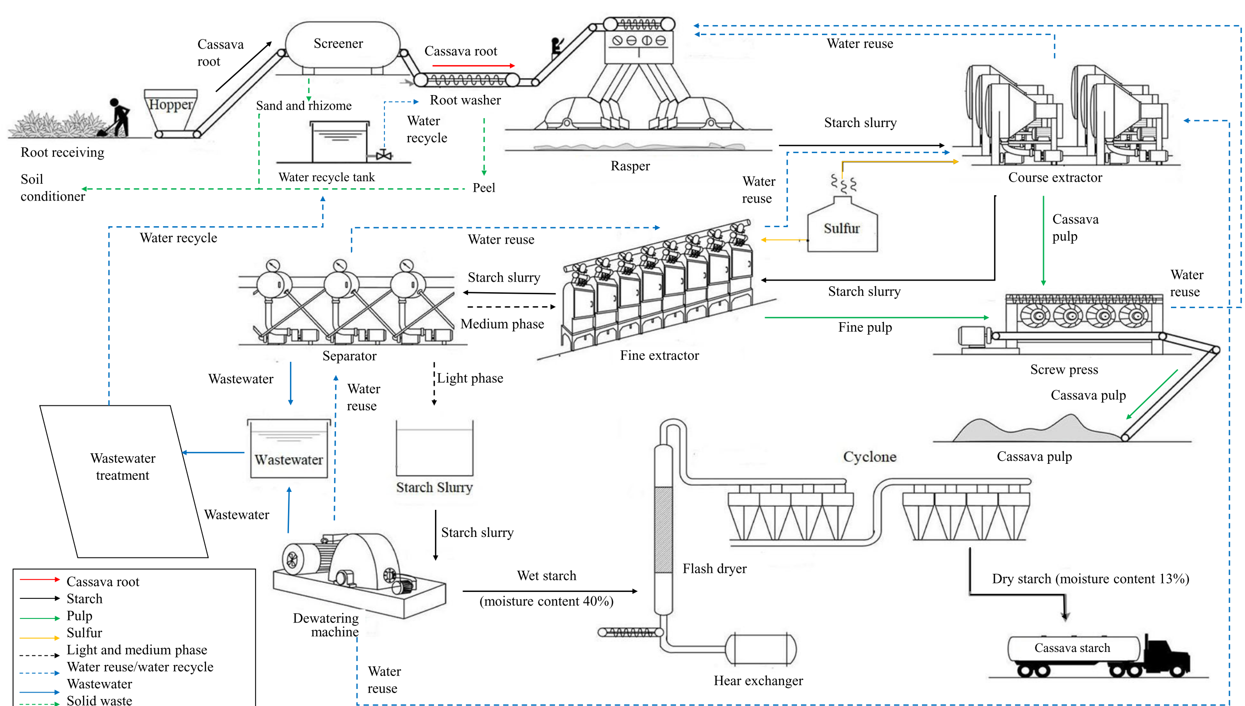

Fig. 1 Schematic diagram summarizing the CSPP

Despite this limitation, other factors to consider for commercial scale biogas production from cassava pulp are the pretreatment technology, substrate conversion technology, and cost-effectiveness of the entire process [19, 20]. If a factory produces biogas from the pulp and uses it instead of fuel oil for power generation such as heat and electricity, their values can be estimated equivalent to 0.01 and 0.02 USD kg^{-1} of cassava pulp, respectively [5]. However, the benefits of biogas produced by cassava pulp in terms of resource use efficiency, and economic and environmental values have not yet been quantified.

This research evaluated the impact of adopting the CE concept to the CSPP by integrating the biogas generation system using both wastewater and cassava pulp as raw materials for the generation of heat and electricity. In addition, the research highlights the main drivers and barriers for implementing the CE concept in the CSPP in Thailand. Three scenarios are considered as follows: Scenario 1 is a factory without a biogas system, Scenario 2 is a factory with biogas generation from the wastewater only, and Scenario 3 is with a factory with biogas generation from both the wastewater and cassava pulp. Since Scenarios 1 and 2 above are typical and well documented, this study focused on investigating the benefits of implementing Scenario 3.

Materials and methods

The experimental procedures were divided into 3 sections: (1) scope and system boundary, (2) data analysis, and (3) drivers and barriers analysis. A systematic methodology to use wastewater and cassava pulp for biogas production in the starch industry (in terms of the economic value, resource efficiency, water recovery, reduction of the GHG emissions, and land use) was proposed in order to compare the benefits of CE concept implementation in the CSPP using cassava pulp and wastewater for biogas generation among different scenarios. The research framework is illustrated in Fig. 2.

Scope and system boundary

Primary data were obtained from a native cassava starch factory in the Northeastern region of Thailand between January and December 2018. The starch production capacity was 5×10^5 kg d^{-1} with 196 working d yr^{-1}. The system boundary was scoped gate-to-gate, where three new CSPP plants with the same receiving capacity of 5×10^5 kg of starch d^{-1} and a 10-yr operational period were selected for comparison between the three studied scenarios. The economic feasibility, resource efficiency, water recovery, reduction of GHG emissions, and land use of these three scenarios were analyzed.

Resource efficiency and water recovery analysis

This study aimed to increase resource efficiency and water recovery including reducing electricity and fuel use in the CSPP. Resource consumption and waste generation (e.g., cassava root, freshwater, recirculating water, electricity, fuel oil, and biogas) were recorded daily. The moisture content of cassava pulp was analyzed according to the Association of Official Analytical Chemists protocol [21]. The starch content of cassava pulp and wastewater was determined using the solid concentration method [8]. COD was measured according to the Standard Methods [22]. Resource and water consumption inputs to the process were calculated using the life cycle inventory. The analysis of resource efficiency and water recovery was performed

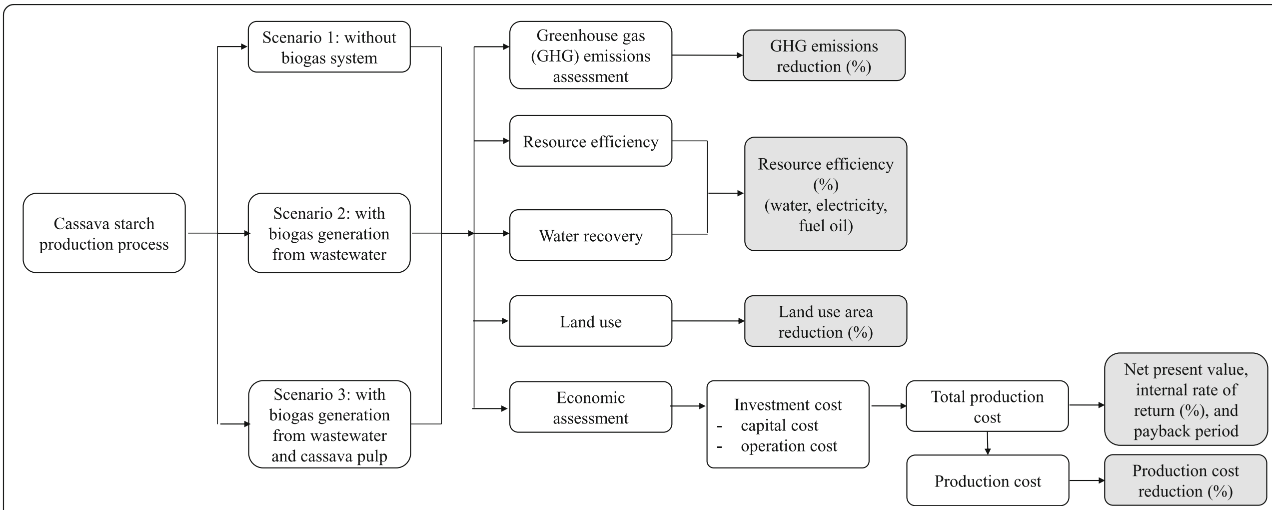

Fig. 2 Research framework

and the results were compared between the three studied scenarios.

A case study was undertaken at a cassava factory generating 6560 m^3 d^{-1} of wastewater with a COD of 12,200 g m^{-3}. The biogas production system employed at this factory was a covered lagoon for the wastewater treatment capacity being 165,970 m^3 in size and with a retention time of 15 d. The daily generation of biogas was 41,000 m^3 with CH_4 composition of 55% by volume (Fig. 3). The system yielded a COD removal efficiency of 92%, achieving a COD at the outlet of 1040 g m^{-3}.

In this same case study, 4.5×10^5 kg d^{-1} of cassava pulp was transported to the biogas plant using a continuously stirred tank reactor (CSTR) as a digester operating at 55 °C and 15% (w/v) total solids (TS). The biogas production capacity from the pulp was 3.2 m^3

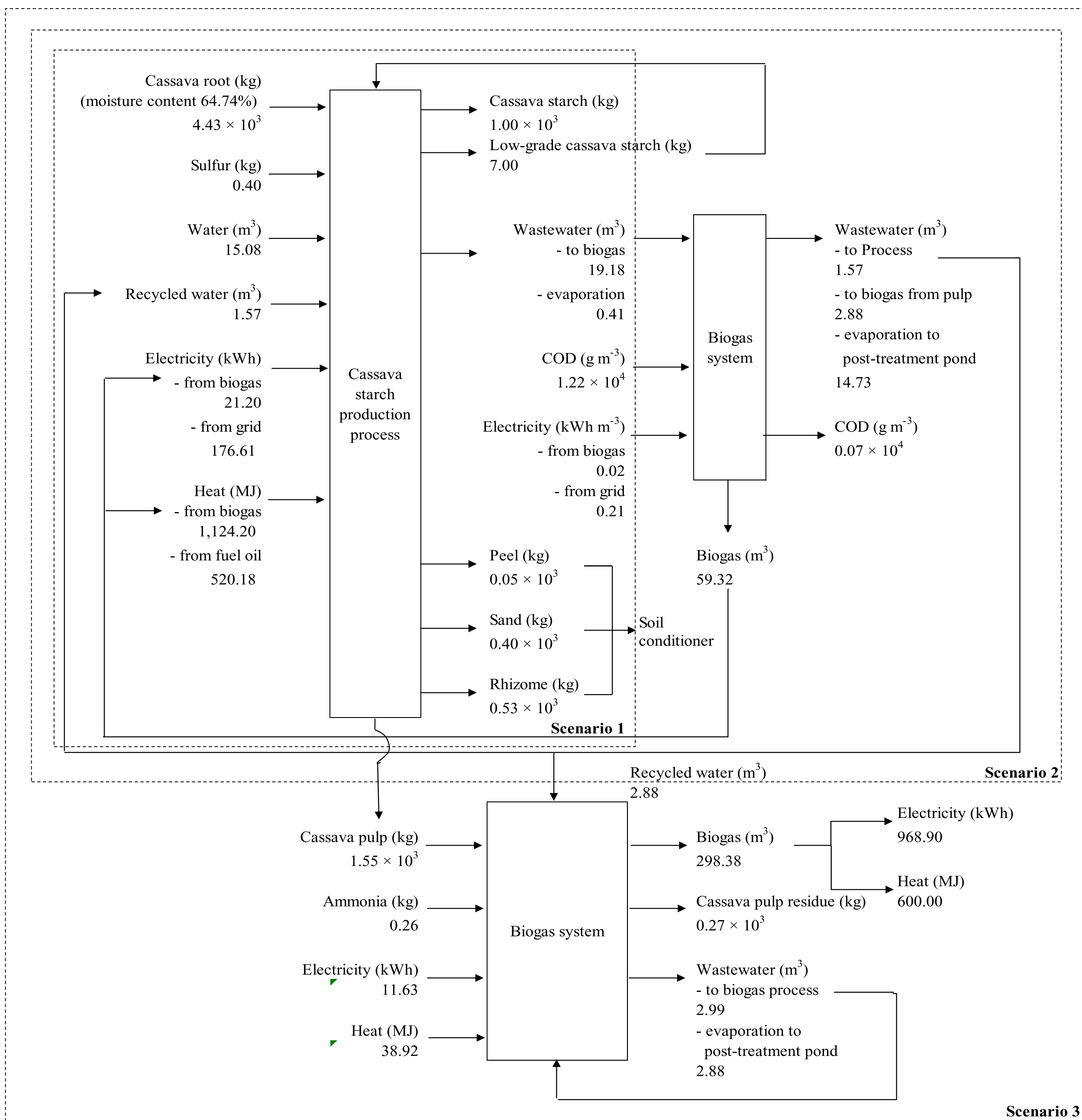

Fig. 3 Resource consumption and waste generation (per 1000 kg of cassava starch produced) from CSPP. Three scenarios of starch production are Scenario 1, a factory without integrated biogas system, Scenario 2, a factory with integrated biogas installation using wastewater as a raw material, and Scenario 3, a factory with biogas system using both wastewater and cassava pulp as raw materials

m^{-3} reactor d^{-1}. The primary and secondary digesters were operated in series, with a buffer tank after the secondary digester. The sediment from the buffer tank was recycled to the primary digester to ensure stable operation of the system and enhance the CH_4 content in the biogas. The average biogas production yield was 0.50 m^3 kg^{-1} TS under a hydraulic retention time of 28 d with the production rate of 22,500 m^3 of biogas d^{-1} (Fig. 3).

Land use analysis
The aim of this study was to minimize land use for waste management. The data of land use were taken from the factory using an open pond for wastewater treatment between 1999 and 2005. The factory subsequently switched to a cover lagoon in 2005 and installed an additional biogas system for cassava pulp in 2018.

Environmental and economic analysis
Environmental assessment
Environmental impact was calculated in terms of the GHG emissions from all sources between the inputs of the resource usage and the outputs of the processed waste and wastewater, where the GHG emissions were determined as the production of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Emission factor data were taken from the 2006 Intergovernmental Panel on Climate Change (IPCC) Guideline for National Greenhouse Gas Inventories and Thailand Greenhouse Gas Management Organization [23, 24]. The CO_2 emission from anaerobic digestion of wastewater and cassava pulp was not considered here as it was of biogenic origin. The CH_4 and N_2O production potential assessed 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 considered an input to the process.

Air emission such as CO_2, CH_4, and NO_x, from fuel combustion was calculated from Eq. (1):

$$\text{Air emission} = \Sigma(\mathrm{Q_i} \times \mathrm{EF_i}) \quad (1)$$

where subscript Q_i is the quantity of fuel type i (MJ FU^{-1}), FU is the functional unit (kg of starch at 0% water content), and EF is the emission factor of fuel type i (kg pollutant MJ^{-1}).

In addition, the general equation to estimate CH_4 generation from the CSPP wastewater was calculated from Eq. (2) as:

$$\mathrm{CH_4generation}\ \left(\mathrm{kg\ FU^{-1}}\right) = \Sigma\ [(\mathrm{TOW{-}S}) \times \mathrm{B_o} \times \mathrm{MCF{-}R}] \quad (2)$$

where TOW is the total organic degradable material in wastewater (kg COD FU^{-1}), S is an organic component removed as sludge (kg COD FU^{-1}), B_o is the maximum CH_4 producing capacity (0.25 kg CH_4 kg^{-1} COD), MCF is the methane correction factor, and R is the amount of CH_4 recovered to the energy source (kg CH_4 FU^{-1}).

Economic impact
The calculations of the net present value (NPV), internal rate of return (IRR), and payback period were based on the data collected over the 10-yr operational period with the capital and operating costs calculated as the total production cost [25]. The first year of operation included the major financial investment where the capital cost included construction of a factory, and purchase of land, machinery, and equipment. The operating costs consisted of costs of raw materials, labor, social fund, tax fund, and depreciation. The material cost was calculated directly from the price of materials used for manufacturing.

The NPV was used to calculate the value of the future project in terms of the present value. The NPV of the investment project was calculated from Eq. (3):

$$\mathrm{NPV} = \sum_{\mathrm{t}=1}^{T} \frac{C_t}{(1+r)^t} - C_0 \quad (3)$$

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.

The IRR was 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. The IRR was calculated from Eq. (4),

$$0 = \sum_{t=1}^{T} \frac{C_t}{(1+\mathrm{IRR})^t} \quad (4)$$

The payback period is the period of time required to recoup the funds expended in the investment and was calculated from Eq. (5);

$$\text{Payback period} = \frac{\text{Cost of investment}}{\text{Annual cash inflow}} \quad (5)$$

Drivers and barriers to apply the CE concept in the Thai CSPP
The drivers and barriers to the implementation of the CE concept were evaluated from surveys, interviews, and questionnaires collected over 12 cassava starch factories. Four of these factories have already followed the CE concept by installing the biogas production system for treating cassava pulp.

Results and discussion

Resource efficiency analysis

Analysis of water consumption and wastewater generation

For each 1000 kg of cassava starch produced, the water consumption in the CSPP was in the range of 9.8 to 62.1 m^3. The water used could be from wastewater recovered and recycled from other processes and local freshwater sources [9, 14, 26]. The water recycling process could reduce 53–73% of the freshwater consumption in the CSPP [26]. In this case, the freshwater consumption within the starch production process in Scenario 1 was 16.7 m^3 and the effluent of 19.6 m^3 was generated, as shown in Table 1 and Fig. 3. The surplus of effluent came from water in cassava roots. The wastewater was disposed of in the open lagoon to allow water loss through evaporation. To minimize the generation of wastewater, wastewater discharge from each processing unit can be reused or recycled based upon its characteristics in the preceding units, e.g., wastewater from the separating unit could be reused in the extracting unit. The used water from the dewatering unit contained protein impurities and was not suitable to be reused in the other stages except for root washing [8, 27]. In Scenario 2, the freshwater consumption (per 1000 kg of cassava starch) was 15.1 and 1.6 m^3 of water was recycled back to the process, generating 19.6 m^3 of effluent. The wastewater entered the covered lagoon and 59.3 m^3 of biogas was produced. In Scenario 3, 15.1 m^3 of freshwater was consumed whereas 1.6 and 5.9 m^3 of water was recycled back to the CSPP and the biogas generation unit using cassava pulp, respectively. The entire process thus produced 17.6 m^3 of wastewater, which was then sent to the covered lagoon where 357.8 m^3 of biogas was generated, as shown in Fig. 3.

The biogas from Scenarios 2 and 3 was used to generate heat and electricity in the CSPP and the treated wastewater was discharged into the open lagoon. Subsequently,

Table 1 The resource usage, waste generation, GHG emission, and land use of the Thai CSPP (per 1000 kg of starch). Three scenarios of starch production are (1) a factory without integrated biogas system, (2) a factory with integrated biogas installation using wastewater as a raw material, and (3) a factory with biogas system using both wastewater and cassava pulp as raw materials

	Scenario 1	Scenario 2	Scenario 3
Resource usage			
Cassava root (kg dry basis)	1.56×10^3	1.56×10^3	1.56×10^3
Fresh water (m^3)	16.7	15.1	15.1
Chemical (kg)	0.26	0.26	0.66
Recycled water (m^3)	0	1.57	4.45
Biogas production (m^3)	0	59.3	357.7
Electricity from grid (kWh)	197.8	176.6	0
Electricity from biogas (kWh)	0	21.2	197.8
Fuel oil consumption (m^3)	4.52×10^{-2}	1.57×10^{-2}	0
Biogas for drying (m^3)	0.0	64.5	98.8
Waste generation			
Wastewater to final open lagoons (m^3)	19.2	14.7	17.6
COD of wastewater to final open lagoons ($g\ m^{-3}$)	12,200	715	715
Cassava pulp (kg dry basis)	1.55×10^3	1.55×10^3	1.01×10^3
Peel (kg dry basis)	50	50	50
Rhizome (kg dry basis)	530	530	530
Sand/soil (kg dry basis)	400	400	400
GHG emission			
Wastewater (kg CO_{2eq})	398.7	15.7	15.7
Cassava pulp fermentation (kg CO_{2eq})	0.71	0.71	0.47
Electricity consumption in biogas system (kg CO_{2eq})	0	0.15	19.93
Electricity consumption in cassava starch production (kg CO_{2eq})	115.2	106.4	33.3
Thermal consumption in biogas system (kg CO_{2eq})	0	0	3.00×10^{-3}
Thermal consumption in cassava starch production (kg CO_{2eq})	121.4	89.6	74.9
Total (kg CO_{2eq})	636.0	212.6	144.3
Land use (m^2)	5.92×10^5	4.72×10^5	1.89×10^5

the treated wastewater could also be distributed to local farms to be used as a liquid fertilizer [27].

Analysis of energy consumption

The previous study showed that 100% of the thermal energy consumption and 21% of the electricity consumption in the CSPP can be covered by the substitution of biogas [26]. In Thailand, the electricity consumption of the CSPP was in the range of 0.20–0.50 kWh kg^{-1} of starch. The heat required for the flash dryer using a fuel oil was estimated between 1.50 and 2.91 MJ kg^{-1} of starch [14]. The difference in energy consumption between cassava starch factories depends on the technology selection and management in the CSPP, amount of machinery, and waste and wastewater utilization [9, 14, 26].

In this study, the estimated electricity consumption of the CSPP was 0.2 kWh kg^{-1} of starch. For Scenario 2, the electricity consumption of biogas system from wastewater was equal to 4.4×10^{-3} kWh kg^{-1} of starch, whereas in Scenario 3 the electricity consumption of thermophilic biogas system from cassava pulp was almost 2.6-fold higher at 1.2×10^{-2} kWh kg^{-1} of starch as shown in Table 1. However, the biogas obtained from the wastewater produced electricity with 0.02 kWh kg^{-1} of starch or 2.54×10^{-3} USD kg^{-1} of starch, while the biogas obtained from the cassava pulp produced electricity with 0.97 kWh kg^{-1} of starch. Therefore, a surplus of 0.77 kWh kg^{-1} of starch from Scenario 3 was generated and could theoretically be sold to the electricity grid as 9.20×10^{-2} USD kg^{-1} of starch as shown in Table 1 and Fig. 3.

The heat required for the flash dryer using fuel oil was evaluated as 1.52 MJ kg^{-1} of starch. Biogas recovery from the wastewater treatment system has shown great potential for 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 a wastewater treatment unit can supply energy with 1.12 MJ kg^{-1} of starch. Moreover, the biogas from Scenario 3 is able to provide energy of 1.72 MJ kg^{-1} of starch, as shown in Table 1. In conclusion, fuel oil is unnecessary for thermal energy in the CSPP. The recovered biogas from anaerobic digestion of wastewater and cassava pulp was used to substitute fuel oil of 2.94×10^{-5} and 1.57×10^{-5} m^3 kg^{-1} of starch, respectively and this helped to reduce the fuel cost by approximately 0.02 and 0.01 USD kg^{-1} of starch, respectively, based upon the cost of fuel oil at 560 USD m^{-3}, as shown in Table 1 and Fig. 3.

Cost reduction

The main production cost in the CSPP is the cost of the raw material, cassava roots, which makes up 83–91% of the total cost. The other expenses are from the consumptions of electricity (3–9%), fuel oil (4–5%), and water (1%), the cost of chemicals (4%), and the cost of labor (2%) [8]. The base case for calculating the potential cost reduction was referred to in this study as Scenario 1, a factory without integrated biogas system. Scenarios 2 and 3 were the improved processes with more effective resource management such as the use of the biogas system from wastewater and cassava pulp. In this case, the reduction in the fuel oil usage and the use of electricity generated from biogas in Scenarios 2 and 3 lowered the total production cost by 4 and 11%, respectively.

The highest resource efficiency was achieved in Scenario 3 due to the use of biogas converted from wastes as a substitute energy source, which further reduced the consumptions of electricity from the grid and fuel oil in CSPP.

Environmental impact assessment

The CE concept generally focuses on reducing the amount of waste to landfill, GHG emission, and energy consumption, but increasing the resource use efficiency, which then enables a new life-cycle, instead of end-of-life, product. Regarding the minimization of the GHG emissions, the CO_2 equivalent from the three scenarios was considered and analysed in this study. Previous studies found that the total GHG emission from cassava starch production without a biogas system was in the range of 0.52–1.07 kg CO_{2eq} kg^{-1} of starch whereas that with a biogas system from wastewater was between 0.13 and 0.39 kg CO_{2eq} kg^{-1} of starch [14, 26]. The adoption of biogas system from wastewater in the CSPP in Thailand reduced GHG emissions by approximately 75% [28].

In this study, the GHG emission was mainly from energy generation (heat and electricity), cassava pulp utilization, and water treatment. The CSPP contributed 0.14–0.64 kg CO_{2eq} kg^{-1} (Table 1). Key factors of variation in GHG emissions from the CSPP among the three different scenarios were the differences in total amounts of electricity, fuel, and water (fresh and recycled water) consumed. In Scenario 1, with no biogas system, the GHG emission of CSPP was 3–4 times higher than that in the biogas scenarios due to the higher methane emission from an open lagoon, the CO_2 emission from fossil fuel combustion, and the higher use of grid electricity. This means that, with an integrated biogas system, the GHG emission from the CSPP in Thailand could be significantly reduced from 2.4 Mt of CO_{2eq} yr^{-1} to approximately 0.6–0.8 Mt of CO_{2eq} yr^{-1}.

In Scenario 3, with the implementation of CE for the CSPP, the use of a covered lagoon and a CSTR for biogas generation from wastewater and cassava pulp, respectively, resulted in a reduction of the GHG emission by 77% as shown in Fig. 4. This result was achieved by the lower electricity consumption from the grid and the reduced GHG emission from wastewater treatment using anaerobic digestion technology.

Land use

The three scenarios were also examined for their effect on land utilization. For a cassava starch factory with the process capacity of 5×10^5 kg d^{-1}, the land can be subdivided into a starch production plant (1.6×10^4 m^2), a covered lagoon for wastewater treatment (1.45×10^5 m^2), a CSTR for biogas production from cassava pulp (1.8×10^4 m^2), and a site for drying the cassava pulp (4.43×10^5 m^2). The total land use areas for Scenarios 1, 2, and 3 were 5.92×10^5, 4.72×10^5, and 1.89×10^5 m^2, respectively. The size of land required is significantly reduced, particularly in Scenario 3, due to the use of a smaller cassava pulp drying area and open pond for wastewater treatment.

Economic impact

The economic viability and the IRR are the main factors of concern to any investor, and the first parameter to consider is the total investment cost. The investment cost of a biogas system depends on the type of feedstock and biogas conversion technology. 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 several ways as an animal feed and a carbon source in an alcohol fermentation process. However, cassava starch factories are not entirely satisfied with the current cassava pulp utilization and disposal options because the cassava pulp still has high starch content. The remaining pulp is viewed as a loss to starch producers; biogas generation from cassava pulp could play a role in solving these problems [5, 16].

The investment cost varied with the size of the reactor and the organic loading rate to the system (kg COD m^3 of digester d^{-1}). The investment and operating costs of the CSTR technology were 180–267 USD m^{-3} biogas system and 0.07–0.17 USD m^{-3} wastewater, respectively [20]. In this study, the investment cost of the biogas production system consisted of costs of land (10–25%), reactor system (18–35%), piping (5–13%), purification system (8–12%), power generator (15–29%), and other (e.g., insulation and equipment installation). The cost of sludge treatment via biogas production from cassava pulp was not included in the operating cost because the digested sludge was disposed to landfill. However, the digested sludge from cassava pulp can potentially be used as a fertilizer or soil conditioner. The key economic indicators for Scenarios 2 and 3 are presented in Table 2. For the biogas generation from Scenarios 2 and 3, the total investment costs were 2.24 and 8.65 million USD, respectively. The payback period for biogas generation

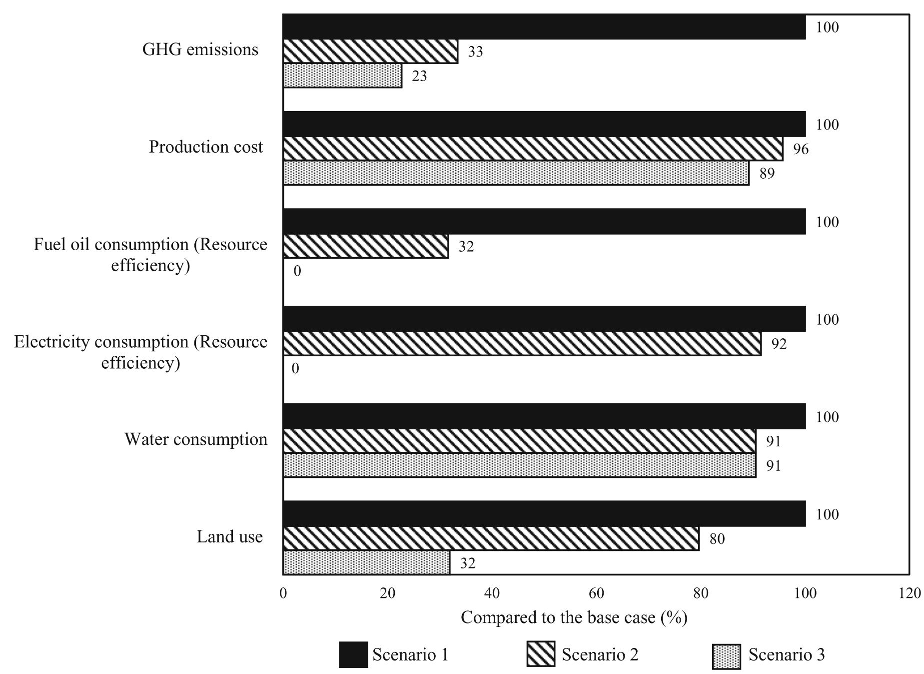

Fig. 4 Overall reduction of GHG emission, production cost, resource use, and land use from the three scenarios of starch production. Scenario 1 refers to a factory without integrated biogas system, Scenario 2 is a factory with integrated biogas installation using wastewater as a raw material, and Scenario 3 is a factory with biogas system using both wastewater and cassava pulp as raw materials

Table 2 Key indicators of Scenarios 2 and 3

Key indicator	Unit	Scenario 2	Scenario 3
Discount rate	%	10	10
Investment cost (First year)	Million USD	2.24	8.65
Net present value	Million USD	1.98	6.14
Internal rate of return	%	18	31
Payback period	Year	5.03	4.37

from Scenario 3 (4.37 yr) was the most economically attractive option with the highest NPV of 6.15 million USD.

Drivers and barriers to CE concept implementation for the CSPP

This study investigated the four main factors (technical, economic, regulatory, and social responsibility), which were the drivers and barriers to CE concept implementation for the CSPP. A driver was defined as a supporting factor whereas a barrier was defined as an inhibiting factor to the implementation of the CE concept, which allows the use of wastewater and cassava pulp to produce biogas for heat and electricity generation on site.

The results showed that the regulatory factors were the most important driver to investors (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 (35%), followed by regulatory, economic, and social responsibility at 23, 22, and 20%, respectively [28, 29]. The drivers and barriers of the CE concept implementation are shown in Table 3 and are detailed as follows.

Technology

Technological drivers In Thailand, the biogas conversion technology is fully mature because the country began to utilize biogas from anaerobic waste treatment systems in the early 1960s [8, 20]. Significant development in biogas research with a wide demonstration network involving both public and private sectors has helped to increase the dissemination and adoption of biogas conversion technology, especially for treating wastewater from the CSPP. Consequently, this provides reassurance to investors to choose the biogas technology that best suits cassava pulp [30].

Technical barriers Biogas production from cassava pulp has technical and cost-effectiveness limitations. Since cassava pulp consists of high lignocellulose, it is difficult to convert into biogas. This necessitates a long retention time inside the biogas reactor, resulting in the need for a large reactor size accordingly [20, 31]. Alternatively,

Table 3 Drivers and barriers to the CE concept implementation for the Thai cassava starch production process (CSPP)

	Drivers	Barriers
Technology	1. A mature biogas conversion technology with full commercial deployment in Thailand	1. Limitations of pretreatment technology *Solution:* Develop low investment and operating cost, high efficiency pretreatment technology for lignocellulosic materials 2. Availability of cassava pulp as waste *Solution:* Develop biogas conversion technology for flexible substrates 3. Lack of a successful model of biogas production from cassava pulp *Solution:* Disseminate the successful models of biogas production from cassava pulp to the industry
Economic	1. Production cost reduction from replacing electricity and fuel oil 2. Revenue earned from selling biogas to grid	1. High investment cost of biogas system *Solution:* Provide government tax relief, benefits and financial support 2. Lack of incentive *Solution:* Create new incentives for high efficiency biogas conversion technology
Regulatory	1. Adoption of Paris Agreement in Thailand 2. Waste and wastewater treatment laws	1. Lack of a conducive legal system *Solution:* Establish one stop service organization for biogas investment 2. Limitation of government support *Solution:* Improve the Alternative Energy Development Plan to support biogas production from cassava pulp
Social responsibility	1. Expansion of communities close to industry	1. Lack of environmental concern from the investors *Solution:* Strictly enforce environmental laws and establish an organization to disseminate knowledge and make policy recommendations for biogas production and educate the public.

pretreatment could be added to the process in order to increase the surface area of cassava pulp, enhancing microorganism accessibility, increasing substrate digestibility, and increasing lignin and hemicellulose solubility [13, 31]. Currently, the degradation time for solid organic waste is approximately 30–60 d.

Cassava pulp, an agricultural residue that is available only during the cassava root harvesting period (from September to April), is difficult to store, and sometimes left on the biogas generation site for mulching purposes [32]. The amount of energy produced from biogas varies with the volume of cassava pulp generated by the factory, making energy management in a factory difficult. Biogas production systems that support a wide range of raw materials and substrates would open up more investment opportunities; however, future research needs to be performed on such systems.

The modified covered lagoon is the most popular system chosen by investors for processing cassava pulp due to the flexibility of the system. The system is able to support the fluctuation/variance of wastewater/solid waste in each production season. In addition, the modified covered lagoon does not require a high investment cost and is relatively easy to operate and maintain. However, it requires a large land area and has low efficiency for organic removal. Most investors are still not confident in the biogas generation system for cassava pulp since, to date, too few successful models show system stability and cost effectiveness.

Economic

Economic drivers Biogas can replace the electricity consumption from the grid and heat consumption from fuel oil, reducing the production cost. Generally, the second main production cost of CSPP is electricity and fuel oil. Moreover, the CSPP with a biogas system from cassava pulp can produce and potentially sell electricity to the grid.

Economic barriers Biogas production from the cassava pulp, which requires a pretreatment step to adjust its physical and chemical properties, will incur higher biogas production cost and investment cost. The biogas investment and operating costs were approximately 6–1000 USD m^{-3} of wastewater and 0.02–2.67 USD m^{-3} of wastewater, respectively, depending on the selection conversion and pretreatment technology, and the feedstock types [20, 31].

Current measures provided by the government such as tax benefits and financial support are not sufficient to motivate investors to build more integrated biogas systems. In addition to this, the process of the funding request for an extension of the support limit, permits, and licenses is difficult and often involves dealing with several governmental agencies. Thus, in order to attract more investment, the bureaucracy needs to be improved.

In 2015, the government announced that they no longer accepted claims and proposals to sell electricity from very small power producers that generate electricity from renewable energy [33]. This caused a slowdown in investment and is of great concern. Currently, the electricity purchase price is close to the production cost, which results in a longer payback period, making this process far less attractive for the private sector to invest in. This is because the Ministry of Energy estimates that the current electricity reserves are approximately 30% [34]. Another issue is the termination of financial assistance, especially in the case of waste and wastewater treatment without efficient technology, causing the private sector to cancel or delay the decision to invest in biogas production systems. Although there is an overall policy to promote renewable energy, in practice the denial of new feed-in tariff approvals is very likely the greatest barrier to investment. It not only denies an increase in the use of renewable resources, but it is contrary to the CE concept implementation.

Regulatory

Regulatory drivers Environmental regulation related to the reduction of GHG emission is one of the main drivers of CE concept implementation for the CSPP. Under COP24, Thailand signed an agreement on the implementation of the guidelines of the Paris Agreement to mitigate and adapt to climate change, and specifically to reduce its GHG emission from the energy, transport, waste and industrial sectors by 20% below the 2010 emission levels by 2030 [35]. The Office of Natural Resources and Environmental Policy and Planning, Ministry of Natural Resources and Environment has set up procedures and guidelines that are related to the COP24 agreement such as the Environmentally Sustainable Transport System Plan and Waste Management Roadmap to promote investment in renewable energy [35].

Furthermore, Hazardous Waste Management laws define cassava pulp as industrial waste, so it is prohibited by law to transport it off-site. This results in the need to treat cassava pulp on site [36].

Regulatory barriers The government, to a great extent, integrates the development strategies of the country into the CE concept, however, this top-down policy has not been well integrated into the actual production stream. For example, investment in biogas systems usually involves the cooperation and coordination of several governmental organizations such as 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 [37].

Additionally, environmental policy, law, and regulation in renewable energy are not stringent enough, particularly for biogas production systems. Thailand has the policies and strategies in place associated with sustainable development, environment, and energy, including the implementation of the Sustainable Development Agenda in 2030. The Alternative Energy Development Plan or AEDP, which was updated in 2018, focused on bio, circular, and green economy [33]. However, various current promotional measures focus on the economic returns and determination of the purchase price of renewable energy is mainly based on the lowest cost of energy.

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 seeking public opinion on this matter as it is also associated with the request for borrowing funds from the bank by the developer.

Social responsibility

Social responsibility drivers With the high demand for living space, communities are expanding closer to the cassava processing factories, which, when first established, were relatively isolated. Communities are clearly concerned about the detrimental environmental effects of the industry and are active in reporting any suspicious activities in their surveillance to the government. This therefore acts as an important driving force for investment in the CE concept implementation in order to minimize emissions and waste from the cassava starch industry.

Social responsibility barriers Thailand's environmental laws have only been set for sewage management, therefore, investors are not interested in installing a high-efficiency biogas production system that involves a large investment. This contrasts with foreign countries, such as Germany and Italy, where there are implemented measures to support/attract the use of more efficient, modern renewable energy technology.

Therefore, Thailand should strongly enforce environmental laws as well as amend other related laws to align with the main environmental legislation. Strong surveillance and reporting, and punishment of any environmental law violation are important driving forces for investment in biogas production systems. This would include the establishment of an organization to disseminate knowledge and make 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.

Conclusions

The purpose of this study was to implement the circular economy concept in the CSPP. The study considered three scenarios as follows: Scenario 1 was a cassava starch factory without a biogas system, Scenario 2 a factory with an integrated biogas system using wastewater as a substrate only, and Scenario 3 is a factory with biogas generation from both wastewater and cassava pulp. The most economical and environmentally attractive option was Scenario 3, which demonstrated the highest net present value per 10-yr operational period (6.14 million USD), the lowest payback period (4.37 yr), and the lowest greenhouse gas emission of 0.14 kg CO_{2eq} kg^{-1}. The advantages of the implementation of CE in the CPSS are improving energy security and resource efficiency, and minimizing the environmental issues such as disturbing odor, GHG emissions, and inefficient land use. However, the barriers to biogas production from cassava pulp are cost and technology for pretreatment of the cassava pulp. Supportive regulations and financial support mechanisms are needed for investors to progress from the early business-planning stage to the stage of operations and commercial sustainability.

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Authors' contributions

Songkasiri, W. designed, directed, and coordinated this research. Songkasiri, W. and Phalakornkule, C. provided conceptual and technical guidance for all aspects 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. commented, reviewed, edited, and approved its completion. The author(s) read and approved the final manuscript.

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Availability of data and materials

Permission to use the datasets analyzed in this study was granted by the corresponding author on reasonable request. The necessary data that were generated and analyzed during the study are included in this published article.

Declarations

Competing interests
The authors declare they have no competing interests.

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