ความสำคัญของการผลิตก๊าซชีวภาพจากอุตสาหกรรม แป้งมันสำปะหลังในประเทศไทย

ปิยะวดี ศรีวิชัย[1,*], ชุมาพร รถสีดา [2], สุพิชญา มีสาด[3]

[1]สาขาวิชาอนามัยสิ่งแวดล้อม คณะสาธารณสุขศาสตร์
มหาวิทยาลัยพะเยา พะเยา
[2]สาขาวิชาอาชีวอนามัยและความปลอดภัย คณะสาธารณสุขศาสตร์
มหาวิทยาลัยพะเยา พะเยา
[3]สาขาวิชาการจัดการธุรกิจระหว่างประเทศ วิทยาลัยนานาชาติ
มหาวิทยาลัยนเรศวร พิษณุโลก
*Corresponding author email: piyavadee.sr@up.ac.th

ได้รับบทความ: 16 กุมภาพันธ์ 2566
ได้รับบทความแก้ไข: 19 มิถุนายน 2566
ยอมรับตีพิมพ์: 1 กรกฎาคม 2566

บทคัดย่อ

ก๊าซชีวภาพเป็นที่รู้จักเป็นอย่างดีว่าเป็นพลังงานทดแทนที่สำคัญ ซึ่งขับเคลื่อนการพัฒนาเศรษฐกิจในประเทศไทย รัฐบาลไทยพบว่าอุตสาหกรรมแป้งมันสำปะหลังเป็นส่วนที่มีศักยภาพและความเป็นไปได้สูงมีความเหมาะสมของภาคอุตสาหกรรม ขณะที่มีเพียงน้ำเสียที่มาจากอุตสาหกรรมแป้งมันสำปะหลังที่ถูกใช้ผลิตก๊าซชีวภาพ แต่อย่างไรก็ตามของเสียอื่นๆ ถูกทิ้งหรือใช้อย่างอื่นที่ได้ผลตอบแทนไม่คุ้มค่า สิ่งเหล่านี้ซึ่งเป็นผลมาจากข้อจำกัดบ้างอย่าง เช่น การขาดความรู้ เทคโนโลยี และอุปสรรคด้านการเงิน ซึ่งล้วนแต่ต้องการการสนับสนุนและส่งเสริมเป็นอย่างมากจากผู้ที่เกี่ยงข้องทั้งหมดประกอบด้วย โรงแป้งมันสำปะหลัง รัฐบาล นักวิจัย ชุมชุนที่อยู่โดยรอบ เป็นต้น ปัจจุบันนี้บทบาทที่สำคัญของการพัฒนาและเทคโนโลยีการผลิตก๊าซชีวภาพในอุตสาหกรรมแป้งมันมันสำปะหลังนี้ สามารถนำไปใช้เป็นต้นแบบและแนวทางของการผลิตก๊าซชีวภาพสำหรับอุตสาหกรรมอื่นๆ ในประเทศไทย

Keywords: การย่อยไม่ใช้อากาศ / ก๊าซชีวภาพ / แป้งมันสำปะหลัง / พลังงานทดแทน / น้ำเสีย

The Importance of Biogas Production from the Cassava Starch Industry in Thailand

Piyavadee Srivichai [1,*], Chumaporn Rodsrida [2], Supichaya Meesad[3]

[1]Program in Environmental Health, School of Public Health, University of Phayao, Phayao

[2]Program in Occupational Health and Safety, School of Public Health, University of Phayao, Phayao

[3]International Business Management, Naresuan University International College, Naresuan University, Phitsanulok

*Corresponding author email: piyavadee.sr@up.ac.th

Received: 19 Febuary 2023

Revised: 19 June 2023

Accepted: 1 July 2023

Abstract

Biogas is well known as an important renewable energy that drives the growth of economies in Thailand. Thai governor found that the cassava starch industry represents the first promising potential in the industrial section. Meanwhile, many organic-rich products and wastes were generated in large quantities from the production process. However, only wastewater was used to produce the biogas. While most others were wasted or widely used in non-financial return ways. These resulted from some limitations, such as the lack of knowledge, technologies, and financial support. Which it requires serious support and encouragement from all stakeholders, such as the cassava starch plants, the government, the researchers, the surrounding communities, etc. Significantly, the vital role of this technological progress and development in the cassava industry can be applied as the model and guideline of biogas production for other industries in Thailand.

Keywords: Anaerobic digestion / Biogas / Cassava starch / Renewable energy / Wastewater

Introduction

Nowadays, biogas plays an important role in mitigating measures of the energy crisis in Thailand. Its advantages include clean energy and environmentally friendly [1] by reducing waste to landfill, obtaining by-product as an organic fertilizer, and a waste to energy conversion. The government has made a lot of effort to attract and encourage several industries to start biogas production. In 2036, upgrading targets of the biogas production from wastewater, manure, and energy crop to generate electricity, thermal and compressed bio-methane gas (CBG) will be equivalent to 1,280 Megawatts (MW), 1,283 kilo-ton oil equivalent (ktoe), and 2,023 ktoe, respectively [2]. Particularly, the cassava starch industry is more interesting than other industries. Thailand has up to 102 cassava starch plants, generating a high amount of starch, at least 34,141 tons per day [3]. Additionally, Thailand is the largest cassava starch exporter [4]. It is a promising sector because of its numerous organic by-products and waste, which can be used for biogas production by converting by-products and wastes to value-added biogas energy. The produced biogas is desirable and can be developed for various purposes. For instance, it was applied to dry starch, produce electricity and thermal energy, etc. It can also be widely utilized by producing CBG as the conventional vehicle fuel.

As mentioned above the cassava starch industry represents a promising and powerful section for biogas production. The Thai government is also interested in acquiring biogas from this industry. Significantly, the important target six industries (cassava, vegetable oil, ethanol, rubber, and food processing) are encouraged to produce biogas, according to the biogas technology promotion program for industry 2008 – 2012 organized by The Office of Natural Resources and Environmental Policy and Planning [5]. This project is the preparation for the future energy crisis and response to Sustainable Development Goal 7 (SDG 7: ensuring access to clean and affordable energy)

This work aimed to literature the present situation and the knowledge base on biogas production from the cassava starch industry in Thailand. The authors hope the readers will find this article useful, and provide more ideas for interested readers in this field.

The use of biogas in Thailand

In 2018, Thailand used renewable energy as approximately 15.28% of overall energy consumption, which can be categorized into three major renewable energy types, as shown in Table 1. Biogas plays a significant role in economic development. It was used up to 528.60 ktoe, which could produce electricity about 505 MW or heat energy about 634 ktoe [6]. Biogas is crucial energy to mitigate further the energy crisis that is continuously much more severe. Recently, the data from the report of the Ministry of Energy indicated that several industries are potential and suitable for biogas production (Figure 1).

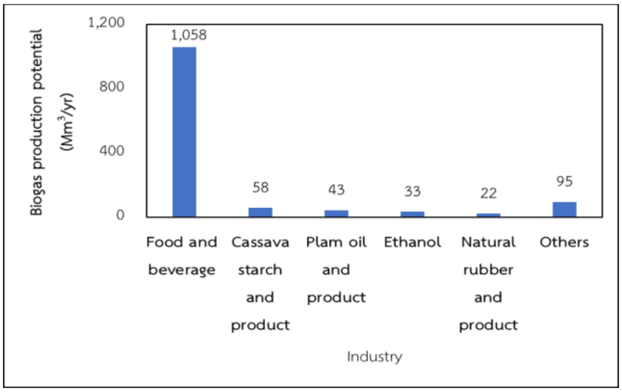

Figure 1 The biogas production potential in different industries

The cassava starch industry is a great biogas source [6]. Consequently, many supporting measures occurred. For instance, the promotion campaign to use an up-flow anaerobic sludge blanket (UASB) technology for wastewater treatment, the development of anaerobic fixed film using nylon wire mesh as media, the financial support from the Ministry of Industry. all led to many constructions of the biogas production system from wastewater in 36 cassava starch plants. But up to 41 plants remain without the biogas production system [7]. This gap is so powerful, attractive, and interesting.

Table 1 The situation of renewable energy use in the year 2018

Renewable energy for electricity production	**Production capacity (MW)**
1. Solar energy	2,715.21
2. Wind energy	927.82
3. Water energy	3,094.13
4. Biomass	3,276.88
5. Biogas	500.15
6. Waste to energy	283.00
7. Geothermal energy	0.30
Total	10,797.50
Renewable energy for thermal energy production	**Production capacity (ktoe)**
1. Solar energy	8.38
2. Biomass	5,831.54
3. Biogas	528.60
4. Waste to energy	98.50
Total	6,467.01
Renewable energy for biofuel production	**Production capacity (ml/d)**
1. Ethanol	4.15
2. Biodiesel	4.19
Total	8.34

The important by-products and wastes from cassava starch production as the potential substrate to produce biogas.

1) Cassava peel

It is estimated that about 30 kilograms of cassava peel is produced from one ton of fresh cassava root used [8]. Therefore, the total amount of cassava peel was approximately 299 tons per year in Thailand. The main component of its peel is carbohydrates, around 38-42%. It has a small protein content of 4-5% [9]. Typically, the cyanogenic glucoside was removed by sun-drying and fermenting before applying it as animal feeds [10]. Some of these were sold as an organic fertilizer in crops and mushroom cultivation. The selling prices of cassava peel are too low, around 1.6-4.8 dollars per kilogram (50-150 baht per kilogram) [11]. Normally, cassava peel has the potential for biogas production because it contains large amounts of cyanogenic glycoside and high protein levels. However, its usage has some limitations, such as it takes a long time for digestion (13 – 20 days) and needs to be prepared before removing cyanide [12].

2) Cassava pulp

About 3.29 million tons of cassava pulp were generated annually in Thailand by calculating based on 330 kilograms per ton of fresh cassava root [13, 8]. About half of its dry weights are high in carbohydrate content but extremely low in protein content, only 2% [14]. Currently, its dumping has relatively high environmental impacts. High organic matter may contribute to groundwater and soil contamination from its digestion. Moreover, its anaerobic digestion in landfills produces a high amount of methane emissions which causes global warming [15]. Only a small portion of pulp was applied in the agriculture and livestock sectors. The average selling price of pulp ranged from 9.6-2.7 dollars per kilogram (300-400 baht per kilogram) [11].

Both cassava peel and pulp characteristics are unsuitable to use as animal feeds due to protein deficiency. Commonly, animal diets are made up of crude protein between 65 and 75% and carbohydrates between 14 and 19% by dry weight [16]. Therefore, they must be mixed with other protein-rich substrates such as soybean and peanut before applying.

3) Wastewater

The wastewater was discharged with a volume of 4.54 cubic meters per ton of fresh cassava root used [17]. Accordingly, the estimated wastewater equal to 45,300 cubic meters per year is intentionally treated. Cassava wastewater generally has pH near acidic. It has high organic matter in BOD values, as shown in Table 2.

The aeration pond was the most popular wastewater treatment system in the cassava starch industry, followed by the activated sludge process and the oxidation pond, respectively. Some serious environmental problems occurred from the wastewater treatment system and caused people to be worried and unhealthy, such as odor nuisance, soil contamination, aquatic toxicity, etc. Thus, a big effort was to induce many companies to change an old wastewater treatment system to an anaerobic one. This will be operated in the closed airtight reactor without odor release. Also, it is beneficial to obtain valuable biogas as a by-product.

Table 2 The wastewater characteristics from the cassava starch industry

Parameter	Value					Unit
Wastewater type	modified cassava wastewater	cassava wastewater	cassava wastewater	cassava wastewater	cassava wastewater	
pH[a]	6.21	4.34	4.1-4.8	3.9-4.5	4.2	-
TDS[b]	13,520	-	-	-	975	mg/l
TS[c]	-	2,252	7,666	17,800	-	mg/l
COD[d]	20,433	8,152	2,240	33,700	1,236	mg/l
BOD[e]	9,750	-	1,450	-	430	mg/l
Reference	[18]	[19]	[20]	[21]	[22]	

[a]: Hydrogen ionic potential, [b]: Total dissolved solids, [c]: Total Solids, [d]: Chemical oxygen demand, [e]: Biochemical oxygen demand

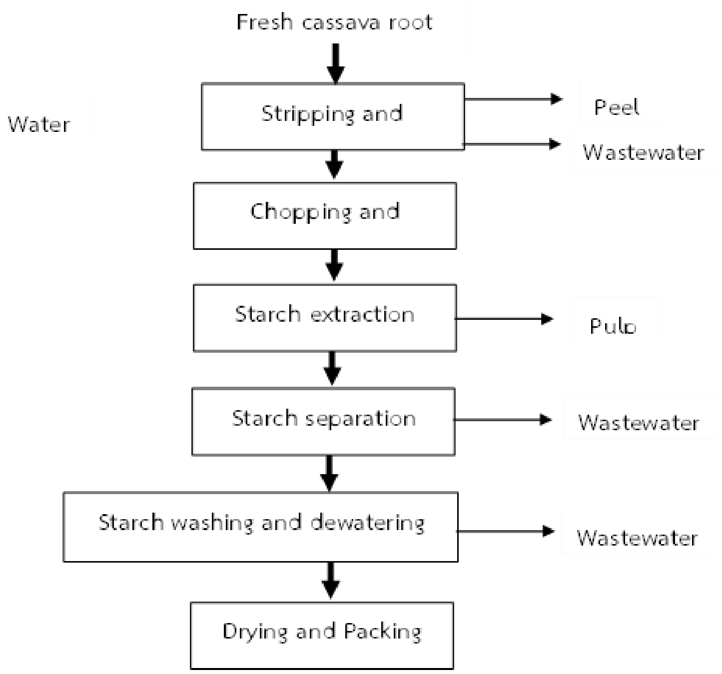

Figure 2 By-products and wastes from the cassava starch production process [23]

The popular anaerobic digestion system is applied to produce biogas from the cassava starch industry [24]

Unfortunately, there was only the wastewater used to produce biogas in Thailand. The Thai governor announced the campaign to promote the use of renewable biogas energy. The popular anaerobic digestion systems were taken to produce biogas from wastewater as follows:

1) **Up-flow anaerobic sludge blanket (UASB)**

Wastewater was filled from the bottom to the topside tank. Bacterial sludge was separated into two layers. At the bottom is a sludge bed, and the upper side is a lighting sludge blanket. The produced biogas will flow through the gas-solid separator that covers the upper part of the tank. This system is unsuitable for wastewater with high suspended solids.

2) Anaerobic fixed film (AFF)

The bacteria are fixed to the media to prevent the washout. This resulted in them resisting the organic shock loads and faster recovery.

3) Continuous stirred tank reactor (CSTR)

In CSTR, the mixing system can help improve the digestion efficiency leading to better biogas yield. This system can receive a high organic loading rate (OLR) by digesting within a shorter time.

4) Anaerobic baffled reactor (ABR)

The ABR long shape reactor is typically made up of many baffles to control the flow direction and velocity in the range of 0.2-0.4 meters per hour. The system can be used for wastewater with high suspended solids. However, there is a limitation on the large land use requirement.

5) Modified covered lagoon (MCL)

The lagoon is covered by high-density polyethylene or polyvinylchloride plastic to collect biogas. The microorganism balance is controlled by pumping out with the sludge separator.

The study of the biogas production from the cassava starch industry

The overview of biogas production capacity from various substrates of the cassava starch industry presents in Table 3. Only pulp and wastewater were conducted to demonstrate the biogas production potential and the methane. Since both are easy and ready to use, the peel must be pretreated to remove the cyanogenic glucoside before use in anaerobic digestion. The literature results indicate that they are the potential substrates for biogas production and methane production. Specially, the wastewater produced the proper biogas consisting of a methane content higher than 50% is the appropriate alternative fuel for other power generations. [25]. Additionally, this level accords with the suggestions from several experts, which it is worth investment. However, additional study of the biogas production from peel, and others should be conducted later.

Table 3 The previous studies and research about the biogas production from the cassava starch industry

Substrate	Digestion system	Digestion condition	Yield		Methane content (%)	Ref.
			Biogas	Methane		
pulp	Bottle 120 ml	At 35 °C, shaking speed 120 rpm, pretreat with ultrasonic 20 m.	-	267±1.51 ml/g VS[a] added	-	[26]
wastewater	Packed–bed reactor 3.64 l	OLR 10 g/l/d, at 25 °C	311 ml/g COD	-	>80	[27]
pulp + wastewater	Bottle 650 ml	Pretreat by alkaline or acid at neutral pH and thermal for 45 m at 200 °C in 5% TS	4,125.5 ml/kg TS	-	-	[28]
wastewater	Horizontal flow filter	OLR 11.8 g COD/l/d, at 33±2 °C	360 ml/ g COD	-	69-81	[29]
pulp	Flask 1.25 l	Feeding rate 58.3 g TS/batch at 55±2 °C	-	0.638-0.395 m^3/kg VS_{added}	-	[30]
wastewater	Two-stage anaerobic digestion with a bottle 500 ml	Feeding rate 15 g/l at the thermophilic condition	-	319.5 l/kg COD	55	[31]
pulp	Semi-continuously feed stirred tank reactor	OLR 35 kg VS/m^3/d at 37 °C	-	118±50 ml/g VS	43±8	[32]

[a]: Volatile solids

The role of biogas from the cassava starch industry

1) Thermal energy production

Biogas can be utilized directly to produce fuel for thermal energy generation. The cassava starch plant obtained a lot of the financial benefits of energy savings by replacing a traditional natural gas vehicle (NGV) and heavy oil with biogas. Because it reduces the large amount of NGV and heavy oil that are required to ignite the burner in the drying process. If one cubic meter of biogas is at 60%, methane can be converted up to 21-24 megajoules of thermal energy [33]. However, the application of biogas may be inappropriate because of various impurities in the biogas, such as humidity, carbon dioxide, or hydrogen sulfide. It needs to be cleaned up before use.

2) Electricity production

The average electricity productivity from biogas was approximately 2.185 kilowatt-hours per cubic meter of biogas [34]. The study by Pennapa and colleagues [35] indicated that one ton of the produced cassava starch can generate renewable biogas of about 117.45 cubic meters. Calculating based on the wastewater was produced of 15 cubic meters per ton of starch produced, and biogas was generated at 7.83 cubic meters per cubic meter of the wastewater. Unfortunately, only the wastewater was taken to produce the biogas for electricity generation. This may have several barriers about the lack of knowledge, technology, and budget. Additionally, there are also some restrictions concerning the electricity generator needs to obtain the building construction permit, the factory license, the electricity generator license, and the control energy production license that need to be received before starting the construction and operation.

3) Vehicle fuel production

It is well known that a weight of 0.5 kilograms of CBG was produced from biogas, approximately one cubic meter. In 2021, the Thai government wanted to encourage the use of CBG in replace of NGV at least 5% [36]. Interestingly, the cassava starch industry is the highest CBG producer, approximately 1,287-1,775 cubic meters per year, followed by the ethanol industry, palm oil industry, rubber industry, and food processing industry from the study by Pennapa and colleagues [35], as shown in Figure 3. The cassava starch industry was seen as the crucial potential sector to drive this target. However, much necessary support from the government is so important and helpful in such cases.Since there are several obstacles, such as the lack of biogas upgrading technology, and the confidence about the use of CBG. Furthermore, the absence of management policy about CBG producer registration and the non-obvious selling CBG price are the significant obstacles [37].

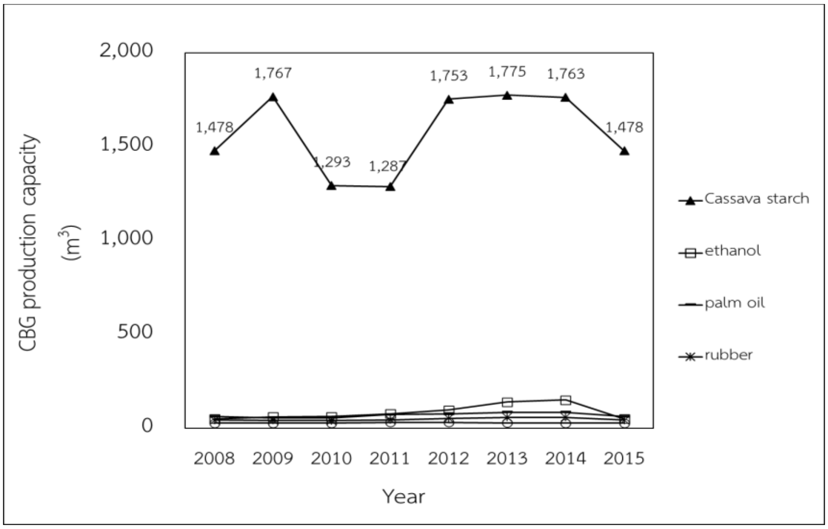

Figure 3 The CBG production capacities of various industries

Conclusion

All data indicates the cassava starch industry has a high potential to develop the utilization of biogas in Thailand. The large volume of organic-rich by-products and wastes from its production process are the prominent substrate in the anaerobic digestion for biogas production. In general, they are wasted or used in inappropriate and uneconomical ways. These are probably due to the lack of knowledge and technologies, including many barriers such as budget, legal, etc. As a result, this issue is one of the significant issues that need to be addressed and continued further study. However, rapid socioeconomic growth is the stronger driving force to accelerate its innovation development in Thailand. Thus, the involved key stakeholders, such as the government, the cassava starch plants, and the community, must accept, engage, and adapt to the challenge of this change.

Acknowledgments

The authors would like to acknowledge Mr. Sirichai Suwanlamai for all his support.

References

1. Shireen B, Payal D. A review: advantages and disadvantages of biogas. Int Res J Eng Tech 2017;4(10):890-3.
2. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Thailand bioenergy policy update 05/2016 [Internet]. 2016 [cited 2022 November 12]. Available from: http://www.thai-german-cooperation.info /admin/uploads/publication/b37f836e88f667d3e74376110293f797en.pdf
3. Jakrawatana N, Pingmuangleka P, Gheewala SH. Material flow management and cleaner production of cassava processing for future food, feed, and fuel in Thailand. J Clean Prod 2016;134(B):633-41.
4. Khandare BV, Choomsook P. Cassava export of Thailand: growth performance and composition. Int J Res Anal Rev. 2019;6(2):847-57.
5. Ministry of Energy. Handbook for development and investment in renewable energy production, set 5 [Internet]. 2011 [cited 2023 June 13]. Available from: https://www.dede.go.th/article_attach/h_biogas.pdf
6. Vanchai B. Renewable energy and conservation energy plan [Internet]. 2019 [cited 2022 November 5]. Available from: https://www.thailand-energy-academy.org/assets/upload/coursedocument/file/
7. Department of Alternative Energy Development and Efficiency, Ministry of energy, Thailand. A guide to renewable energy development and investment [Internet]. 2011 [cited 2022 October 2]. Available from: https://www.thebangkokinsight.com/news/environmental-sustainability/584784/

8. Yuvadee M. The utilization of cassava peel and pulp for biogas production. (Master thesis, Chulalongkorn University, Bangkok, Thailand) [Internet]. 2016 [cited 2022 December 1]. Available from: http://cuir.car.chula.ac.th/handle/123456789/55736
9. Pondja JEA, Persson KM, Matsinhe NP. The potential use of cassava peel for treatment of mine water in Mozambique. J Env Prot 2017;8(03):277-89.
10. Sudharmono, Ekawati AW, Setijawati D. Fermented cassava peel evaluation. Int J Chem Tech Res 2016;9(7):421-26.
11. The Thai Tapioca Product Factory Association. The price of cassava pulp from 2014 to the present [Internet]. 2021 [cited 2022 November 8]. Available from: http://thaitapioca.org
12. Ismail N, Fauzi NF, Salehabadi A, Latif S, Awiszus S, Müller J. A study on biogas production from cassava peel and stem in anaerobic digestion reactor. Int J Env Sci Tech 2022;19:1695-704.
13. Ghimire A, Sen R, Annachhatre AP. Biosolid management options in cassava starch industries of Thailand: present practice and future possibilities. Proc Chem 2015;14:66-75.
14. Titima P, Kamlai L, Paiboolya G, Klanarong S. Solid state cultivation of fungi for protein-enriched cassava pulp. Suranaree J Sci Tech 2015;25(1):91-100.
15. Ghimire A, Sen R, Annachhatre AP. Biosolid management options in cassava starch industries of Thailand: present practice and future possibilities. Proc Chem 2015;14:66-75.
16. Grant RJ. G91-1027 protein and carbohydrate nutrition of high producing dairy cows [Internet]. 1991 [cited 2022 November 12]. Available from: https://digitalcommons.unl.edu/extensionhist/438
17. Chavalparit O, Ongwandee M. Clean technology for the tapioca starch industry in Thailand. J Clean Prod 2009;17(2):105-10.
18. Nurul AE, Alawi S, Siti NAR. Enzymatic saccharification of tapioca processing wastes into bio sugars through immobilization technology. Biofuel Res J 2014;1:2-6.

19. Torres DGB, Lucas SDM, Andreani CL, Carvalho KQD, Coelho SRM, Gomes SD. Hydrogen production and performance of anaerobic fixed-bed reactors using three support arrangements from cassava starch wastewater. E Agri 2017;37(1):160-72.
20. Ana, PT, Eduardo, BL, Fabio LF, Kauanna UD, Simone DG. Cassava wastewater treatment by coagulation/flocculation using moringa oleifera seeds. Chem Eng Trans 2019;74:367-72.
21. Achi CG, Hassanein A, Lansing S. Enhanced biogas production of cassava wastewater using zeolite and biochar additives and manure co-digestion. Ener 2020;13(2):1-13.
22. Oghenejoboh KM. Effects of cassava wastewater on the quality of receiving water body intended for fish farming. Br J Appl Sci Tech 2015;6(2):164-71.
23. Aristizabal J, Garcia JA, Ospina B. Refined cassava flour in bread making: a review. Ingen e Invest 2017;37(1):25-33.
24. Thai Tapioca Starch Network. Treatment and utilization of wastewater [Internet]. 2021 [cited 2022 November 4]. Available from: http://www.thailandtapiocastarch.net/technology-detail/2/3/
25. Ahmmad MR, Haque S. Providing electricity by digester types on biogas productions from municipal solid waste in Dhaka city, Bangladesh. Int J Ener, Inform Commun 2014;5(3):13-22.
26. Kongiak L, Punsa L, Weerachai A. Bio - methane production from cassava pulp using ultrasonic wave as a pretreatment process. Proceedings of the 3 rd Conference on Farming Engineering and Automation Technology [Internet]. 2016 [cited 2022 December 3]. Available from: https://feat.kku.ac.th/03conference/03FEAT3/feat3/09FEAT09กงจักร.pdf
27. Araujo IRC, Gomes SD, Tonello TU, Lucas SDM, Mari AG, Vargas RJD. Methane production from cassava starch wastewater in packed-bed reactor and continuous flow. E Agri 2018;38(2):270-6.
28. Htay AP, Nittaya B, Usa Y, Chatlada P. Effect of acid - alkaline and thermal pre-treatment to cassava pulp feed for batch reactors in optimization of bio–methane yield. Appl Env Res 2018;40(2):51-60.

29. Colin X, Farinet JL, Rojas O, Alazard D. Anaerobic treatment of cassava starch extraction wastewater using a horizontal flow filter with bamboo as support. Biores Tech 2006;98(8):1602-7.
30. Zhang J, Xu JY, Wang DQ, Ren NQ. Anaerobic digestion of cassava pulp with sewage sludge inocula. Bio Resour 2016;11(1):451-65.
31. Khongkiiang P, Kongian P, O-Thong S. Hydrogen and methane production from starch processing wastewater by thermophilic two-stage anaerobic digestion. Ener Proc 2017;79:827-32.
32. Panichnumsin P, Nopharatana A, Ahring B, Chaiprasert P. Production of methane by co-digestion of cassava pulp with various concentrations of pig manure. Biom Bioener 2010;34(8):1117-24.
33. Bond T, Templeton MR. History and future of domestic biogas plants in the developing world. Ener Sustain Devel 2011;15(4):347-54.
34. Wattanasilp C, Songprakorp R, Nopharatana A, Khompatraporn C. Techno-cost-benefit analysis of biogas production from industrial cassava starch wastewater in Thailand for optimal utilization with energy storage. Ener 2021;14(2):1-22.
35. Pennapa T, Apichit T, Itthichai P. Overview of biogas production potential from industry sector to produce compressed bio-methane gas in Thailand. Ener Proc 2017;138:919-24.
36. Energy Policy and Planning Office, Ministry of energy, Thailand. Alternative energy development plan: AEDP 2012-2021 [Internet]. 2015 [cited 2022 November 12]. Available from: http://www.eppo.go.th/index.php/th/plan-policy/tieb/aedp
37. Thepsaskul W, Wongsapaib W, Koonnaphapdeelertc S, Chaichana C, Daroon S. Business model for the commercialization of compressed bio-methane gas by substituting conventional fossil fuels in Thai industrial sector. Chem Eng Trans 2018;63:331-36.