CHEMICAL ENGINEERING TRANSACTIONS
VOL. 122, 2025
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Jeng Shiun Lim, Bohong Wang, Guo Ren Mong, Petar S. Varbanov

ISBN 979-12-81206-23-6; **ISSN** 2283-9216
DOI: 10.3303/CET25122091

Global Warming Potential of Electricity from Sodium Hydroxide Pretreated Napier Grass Biogas: A Cradle-to-Gate Life Cycle Assessment

Phairat Usubharatana[a], Atitaya Kuwalairat[a,b], Harnpon Phungrassami[a,*]

[a]Chemical Engineering Department, Thammasat School of Engineering, Faculty of Engineering, Thammasat University, Thailand
[b]Sirindhorn International Institute of Technology, Thammasat University, Thailand
pharnpon@engr.tu.ac.th

Napier grass was investigated as a bio-energy feedstock for Thailand. Laboratory anaerobic digestion and cradle-to-gate life cycle assessment (LCA) determined electricity generation's global warming potential (GWP). Untreated and 1 % w/v NaOH pretreated biomass were digested. Pretreatment significantly increased cumulative biogas yield by up to 49 %, with 538.9 ± 22.3 mg/gVS at the highest F/I ratio. The LCA, based on primary experimental data and adjusted secondary data for the 2019 Thai electricity mix, characterized GWP per 1 kWh. Untreated systems exhibited GWP between 2.86–3.82 kg CO_2e/kWh. However, pretreatment raised emissions to 7.01–8.26 kg CO_2e/kWh; this was primarily due to the high emissions from NaOH manufacture and neutralization. Substituting 40 % of synthetic nitrogen fertilizer with cattle manure nearly halved both footprints, and a fully organic regime resulted in the untreated system's GWP being reduced to 0.57 kg CO_2e/kWh, which falls below the 2019 Thai grid factor of 0.599 kg CO_2e/kWh. These findings indicate that while reactor performance is improved by NaOH pretreatment, climate benefits are offered only when aggressive fertilizer optimization.

1. Introduction

Thailand aims for a 40% reduction in economy-wide greenhouse gas emissions by 2030 and a 30% renewable share in national electricity generation by 2036 (Chaichaloempreecha et al., 2024). Despite these goals, approximately 79% of power in 2020 was supplied by fossil fuels (Lau, 2022). Dispatchable renewable options, such as anaerobic digestion of agricultural biomass, are crucial for balancing variable solar and wind resources. Anaerobic digestion also offers benefits by diverting open-burned residues, reducing local air pollution, and providing rural income.

Napier grass is a promising Thai bio-energy crop with high yields (35–50 t/ha/y) even on marginal land (Sawasdee and Pisutpaisal, 2014). However, its high lignin content (16–18 % dry weight) and carbon-to-nitrogen (C : N) ratio (approaching 40) hindering digestion (Weerayutsil et al., 2016; Ta and Babel, 2019). Alkaline pretreatment disrupts lignin-carbohydrate complexes, enhancing cellulose accessibility and increasing methane yields by 25–60 % (Narinthorn et al., 2019). Nevertheless, NaOH production is energy – intensive (1.4–2.1 kg CO_2e/kg) and generates chloride-rich effluents (Abraham et al., 2020), potentially negating climate benefits.

Previous life-cycle studies on lignocellulosic biogas have shown varied cradle-to-gate footprints, ranging from 0.222 kg CO_2e/kWh (Whiting and Azapagic, 2014) to 0.431 kg CO_2e/kWh for Maize silage (Czubaszek et al., 2020). However, few analyses have specifically examined the environmental impact of NaOH pretreatment under Southeast-Asian conditions. Crucially, none has combined primary laboratory batch digestion data with comprehensive region-specific inventories for both cultivation and energy conversion under Thai-specific conditions. Upstream agricultural inputs, especially synthetic nitrogen fertilizer, are often found to dominate energy-crop carbon footprints (Boulamanti et al., 2013). While organic manure substitution and digestate recycling could mitigate these emissions, their effectiveness for pretreated Napier grass remains unverified.

Paper Received: 15 October 2025 ; Revised: 30 November 2025 ; Accepted: 19 December 2025
Please cite this article as: Usubharatana P., Kuwalairat A., Phungrassami H., 2025, Global Warming Potential of Electricity from Sodium Hydroxide Pretreated Napier Grass Biogas: a Cradle-to-Gate Life Cycle Assessment, Chemical Engineering Transactions, 122, 541-546 DOI:10.3303/CET25122091

This study coupled laboratory batch digestion with a cradle-to-gate LCA, specifically tailored to central-Thai conditions, to quantify the GWP of electricity from untreated and 1 % w/v NaOH-pretreated Napier grass. The aims were to identify emission hotspots and evaluate manure-based fertilizer strategies as effective mitigation measures. Insights gained will guide policymakers and researchers in developing climate-efficiency biogas systems for Thailand's Bio-Circular-Green Economy objectives.

2. Methodology

2.1 Feedstock and inoculum preparation

Napier grass was harvested from a commercial field in Nakhon Pathom, Thailand. Biomass was chopped (≈ 5 mm), air-dried to below 15 % moisture. A portion served as untreated control; the remainder was pretreated by soaking in a 1 % w/v NaOH for 24 hours at ambient temperature, rinsed, and redried. Anaerobic sludge, collected from a dried-fruit factory digester in Samut Sakhon Province, was used as inoculum, stored at 4 °C and acclimated for 12 hours at 34 °C before use. The physical characteristics of substrates were analyzed in triplicate. Mean values are presented in Table 1.

Table 1: Physical characteristics of feedstock (Napier grass) and Inoculum.

Parameters	Units	Untreated Napier grass	Pretreated Napier grass	Inoculum
Carbon (C)	(%)	43.64	45.51	24.49
Nitrogen (N)	(%)	1.18	0.64	3.03
C/N ratio	-	36.98	71.11	8.08
Total Solid (TS)	(%)	21.15 ± 0.03	28.49 ± 0.23	3.74 ± 0.02
Volatile Solid (VS)	(%)	18.77 ± 0.08	27.58 ± 0.25	1.88 ± 0.01
pH	-	6.61	7.18	6.57

2.2 Batch anaerobic digestion and analytical procedures

One-litre serum bottles were used as batch reactors at 34 ± 1 °C. Untreated and pretreated substrates were mixed with inoculum at feedstock-to-inoculum (F/I) ratios of 0.5 : 1, 1 : 1 and 2 : 1 (VS basis) in triplicate. Reactor headspaces were purged with N_2. Gas production was monitored until cumulative curves plateaued (120 days). Biogas volume was measured (100 mL syringe, STP-normalized). Methane, carbon dioxide, and nitrogen fractions analyzed by gas chromatography. Volatile fatty acid (VFA) and alkalinity in digestate obtained by titration.

2.3 Life Cycle Assessment

The LCA consisted of four main steps: (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact assessment, and (iv) Interpretation and sensitivity analysis–followed the standard ISO 14040/14044 to quantified cradle-to-gate GWP for electricity from untreated and 1 % w/v NaOH-pretreated Napier grass at various F/I ratios. The functional unit was 1 kWh of net electricity to the Thai grid, comparable to the 2019 grid factor (0.599 kg CO_2e/kWh). The system boundary (Figure 1) covered five process stages; cultivation, pretreatment, anaerobic digestion, biogas purification, and CHP generation (35 % electrical efficiency), while infrastructure and all transport were excluded from the scope of this study based on previous screening indicated contributions below 1 % of total GWP. Only GWP was characterised, using 100-year IPCC (2014) AR5 factors. Primary data included substrate/inoculum properties, pretreatment and cumulative yields from batch trials. Cultivation and harvesting inventories were sourced from Bangprasit et al. (2017), aligned with Sawasdee and Pisutpaisal (2021), with gasoline input referring exclusively to on-field machinery. Biogas upgrading, and CHP were taken from Ardolino et al. (2018) and calibrated to the 2023 Thai electricity mix. The experimental NaOH dose (1 % w/v) was modelled using Ecoinvent v3.8 and linked to the Thai grid. Direct N_2O emissions were determined using the IPCC Tier 1 factor (1.25 % of applied N). Digestate use was credited for displaced synthetic fertilizer based on Thai agricultural databases. Interpretation involved identifying emission hotspot (expressed as kg CO_2e/kWh) and assessing influential parameters. Sensitivity analysis explored mitigation potential through various fertilization scenarios, including partial synthetic nitrogen replacement with cattle manure and a full organic regime utilizing digestate. These analyses aimed to confirm the essential role of fertilizer optimization for climate-efficient biogas deployment.

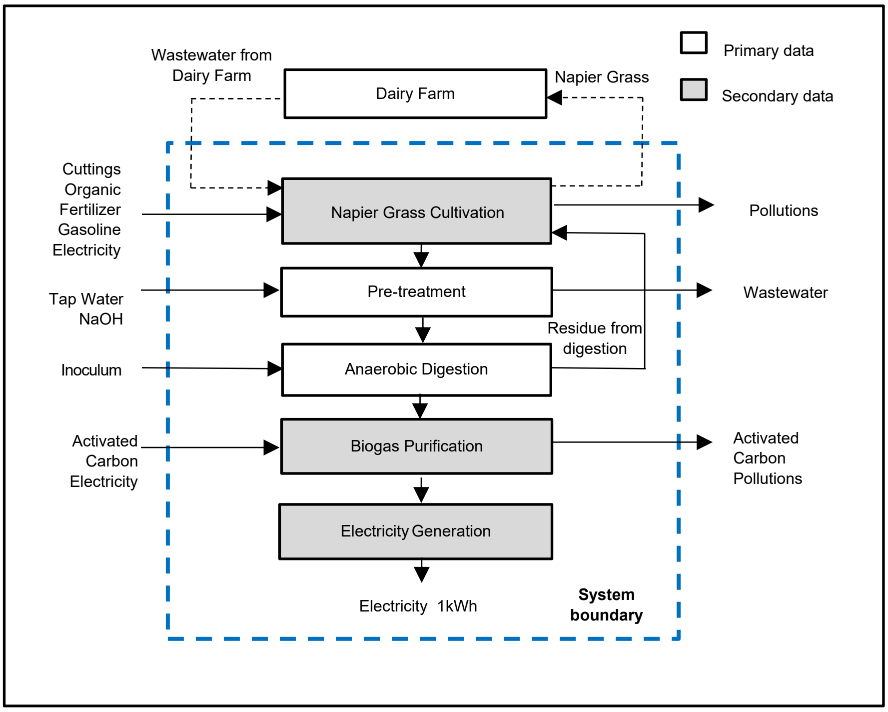

Figure 1: System boundary

3. Result and discussion

3.1 Biogas production

NaOH pretreatment (1 % w/v) significantly altered the elemental balance of Napier grass, resulting in its C : N ratio being increased from 36.98 to 71.11 (Table 1). At the highest F/I ratio (2 : 1), the pre-treated material combined with inoculum (C : N = 8.09) resulted in a composite C : N of 26.8, which is favorable for mesophilic methanogenesis (Egwu, 2021). This adjustment indicated that alkaline pretreatment not only modified lignocellulosic structure but also improved feedstock-to-inoculum stoichiometry.
Cumulative biogas curves (Figure 2) demonstrate that gas evolution was accelerated and final yield was increased by pretreatment across all F/I ratios. Untreated feedstock produced 342 ± 11, 347 ± 5 and 361 ± 7 mL/gVS at F/I ratios of 0.5 : 1, 1 : 1 and 2 : 1, respectively. Pre-treated feedstock yielded 492 ± 5, 495 ± 8 and 539 ± 22 mL/gVS, representing relative improvements of 44 %, 42 % and 49 %. The shortened lag phase in pretreated Napier grass, indicating enhance hydrolysis after lignin-carbohydrate disruption, enabling faster microbial access to cellulose and supporting higher methane conversion efficiency. Methane fractions in the best runs averaged 52.1 % (untreated) and 53.9 % (pre-treated). Process stability, as indicated by pH (6.5–7.5) and VFA-to-alkalinity ratio (< 0.3) throughout digestion, confirmed healthy methanogenic activity.
Benchmarking the highest pre-treated yield (539 mL/gVS) against other lignocellulosic substrates (Table 3) shows that NaOH-treated Napier grass outperformed rice straw (353 mL/gVS) and algal biomass (334 mL/gVS) but remained below mixed vegetable wastes (907 mL/gVS). These results confirm moderate alkaline pretreatment as an effective strategy for enhancing Napier grass digestibility.

Table 2: Methane concentration and biogas yield across experimental conditions

Reactor	Treatment	F/I Ratio (gVS/gVS)	C/N Ratio	Methane (%)	Biogas Yield (mL/gVS_{added})
1	Untreated	0.5 : 1	12.81	32.12	342.0 ± 10.7
2	Untreated	1 : 1	16.22	35.58	347.3 ± 5.1
3	Untreated	2 : 1	20.79	52.13	360.7± 7.2
4	Pretreated	0.5 : 1	14.12	34.75	492.4 ±4.8
5	Pretreated	1 : 1	19.09	49.49	494.5 ± 8.3
6	Pretreated	2 : 1	26.81	53.90	538.9 ± 22.3
7 (Control)	-	0 : 1	8.09	21.41	64.0 ± 8.2

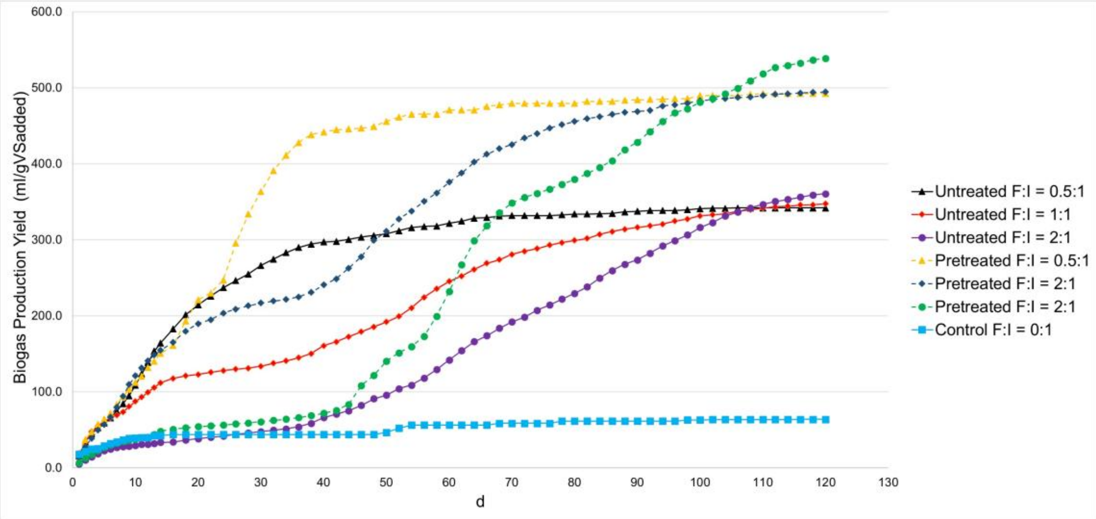

Figure 2: Biogas production yield from Napier grass at various conditions

Table 3: Comparison of biogas production at different substrates

Substrates	Optimum conditions	Biogas yield (mL/gVS_{added})	References
Mixed vegetable wastes	Mixed vegetable wastes and granular sludge (F/I of 0.5 : 1 gVS/gVS) with 300 $mg/gVS_{feedstock}$ $NaHCO_3$ added	907.0	Ta and Babel (2019)
Rice straw	Rice straw with fungal pretreatment at 30 days prior milling and anaerobic sludge obtained from biogas plant	353.0	Mustafa et al. (2017)
Algal biomass	Co-digestion with equal amounts of algal biomass, food waste leachate, and raw sludge at ratio 1 : 1	334.0	Kim and Kang (2015)
Napier grass	(1) Napier grass with cow dung at ratio of Napier grass : cow dung : water = 10 : 10 : 80	346.7	Sawanon et al. (2017)
	(2) Pretreated napier grass with 1 % w/v NaOH with sludge from fruit processing plant at F/I ratio of 2 : 1 gVS/gVS	538.9	This study

3.2 Life cycle assessment

Global-warming potentials for the seven configurations (Reactors 1–7) are shown in Figure 3. Electricity from untreated Napier grass (Reactors 1–3) ranged from 2.86 to 3.82 kg CO_2e/kWh with synthetic fertilizer manufacture, including direct emission of N_2O from fertilizer application, dominated (60–68% of total GWP). Introduction of 1 % w/v NaOH pretreatment (Reactors 4–6) resulted in the footprint being increased to 7.01–8.26 kg CO_2e/kWh due to the electricity-intensive chlor-alkali route required for upstream NaOH production and wastewater handling contribued 55–57% of total emissions. While, the GWP for the control (Reactor 7), utilized biogas without Napier grass feedstock, was 0.91 kg CO_2e/kWh (driven mainly by upgrading), This value was higher than the range of other reactors (0.466–0.665 kg CO_2e/kWh) due to its lower methane content, required greater energy input for the biogas upgrading process. These indicated that although pretreatment improved methane yield, its chemical and energy requirements substantially elevate upstream burdens.

Emission profiles differed markedly between untreated and pretreated chains. In untreated systems, upstream synthetic nitrogen dominated, consistent with other energy-crop studies reporting strong N_2O sensitivity. In contrast, pretreated systems shifted the hotspot toward chemical pretreatment; confirming that alkaline reagents can outweigh energy gains. Mitigation measures, such as partially substituting mineral nitrogen with cattle manure (40% reduction), lowered every footprint by up to 48%. The fully organic variant reduced the untreated chain's GWP to 0.572 kg CO2e/kWh, falling below the grid benchmark, highlighting cultivation practice as the decisive factor without chemical pretreatment.

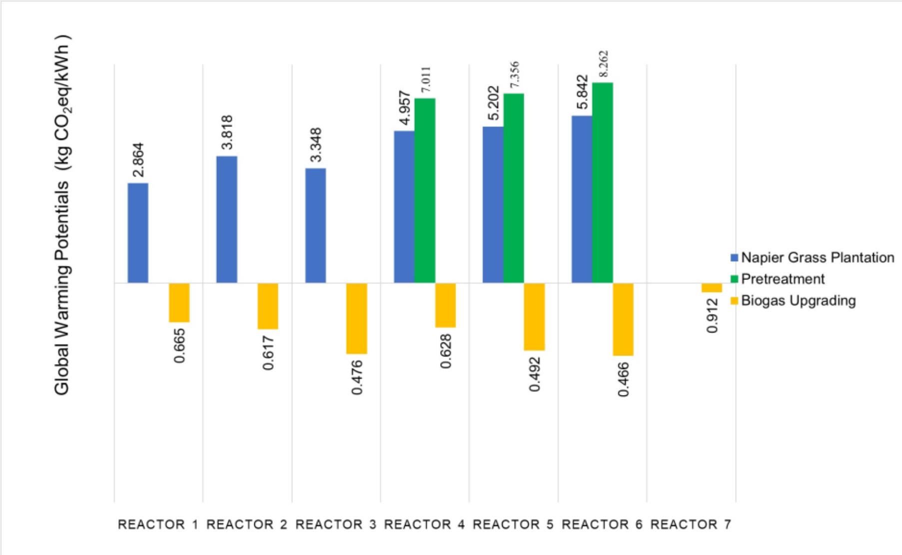

Figure 3: Global warming potentials of 1 kWh electricity production from anaerobic digestion.

A literature comparison (Table 4) shows the untreated baseline (0.572 kg CO_2e/kWh from this study) aligns with values for other biogas raw materials, including other Napier grass studies (e.g., 0.377 kg CO_2e/kWh). Higher values in certain lignocellulosic systems reflect differences in fertilizer regimes, digestion efficiencies and grid mixes. The higher footprints in pre-treated figures align with other NaOH-conditioned lignocellulosic systems, reinforcing the dominance of chlor-alkali reagents unless recovery or lower-impact bases are used and must be paired with fertilizer optimization to achieve net climate benefits.

Table 4: Comparison of the GWP of electricity generation in each raw material

Type of raw material	GWP (kg CO_2e/kWh)	References
Biogas		
- Agricultural wastes	0.222	Whiting and Azapagic (2014)
- Sewage sludge and organic waste	0.259	Iordan et al. (2016)
- Cattle slurry and grass silage	0.302	Perez-Camacho et al. (2019)
- Maize silage	0.431	Czubaszek et al. (2020)
- Napier grass	0.377	Bangprasit et al. (2017)
- Napier grass	0.572	This study

4. Conclusion

Laboratory digestion confirmed 1 % w/v NaOH pretreatment improved Napier-grass performance, increasing cumulative methane yield by 42–49 %. However, the cradle-to-gate LCA showed that electricity from untreated reactors emitted 2.86–3.82 kg CO_2e/kWh, while pretreatment raised the footprint to 7.01–8.26 kg CO_2e/kWh. Alkali manufacture, neutralization and wastewater handling accounted for over half of total emissions.
Significant mitigation occurred with fertilizer optimization: footprints were reduced by up to 48 % when 40 % of synthetic nitrogen was replaced with cattle manure. A fully organic regime lowered the untreated chain's GWP to 0.572 kg CO2e/kWh (below the 2019 Thai grid factor). These results demonstrate that climate benefits are provided by NaOH pretreatment only with aggressive fertilizer optimization and ideally, alkali recovery.
Untreated Napier grass under organic cultivation already meets the national benchmark. The study was limited to batch scale and a single NaOH dose; future work should consider continuous trials, closed-loop chemical recovery, and broader impact metrics.

Acknowledgements

Gratitude is expressed to Thammasat School of Engineering, Faculty of Engineering, Thammasat University for their invaluable support and resources during this research.

References

Abraham A., Mathew A.K., Park H., Choi O., Sindhu R., Parameswaran B., Pandey A., Park J.H., Sang B., 2020, Pretreatment strategies for enhanced biogas production from lignocellulosic feedstocks, Bioresource Technology, 301, 122725.

Ardolino F., Parrillo F., Arena U., 2018, Biowaste-to-biomethane or biowaste-to-energy? An LCA study on anaerobic digestion of organic waste, Journal of Cleaner Production, 174, 462–476.

Bangprasit P., Chavalparit O., Usapein P., 2017, Life cycle assessment of Napier Pakchong 1 grass as a feedstock for anaerobic digestion to produce electricity: a case study in Thailand, Proceedings of 2017 International Conference on Green Energy and Application, 123–129.

Boulamanti A.K., Maglio S.D., Giuntoli J., Agostini A., 2013, Influence of different practices on biogas sustainability, Biomass and Bioenergy, 53, 149–161.

Chaichaloempreecha A., Pradhan B.B., Rajbhandari S., Chunark P., Fujimori S., Oshiro K., Hanaoka T., Limmeechokchai B., 2024, Macroeconomic impacts and co-benefits of deep-decarbonization in Thailand, Energy, Ecology and Environment, 9, 486–501.

Czubaszek R., Wysocka-Czubaszek A., Banaszuk P., 2020, GHG emissions and efficiency of energy generation through anaerobic fermentation of wetland biomass, Energies, 13, 6497.

Egwu U., 2021, Improvement of biomethane potential of elephant grass (Napier grass, Pennisetum purpureum Schum) by addition of biomass ash and ash-extracts as supplements, Bioresource Technology Reports, 15, 100760.

Iordan C., Lausselet C., Cherubini F., 2016, Life-cycle assessment of a biogas power plant with application of different climate metrics and inclusion of near-term climate forcers, Journal of Environmental Management, 184(3), 517–527.

IPCC, 2014, Climate Change 2014 –synthesis report (Fifth Assessment Report), Geneva.

Kim J., Kang C.M., 2015, Increased anaerobic production of methane by co-digestion of sludge with microalgal biomass and food waste leachate, Bioresource Technology, 189, 409–412.

Lau H.C., 2022, Decarbonizing Thailand's Economy: A Proposal, Energies, 2022, 15(24), 9498.

Mustafa A. M., Poulsen T. G., Xia Y., Sheng K., 2017, Combinations of fungal and milling pretreatments for enhancing rice straw biogas production during solid state anaerobic digestion, Bioresource Technology, 224, 174–182.

Narinthorn R., Choorit W., Chisti Y., 2019, Alkaline and fungal pretreatments for improving methane potential of Napier grass, Biomass and Bioenergy, 127, 105262.

Perez-Camacho M. N., Curry R., Cromie T., 2019, Life cycle environmental impacts of biogas production and utilization substituting for grid electricity, natural gas grid and transport fuels, Waste Management, 95, 90–101.

Sawanon S., Sangri P., Leungprasert S., Sinbuathong N., 2017, Methane production from Napier grass by co-digestion with cow dung, Energy Solutions to Combat Global Warming, 169–180.

Sawasdee V., Pisutpaisal N., 2014, Feasibility of biogas production from Napier grass, Energy Procedia, 61, 1229–1233.

Sawasdee V., Pisutpaisal N., 2021, Potential of Napier grass Pak Chong 1 as feedstock for biofuel production, Energy Report, 7, 519–526.

Ta A.T., Babel S., 2019, Utilization of green waste from vegetable market for biomethane production: influences of feedstock to inoculum ratios and alkalinity, Journal of Material Cycles and Waste Management, 21, 1391–1401.

TGO, 2019, Thai National LCI Database: Emission factors, TIIS-MTEC-NSTDA.

Weerayutsil P., Khoyun U., Khuanmar K., 2016, Optimum ratio of chicken manure and Napier grass in single stage anaerobic co-digestion, Energy Procedia, 100, 22–25.

Whiting A., Azapagic A., 2014, Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion, Energy, 70, 181–193.