Bioenergy Potential from Agricultural Residues and Industrial Wastes in Indonesia

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1. Introduction

Being a highly populated country with 16,056 islands makes it challenging for Indonesia to provide affordable energy and to optimize local resources for renewable energy. Indonesian Law No. 30 (2007) established National Energy Board (DEN) to develop the roadmap to shift non-renewable fuel consumption into new and renewable energy). National Energy Plan (RUEN) was based on 2015’s energy mix with the total energy consumption of 166 MTOE, which is illustrated in Fig. 1 as the baseline condition for establishing National Energy Plan (RUEN)².

With respect to new and renewable energy, RUEN has set a target to achieve 23% of NRE contribution in the energy mix by 2025. In the targeted portion of NRE, bioenergy comprises the highest percentage among other types of NRE (Fig. 2)². Three years after the launching of RUEN, in 2018, the utilization of NRE for electricity generation is still low due to high NRE power plant production cost. This makes it difficult to compete with fossil fuel power plants, especially coal³.

The government has stipulated a number of regulations to accelerate the realization of National Energy Plan, which are ³): 1) Presidential Regulation No. 4 of 2016 (Article 14) about The Central Government and/or Regional Government to push NRE contribution, including bioenergy, in supplying electricity to national electricity company, 2) Presidential Regulation No. 66 of 2018 on the Second Amendment of Presidential Regulation No. 61 of 2015 on collection and use of Palm Oil Plantation Funds, 3) Minister of Energy and Mineral Resources Regulation No. 49 of 2017 on Principles in electricity sales and purchase agreement.

Nevertheless, the success in identifying the most appropriate technology to convert Indonesian potential bioenergy sources into consumable forms of energy will be the key to realize the aforementioned NRE target in 2025. The variations of bioenergy sources among Indonesia’s thousands islands are so vast that the choice of technology cannot be simplified into a single solution. On the other hand, the choice of technology must be site-specific by taking into consideration the most abundantly available biomass in the area.

In order to choose the optimum technology, it is necessary to develop an accurate and reliable database of biomass, which especially covers the commodities ready for large-scale bioenergy production. Unfortunately, such information has not been available yet. The data are actually recorded in several ministries. Nevertheless, they are scattered and not regularly evaluated nor coordinated across stakeholders. With inadequate spatial data of Indonesian biomass potentials, the policy of renewable energy development in Indonesia tends to be a single solution nationwide.

Fig. 1 Indonesia’s energy mix in 2015 (Source: National Energy Plan/RUEN)

Fig. 2 Bioenergy contribution in 2025 Indonesian NRE target (Source: National Energy Plan/RUEN)

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Bioenergy Potential from Agricultural Residues and Industrial Wastes in Indonesia (BUDHIJANTO, ARIYANTO, CAHYONO)

which will never be a success due to the heterogeneity of the geographical, sociological, political, and economical situations.

If all of the biomass recorded in current database are assumed to be successfully converted into bioenergy, then the total bioenergy potential in Indonesia is 33 MWe in the forms of biomass/biofuel and biogas. In fact, current realization of bioenergy in Indonesia is still less than 5% of the predicted potential. This is an indication that there should be a significant change in the ways of research, innovation, technology development, and regulations being navigated concurrently by the government to be supportive to each other.

Moreover, biomass resources are not evenly distributed across Indonesia. As shown in Fig. 3, most of bioenergy sources are located on Western Indonesia 7). Sumatera is leading in terms of the biomass potential. On the other hand, the data from the eastern part of Indonesia have not been convincing yet. The values of bioenergy potential for the islands of eastern Indonesia (Borneo, Celebes, Papua, and scattered small islands) were recorded very low in Fig. 3. This can be due to two possible causes, i.e. 1) the biomass data were accurately obtained and the values were indeed low, 2) the biomass data were not very well documented for the eastern part of Indonesia. The second possibility is more likely to be true because eastern part of Indonesia is less populated than the western part so that there are still a large portion of unpopulated areas in which data collection with conventional methods cannot be very accurate.

The information on biomass with respect to the potential of renewable energy derived from it plays an ultimately important roles in the implementation because some studies highlighted that the social acceptance for renewable energy depended upon accurate prediction about the stability of raw material supply, in terms of quantity and price. Not only in Indonesia, but also in many other developing countries, there is still a big gap of understanding in bioenergy-related information especially between policymakers, investors, and the general public 9).

Vast arrays of scattered data on biomass potential confuses all stakeholders and prospective collaborators and leads to slow implementation of appropriate bioenergy technology in Indonesia. This review aims to briefly summarize Indonesian biomass data covered in previous publications (scientific publication, official release of relevant ministries, and digital data in popular media), especially those which are originally written in the national language of Bahasa Indonesia, to update the international audience about the richness of Indonesian biomass resources and hence enhance mutually beneficial collaborations in the future.

2. Overview on biomass resources and wastes in Indonesia

“Biomass” is defined as biological materials which can be used directly or indirectly as fuels after being processed appropriately.

In this study, the term “biomass” covers both the crops and the wastes remained after harvest and also the wastes from the crop processing, such as the wastes of oil palm derivative industries, sugarcane/bioethanol industries, and others. “Bioenergy” is defined as all energy forms derived from biomass, such as biodiesel, bioethanol, biomethanol, biogas, etc.

There are varied numbers about the estimate of the potential of Indonesian biomass based energy potential. One publication based on government data 7) stated that the predicted biomass residue from agriculture, forestry, plantation, and municipal solid waste reached 200 million tons/year, which is theoretically equivalent to 49,810 MW. Unfortunately, currently only 302.4 MW or merely 0.64% of the aforementioned prediction has been realized 7). The hindrance in the utilization of Indonesian biomass to produce bioenergy is, among others, the lack of data on the spatial distribution of the biomass throughout Indonesia.

Another publication stated that Indonesian biomass potentials is estimated to be 50,000 MW 8). It consist of 15.45 million cubic meters of forest residues per year, 64 million tons of plantation residue per year, 144,50 ton agricultural waste per year, and 11,330 tons of municipal solid waste per day. These numbers are the competitive benefit for Indonesia in terms of bioenergy business because it is highly exceeding the biomass availability in other countries.

In general, the available solid agricultural biomass for bioenergy production comprises six main commodities, which are rice waste (54.25%), corn waste (9.74%), cassava wataste (6.45%), oil palm waste (2.29%), coconut waste (2.3%), and production forest waste (24.69%) 7). Estimated heating value of each commodity is presented in Table 1. More detailed discussion is elaborated in the next section on the most attractive commodities with respect to its local abundance relative to other ones in Table 1.
2.1 Oil palm

Indonesia is the biggest producer of oil palm with 16.18 million hectares of plantation (mostly in Sumatera and Borneo Islands) and 7.8 millions of workers. However, the land used for oil palm plantation is actually only one third of the land usage for other biomass crops in Indonesia, such as rice and corn as the staple foods for most Indonesian people. Interestingly, palm oil total biomass productivity (tons/hectare) is about three times higher than the average of other crops. While the heating value of oil palm biomass is similar to other biomass, oil palm is the most efficient bioenergy provider compared to other crops.

There are indeed negative appraisements which blame oil palm plantation for some social and environmental issues. A study has been published to introduce a fair system to determine the status of sustainability, i.e. by applying sustainability index assessment of palm oil based bioenergy in Indonesia. In addition, the government currently stops oil palm plantation expansion and push intensification to enforce sustainable production of oil palm.

According to Ministry of Energy and Mineral Resources Regulation No. 32/2008, biodiesel B30 is set as mandatory by 2020. Starting 2015, Indonesian Government established a specific body named Indonesia Oil Palm Plantation Fund Management Agency (BPDPKS). The functions of the agency can be summarized in three main tasks, i.e.: 1) to offset the difference between fossil diesel and biodiesel prices for Indonesian consumers; 2) to support intensification in plantations; 3) to support research and development for sustainable palm oil plantation/industry.

Besides biodiesel, renewable energy is also generated from oil palm wastes, such as palm oil mill effluent conversion into biogas and thermal conversion of residual biomass (empty fruit bunch and trunks). The government encourages research to establish appropriate and affordable technology for extracting energy from oil palm wastes, which is estimated to account for 400 MWe from total liquid waste produced and 3.45 MWh/ton of solid waste. Energy extraction from all possible parts of oil palm will make the efficiency of its bioenergy conversion even higher and at the same time improve the profitability of oil palm plantations so that land expansion is not needed anymore.

Even the liquid waste of palm oil factory is a huge potential of biomass feedstock for biogas production. The liquid waste is a large amount of water with dispersed palm oil in it. The waste comes from the water used in the process of palm oil production hence it is called Palm Oil Mill Effluent (POME). Table 2 lists the palm oil mills in 2014 along with their production capacity. The total production capacity is 34,280 tons FFB/hour, which is a huge amount.

| Number | Province | Number of Palm Oil Mills | Production capacity (tons FFB/hour) |
|--------|----------|--------------------------|-----------------------------------|
| 1      | Nanggroe Aceh Darussalam | 25 | 980 |
| 2      | North Sumatra | 92 | 3,815 |
| 3      | West Sumatra | 26 | 1,645 |
| 4      | Riau | 140 | 6,660 |
| 5      | Riau Islands | 1 | 40 |
| 6      | Jambi | 42 | 2,245 |
| 7      | South Sumatra | 58 | 3,555 |
| 8      | Bangka Belitung | 16 | 1,235 |
| 9      | Bengkulu | 19 | 990 |
| 10     | Lampung | 10 | 375 |
| 11     | West Java | 1 | 30 |
| 12     | Banten | 1 | 60 |
| 13     | West Kalimantan | 65 | 5,475 |
| 14     | Central Kalimantan | 43 | 3,100 |
| 15     | South Kalimantan | 15 | 770 |
| 16     | East Kalimantan | 29 | 1,545 |
| 17     | Central Sulawesi | 7 | 590 |
| 18     | South Sulawesi | 2 | 150 |
| 19     | West Sulawesi | 6 | 260 |
| 20     | Souteast Sulawesi | 3 | 260 |
| 21     | Papua | 3 | 140 |
| 22     | West Papua | 4 | 360 |
| TOTAL | | 608 | 34280 |

Table 1

| Biomass waste | Higher heating value |
|---------------|---------------------|
| Rice waste [7] | 3,052.9 |
| Corn [7] | 3,205.4 |
| Cassava [7] | 3,674.6 |
| Oil palm [8] | 4,004.8 |
| Coconut [7] | 4,128.9 |
| Forest product [7] | 3,992.6 |

1ton calories/ton of biomass
\[2\text{MJ/kg of biomass}\]
inhabited areas so that the existence does not directly affect the surrounding, its environmental impacts can be very damaging because open lagoons release greenhouse gases 19). So converting POME into biogas, which can be tapped for renewable fuel for electricity, is not only solving energy distribution system in the remote area but also contributes to the efforts to reduce the emission of greenhouse gases 40).

In 2011, some palm oil companies started to look at the economic benefits of using the methane in biogas for electricity generation. In 2013, Ministerial Regulation number 04/2012 about feed-in-tariffs for renewable energy from biomass and biogas increased interest in grid-connected power from POME-to-energy projects. Under the regulation, biogas project owners can sell power through Power Purchase Agreements (PPAs) or excess power through excess power agreement with Perusahaan Listrik Negara (Persero). This government support makes the biogas project financially more viable and sound to be implemented 40).

In order to capture methane from POME, many palm oil mills currently used covered lagoon technology, i.e. covering their existing lagoon with a gas-tight cover to capture the biogas and prevent methane release to the atmosphere. This method requires a hydraulic retention time of about 20–90 days and consequently has a large footprint. With the availability of land in the area of most palm oil mills, the area required for anaerobic covered lagoon and three other additional lagoons for fat trap, cooling, and aerobic ponds are not a problem. However, the biogas formation in covered lagoon is actually poor and hence reduce the economic feasibility of electricity production from POME biogas 40).

Other technology starts to emerge in the area of biogas production from organic waste at large scale. One of the technology is up-flow anaerobic sludge blanket (UASB) reactor. Upflow anaerobic sludge blanket reactors allow the microorganisms to grow in aggregations. Because of this, microorganisms remain in the reactor despite a strong inflow of substrate. The system pumps in new material with sufficient power to mix it, creating contact between the microorganisms and the substrate 40).

The biggest challenge in POME conversion into biogas is the existence of long chain fatty acids (LCFA). This LCFA is the intermediate product in the pathway of methane formation from triglycerides which is existing in POME as stable oil emulsion in water. Unfortunately, LCFA is toxic for anaerobic microbes 20)). Therefore, covered lagoon is not the best option because it does not have protection mechanism toward anaerobic microbes against LCFA. UASB is more preferable than covered lagoon because the microbes inside UASB will form granules as one of the mechanism to protect themselves from inhibitors. The protection mechanism can be improved by adding zeolite/ bentonite powder into the reactor to make anaerobic fluidized bed reactor (AFBR) 12), (15), (21), (22).

In order to tap the potential of POME into electricity, it is very important to consider the challenge of inhibitory compounds in POME and also the choice of appropriate technology to overcome the challenge. As recently the Government enforces strict regulation on the compulsary task for all palm oil mills to prevent greenhouse gases release and to comply with waste water quality standards, innovations in biogas production from POME would have a very good market.

2.2. Sugarcane

Total sugar cane plantation is currently 450,000 hectares, mostly located in Java (more than 60%) and Sumatera Islands and dominated by smallholder farmers.

Renewable energy generated from sugar cane industries includes bioethanol from molasses, heat from bagasse, and biogas from stillage. In many sugar cane plants, bagasse is utilized by direct burning in their boilers. With respect to bioethanol, the government has set the target of gasoline E10 by 2020 40). All bioethanol plants in Indonesia use molasses from sugar cane factories as raw material. Due to economic feasibility concerns of current technology, the mandate has not been enforced yet. However, renewable energy extraction from stillage and bagasse are developed to improve the profitability of sugar production 29).

While bioethanol market has not been strong enough currently in Indonesia, this country is still one of the leading sugarcane producers in the world with 33,700 Mt/year production 24). This implies that Indonesia is potentially leading also in the production of bioethanol given the market price issues against its fossil fuel counterparts have been solved.

Another potential biomass from sugarcane derivative is stillage or vinasse, i.e. the liquid waste emitted from the bottom of distillation column in bioethanol rectification. The production of vinasse in a traditional bioethanol plant ranges between 8-20 L per liter of bioethanol produced 24). Without proper treatment, this waste is problematic to environment because of its high organic content, which can reach 27,500-299,250 mg COD/L at quite high temperature of 65°C 24). Conversion to biogas is also a plausible solution for the problem of vinasse. Vinasse contains inhibitory compounds which are usually in the form of phenolic compounds, sulphates, and nitrogen compounds 24), 28). Hence, just the same as the case of POME, conversion of vinasse into biogas needs to take into consideration the design to protect microbes from the toxic in the feed. One of the strategy is adding suitable adsorbent which can also serve as protective immobilization media for anaerobic microbes, such as zeolite and bentonite 26)-28). With the addition of media in the process, the most appropriate technology would be anaerobic fixed bed reactor (anaerobic filter) or anaerobic
fluidized bed reactor\textsuperscript{39, 30}.

The aforementioned technology for conversion of vinasse to biogas is not practiced in Indonesia yet at commercial scale, as the production of bioethanol is still unstable. But in the future when bioethanol has been successful to replace the relevant fraction of fossil fuel, then the technology to extract energy from bioethanol waste has to be prepared, too.

2.3. Organic fraction of municipal solid waste (OFMSW)

Indonesian population emits 31.2 million m\textsuperscript{3} of MSW/day, 60-70\% of which is biodegradable organic fraction\textsuperscript{31}. The energy potential in the form of biogas is equivalent to 8.33 TWh/ million ton wet. This number is very big, nevertheless it reflects unsuccessful effort of waste reduction and recycling in Indonesia. Therefore, up to now only limited pilot scale converting OFMSW to bioenergy has been built\textsuperscript{32}. Realization of bioenergy extraction from OFMSW in large scale is also hindered by the lack of enforcement in waste sortation at household level.

Besides, converting OFMSW to bioenergy has problem which need to be resolved. High organic content of Indonesian OFMSW emits liquid waste called leachate, which is a serious threat to nearby watershed. While government program on waste reduction is still struggling for success, affordable technology for leachate treatment is urgently needed to protect clean water sources around landfill\textsuperscript{31}.

On average, Indonesian generates 0.76 kg/day of solid waste. Thus, with total population of 253 million in 2014, Indonesia would generate around 190,000 ton/day of MSW which is administratively distributed into 34 provinces and more than 465 municipalities\textsuperscript{31}. MSW management in Indonesia is the responsibility of municipality (local government). However, MSW management focuses largely on waste collection, treatment (composting) and disposal. Thus, most local authorities prefer open dumping, creating a despondent situation in the landfill site. This way is the easiest but has many disadvantages for health, safety, and environmental threats, such as spreading of disease & foul odors, causing slide down, contaminate the ground water, etc. Considering these facts, thermal based WtE of MSW management system should be considered by local government in Indonesia. The planning of using thermal-based process in waste management system in Indonesia could promise good economic feasibility. Air and plasma gasification would be able to consume MSW for then producing electricity to get profit. As the benefit, the waste disposal facilities do not need area expansion\textsuperscript{31}.

The ideal treatment of MSW is rooted on the discipline of general public in sorting the waste at the point of its generation. Unfortunately, the biggest problem faced by Indonesia is unsorted MSW. Initiatives have been observed at community level with various activity, such as the so-called garbage bank, small-scale composting, etc.

2.4. Production forest residues

Indonesia is blessed with abundant forest waste generated from the harvesting of natural production forest and industrial forest plantation, and wood processing residue. The estimated total potential forest biomass in Indonesia from bioenergy was 132 PJ in 2013 (around 50\% from harvesting residues and the other 50\% from wood processing residues)\textsuperscript{34}.

Forest residue is actually very versatile. By choosing an appropriate pathway, wood residues can produce bioenergy in the form of electricity, heat, bioethanol, synthetic gasoline and diesel, methane or hydrogen. Bioethanol production from forest residue is categorized into 2\textsuperscript{nd} generation of bioethanol. Scientists still argue to each other whether 2\textsuperscript{nd} generation bioethanol is profitable or not. Some scientists stated that bioethanol production using wood residues result in negative energy return. The reason for this observation was because the production of bioethanol requires 57\% more fossil energy input than the heating value of the resulting bioethanol\textsuperscript{35}. On the other hand, the aforementioned premise was argued by many groups of scientists with different point of view. One of the arguments pointed out that opportunity cost should be considered in making assessment on the economic feasibility of any new and renewable energy production, including the 2\textsuperscript{nd} generation of bioethanol. Opportunity cost includes technology change and raw material choice which might reverse the previous finding about the feasibility of 2\textsuperscript{nd} generation bioethanol\textsuperscript{36}. The controversy on the “real sustainability” of 2\textsuperscript{nd} generation bioethanol adds the complication of its uncompetitive price in current fossil fuel market. Therefore, bioethanol is not the best option to utilize the abundant resource of forest and wood residues in Indonesia.

Another option, which is much simpler than bioethanol, is wood pellet. This option is especially attractive for Indonesian situation, because the scale of the industry is flexible to be still economically feasible in various scale from small to large depending upon available investment and location of the wood residues. Wood pelletizing has been evaluated to be the one providing excellent positive energy return. This is consistent with the fact that wood pelletizing is one of growing industry in the sector of renewable energy\textsuperscript{37}. In Indonesia, there are no record yet on prominent wood pellet industry, although there are some small and medium enterprises that start to produce it. On the other hand, the potential of forest and wood residues in Indonesia are huge as shown in Table 3. To ensure the target of utilizing wood pellet for modern bioenergy source, research on techno-economics as well as socio-politics aspects of the industrial development of wood pellet as one of prominent bioenergy source in Indonesia will be required in the near future.
Table 3  Summary of the estimated total bioenergy potential from harvesting and wood processing residues (2013) 16

| No. | Source of wood residue | Potential bioenergy (GJ) |
|-----|------------------------|-------------------------|
|     | Harvesting residue     | Wood processing residue |
| 1   | Natural production     | 15,237,863              |
| 2   | Industrial production  | 51,366,803              |
| 3   | Sawnwood               | 8,718,833               |
| 4   | Plywood                | 23,154,244              |
| 5   | Veneer                 | 6,488,478               |
| 6   | Chipwood               | 27,190,564              |
|     | TOTAL                  | 65,552,118              |

3. Challenges of bioenergy in Indonesia

Regardless the huge potential of biomass in Indonesia, the fact is Indonesian biomass is still under-tapped. The following discussion highlights the problems to be firstly addressed by the government in order to move forward in the realization of bioenergy targets in Indonesia.

The central challenge faced by Indonesia in achieving its bioenergy target is quite similar to those in other countries, which is known as “energy trilemma” 37). Energy trilemma is defined as the conflicting demands of energy security, climate change mitigation, and energy poverty (particularly in developing countries). It is crucial for the government to understand the connectivity among those three aspects so that credible governance strategies can be established.

Bioenergy needs to be produced at its economical scale. All industries are designed and run under the assumption that both raw materials and product are obtained with homogeneous and consistent characteristics. On the other hand, all aforementioned potential as raw material for the bioenergy are heterogeneous and could change depending upon the seasons. It takes appropriate pretreatment to homogenized the raw material and also at the same time remove the inhibitor 37). Most of the published work concern only on the processing aspects. Work reporting the methods used for pretreatment was very few. With proper pretreatment, the production of bioenergy from biomass can be optimized although variations in the raw material is unavoidable 38). Up to date, there are no reliable pretreatment technology which is flexible to be applied in Indonesian bioenergy industry with possibly large variability.

Bioenergy production from biomass is strongly connected to plantations, which inherently include the complication of land use change. This situation is reflected in the aforementioned ‘Energy Trilemma’. While feasibility studies mostly focuses on the technical aspects to determine profitability potentials, sustainability approach is still missing in the current status of bioenergy technology development.

Last but not least, the government commitment is the central key to shift the current dependence on fossil fuel to the renewable energy including bioenergy. Previous study comparing the case of renewable energy policies and strategies between India and Indonesia (both are developing countries) revealed that India has demonstrated better achievement than Indonesia 9). India has been successful in focusing on technology development and instilling strong mutual vision among all organizations/institutions involved. Despite the huge potential of biomass for bioenergy in Indonesia, its usages are still in traditional ways, such as cooking and lighting in rural areas.

4. Conclusion

Indonesia’s richness of natural resources, including biomass, is almost unparalleled. Indonesia is currently in the process of developing appropriate and affordable technologies by also considering the unique social, economic, and geographical situations of Indonesia. Government mandate is very important to achieve bioenergy targets. Additionally, profitability of bioenergy can be improved by taking it into the constellation of water-food-energy nexus as one sustainability package.

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References

1) Indonesian Law No. 30. 2007.
2) Appendix of Republic of Indonesia President Decree No. 22. 2017.
3) National Energy Council, “Indonesia Energy Outlook 2019,” 2019.
4) Directorate General of New and Renewable Energy, “Statistics of New and Renewable Energy,” 2017.
5) M. K. Biddinika, R. P. Lestari, B. Indrawan, K. Yoshikawa, K. Tokimatsu, and F. Takahashi, “Measuring the readability of Indonesian biomass websites: The ease of understanding biomass energy information on websites in the Indonesian language,” Renew. Sustain. Energy Rev., vol. 59, pp. 1349–1357, Jun. 2016.
6) Ministry of Energy and Mineral Resources Regulation No. 32. 2008.
7) B. Pranoto, M. Pandin, S. R. Fithri, and S. Nasution, “Peta Potensi Limbah Biomassa Pertanian Dan Kehutanan Sebagai Basis Data Pengembangan Energi Terbarukan,” Ketenagalistrikan Dan Energi Terbarukan, vol. 12, no. 2, pp. 123–130, 2013.
8) R. Singh and A. D. Setiawan, “Biomass energy policies and strategies: Harvesting potential in India and Indonesia,” Renew. Sustain. Energy Rev., vol. 22, pp. 332–345, Jun. 2013.
9) F. R. A. Abdul Wahid, S. Saleh, and N. A. F. Abdul Samad, “Estimation of Higher Heating Value of Torrefied Palm Oil Wastes from Proximate Analysis,” Energy Procedia, vol. 138, pp. 307–312, Oct. 2017.
10) Center for Data and Information System on Agriculture, “Statistics of Agricultural Land Usage 2013-2017.”

11) P. Papilo, Marimin, E. Hambali, and I. S. Sitanggang, “Sustainability index assessment of palm oil-based bioenergy in Indonesia,” J. Clean. Prod., vol. 196, pp. 808–820, Sep. 2018.

12) L. I. Ramadhani, S. I. Damayanti, H. Sudibyo, and W. Budhijanto, “Kinetics of Anaerobic Digestion of Palm Oil Mill Effluent (POME) in Double-Stage Batch Bioreactor with Recirculation and Fluidization of Microbial Immobilization Media,” in IOP Conference Series: Materials Science and Engineering, 2018, vol. 316, no. 1.

13) Ministry of Energy and Mineral Resources, Indonesia 2050 Pathway Calculator. 2018.

14) Winrock International, “Handbook POME-to-Biogas,” 2015.

15) P. A. H. Setyowati, L. Halim, M. Mellyanawaty, H. Sudibyo, and W. Budhijanto, “Anaerobic treatment of palm oil mill effluent in batch reactor with digested biodiesel waste as starter and natural zeolite for microbial immobilization,” in AIP Conference Proceedings, 2017, vol. 1840.

16) E. Hambali and M. Rivai, “The Potential of Palm Oil Waste Biomass in Indonesia in 2020 and 2030,” IOP Conf. Ser. Earth Environ. Sci., 2017.

17) U. Hasanudin, R. Sugiharto, A. Haryanto, T. Setiadi, and K. Fujie, “Palm oil mill effluent treatment and utilization to ensure the sustainability of palm oil industries,” Water Sci. Technol., 2015.

18) E. D. Ayu, L. Halim, M. Mellyanawaty, H. Sudibyo, and W. Budhijanto, “The effect of natural zeolite as microbial immobilization media in anaerobic digestion at various concentrations of palm oil mill effluent (POME),” in AIP Conference Proceedings, 2017, vol. 1840.

19) S. N. B. A. Khadaroo, P. E. Poh, D. Gouwanda, and P. Grassia, “Applicability of various pretreatment techniques to enhance the anaerobic digestion of Palm Oil Mill Effluent (POME): A review,” J. Environ. Chem. Eng., vol. 7, no. 5, p. 103310, Oct. 2019.

20) R. A. Labatut, L. T. Angenent, and N. R. Scott, “Conventional mesophilic vs. thermophilic anaerobic digestion: A trade-off between performance and stability?,” Water Res., vol. 53, pp. 249–258, Apr. 2014.

21) L. Halim, M. Mellyanawaty, R. B. Cahyono, H. Sudibyo, and W. Budhijanto, “Anaerobic digestion of palm oil mill effluent with lampung natural zeolite as microbe immobilization medium and digested cow manure as starter,” in AIP Conference Proceedings, 2017, vol. 1840.

22) M. Mellyanawaty, F. M. A. Chusna, H. Sudibyo, N. Nurjanah, and W. Budhijanto, “Influence of Nutrient Impregnated into Zeolite Addition on Anaerobic Digestion of Palm Oil Mill Effluent (POME),” in IOP Conference Series: Materials Science and Engineering, 2018, vol. 316, no. 1.

23) C. W. Purnomo, M. Mellyanawaty, and W. Budhijanto, “Simulation and Experimental Study on Iron Impregnated Microbial Immobilization in Zeolite for Production of Biogas,” Waste and Biomass Valorization, vol. 8, no. 7, pp. 2413–2421, 2017.

24) M. Parsae, M. Kiani Deh Kiani, and K. Karimi, “A review of biogas production from sugarcane vinasse,” Biomass and Bioenergy, vol. 122, pp. 117–125, Mar. 2019.

25) L. S. M. Kiyuna, L. T. Fuess, and M. Zaiat, “Unraveling the influence of the COD:sulfate ratio on organic matter removal and methane production from the biodigestion of sugarcane vinasse,” Bioresour. Technol., vol. 232, pp. 103–112, May 2017.

26) L. Ho and G. Ho, “Mitigating ammonia inhibition of thermophilic anaerobic treatment of digested piggery wastewater: Use of pH reduction, zeolite, biomass and humic acid,” Water Res., vol. 46, no. 14, pp. 4339–4350, Sep. 2012.

27) N. Zhang et al., “Enhanced bio-methane production from ammonium-rich waste using eggshell-and lignite-modified zeolite (ELMZ) as a bio-adsorbent during anaerobic digestion,” Process Biochem., vol. 81, pp. 148–155, Jun. 2019.

28) M. Pirsaehe, H. Hossaini, and J. Amini, “Evaluation of a zeolite/ anaerobic baffled reactor hybrid system for treatment of low bio-degradable effluents,” Mater. Sci. Eng. C, vol. 104, Nov. 2019.

29) I. Ersever, R. Ravindran, H.-H. Tsai, and M. Pirbazari, “Modeling and design of anaerobic fluidized bed reactor with recycling for denitrification of reverse osmosis concentrates,” Chem. Eng. Sci., vol. 108, pp. 111–122, Apr. 2014.

30) S. Montalvo et al., “Application of natural zeolites in anaerobic digestion processes: A review,” Applied Clay Science, vol. 58. pp. 125–133, Apr-2012.

31) H. Sudibyo, Y. S. Pradana, A. Budiman, and W. Budhijanto, “Municipal Solid Waste Management in Indonesia - A Study about Selection of Proper Solid Waste Reduction Method in D.I. Yogyakarta Province,” Energy Procedia, vol. 143, pp. 494–499, Dec. 2017.

32) T. Ariyanto et al., “Utilization of fruit waste as biogas plant feed and its superiority compared to landfill,” Int. J. Technol., vol. 8, pp. 1385–1392, 2017.

33) H. Sudibyo, A. I. Majid, Y. S. Pradana, W. Budhijanto, Deendarljan, and A. Budiman, “Technological Evaluation of Municipal Solid Waste Management System in Indonesia,” Energy Procedia, vol. 105, pp. 263–269, May 2017.

34) B. C. H. Simangunsong et al., “Potential forest biomass resource as feedstock for bioenergy and its economic value in Indonesia,” For. Policy Econ., vol. 81, pp. 10–17, Aug. 2017.

35) D. Pimentel and T. W. Patzek, “Ethanol Production Using Corn, Switchgrass, and Wood,” Nat. Resour. Res., vol. 14, no. 1, pp. 65–76, 2005.

36) J. Wesseler, “Opportunities (’costs) matter: A comment on Pimentel and Patzek ‘Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower,’” Energy Policy, vol. 35, no. 2, pp. 1414–1416, Feb. 2007.

37) N. Gunningham, “Managing the energy trilemma: The case of Indonesia,” Energy Policy, vol. 54, pp. 184–193, Mar. 2013.

38) H. Carrere et al., “Review of feedstock pretreatment strategies for improved anaerobic digestion: From lab-scale research to full-scale application,” Bioresour. Technol., vol. 199, pp. 386–397, 2016.