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ORIGINAL RESEARCH PAPER

Strategies to Promote Biogas Generation and Utilisation from Palm Oil Mill Effluent

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Abstract

Palm oil mills generate a large amount of wastewater, known as palm oil mill effluent, during the production of crude palm oil. The high organic contents in palm oil mill effluent have an excellent potential for biogas utilisation. Besides, such effluent must be further treated before discharge or reused in milling processes. In this respect, an integrated biogas and wastewater treatment system should be developed. The aim of this paper is to synthesise and optimise an integrated biogas and wastewater treatment system via a process systems engineering tool that yields maximum economic performance. To illustrate the proposed approach, a typical palm oil mill case study in Malaysia is presented. The variation in palm oil mill effluent availability is considered to evaluate the changes in performance and ensuring the flexibility of the developed system. As shown in the results, implementation of integrated biogas and wastewater treatment system in a typical 60 t/h mill in Malaysia could export up to 1.9 MW electrical power on average. Alternatively, 110,800 GJ/year of compressed biomethane can be produced when feed-in to the national grid is not available. The implementation of integrated biogas and wastewater treatment system successfully reduces greenhouse gas emissions by 50,430 t CO_{2e}/year as compared with the conventional open ponding system practiced in the industry. Lastly, feasibility studies and strategies to promote biogas utilisation in the industry are performed.

Keywords Anaerobic digestion · Compressed biomethane · Process systems engineering · Process synthesis · Mathematical optimisation

Introduction

Palm oil production is the highest among other major vegetable oils, dominating more than 35% of total global oils and fats production in 2018 (USDA 2019). It is the most consumed oil in the planet, which plays an essential role in global food security and economic development (IUCN 2018). As the second-largest exporter of palm oil products after Indonesia, Malaysia produced up to 20.5 Mt of crude palm oil (CPO) annually (USDA 2019). It translates to a total of 44.72 billion MYR/year (~ 6%) in Malaysia's gross domestic product (DOS 2018).

The current practice in the palm oil industry requires 5–7.5 m^3 of utility water to produce one ton of CPO (Ahmad et al. 2003). However, more than 50% of them ended up as liquid waste, known as palm oil mill effluent (POME). With this respect, approximately 50–75 million m^3 of POME are generated in Malaysia annually. This waste effluent contains high organic content, which leads to high biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels (Ahmed et al. 2015). Table 1 shows the typical characteristics of POME released from palm oil mill (POM) during CPO productions. Direct discharge of POME to the watercourse will cause severe environment pollution (Poh and Chong 2009). To minimise the pollution, strict regulatory control through Malaysia Environmental Quality (Sewage and Industrial Effluents) Regulations 1979 is enforced where BOD and COD under 50 and 100 mg/L, respectively, must be

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Table 1 General characteristics of POME (Ahmed et al. 2015)

Parameter	Concentration range
Chemical oxygen demand (COD) (mg/L)	15,000–100,000
Biochemical oxygen demand (BOD@30 °C) (mg/L)	10,250–43,750
Total solid (mg/L)	11,500–79,000
Total suspended solid (mg/L)	5000–54,000
Oil and grease (mg/L)	130–18,000
Temperature (°C)	80–90
pH	3.4–5.2

POME characteristics change subject to fruits condition, milling processes, crop seasons, climate, etc.

achieved upon discharge to the environment (Ong 1979). Meanwhile, a more stringent requirement has been imposed for POMs located in water catchment areas, specifically in East Malaysia with BOD and COD discharge limits set at 20 and 50 mg/L, respectively (Ong 1979; Asis et al. 2016).

In an effort to overcome this issue, open ponding system is commonly used in the current industry to treat POME for discharge due to low capital and operating costs (Tong and Jaafar 2004). In such a system, POME is treated in several ponds with different functions (e.g. cooling, mixing/de-oiling, acidification and facultative, anaerobic and aerobic ponds) (Hassan et al. 2005). Most of the organic compounds are broken down to produce biogas in a sequence of reactions, hydrolysis, fermentation (acidogenesis/acetogenesis) and methanogenesis (Gerardi 2003) in the anaerobic pond, with the presence of microbes and microorganisms (Ohimain and Izah 2017). The aerobic pond then removes the remaining organic compounds in POME before sending to settling pond for final discharge. It is estimated that every m^3 of POME treated releases 34 Nm^3 biogas containing 54.4% or 12.36 kg methane (CH_4) (Yacob et al. 2006). The biogas dissipated into the atmosphere causes a catastrophic impact on the environment as CH_4 has 25 times higher global warming potential than carbon dioxide (CO_2) (Gardner et al. 1993).

The high methane concentration in biogas contributes to a calorific/heating value of 17.9–29.9 MJ/Nm^3 (Igoni et al. 2008), making it a suitable alternative to replace natural gas for power generations. This aligns with the Eighth Malaysia Plan to include renewable energy under the Five Fuel Diversification Policy to contribute 5% of the total energy mix in Malaysia (Economic Planning Unit 2000). Following that, legislative strategies such as the National Renewable Energy Policy and Action Plan (KeTTha 2008), National Green Technology Policy (KeTTha 2009) and Renewable Energy Act (KeTTha 2011) were executed to boost the national economy while promoting sustainable development. Meanwhile, the fifth core Entry Point Project under Palm Oil National Key Economic Areas programme plan also urges every POM in Malaysia to trap and utilise the biogas released (Dompok 2010).

During the 15th Conference of Parties (COP 15) at the United Nations Climate Change Conference 2009, the Malaysian government has pledged a voluntary 40% reduction of greenhouse gas (GHG) emission intensity from its 2005 level by 2020 (Peterson et al. 2011). In 2015, the commitment was enhanced to 45% by 2030 at the COP 21 held in Paris, France (UNFCCC 2016). In line with the increasing concern on sustainable waste management to mitigate climate change, international GHG emission reduction schemes such as Clean Development Mechanism (UNFCCC 2014) and International Sustainability Carbon Certification (ISCC 2018) were introduced. These schemes allow developing countries such as Malaysia to generate higher revenue by selling certified emission reduction (CER), promoting sustainable use of waste materials (i.e. POME) to reduce GHG emissions.

Integrated biogas and wastewater treatment (IBWT) system is developed to treat POME with a closed anaerobic digester, capturing and utilising the biogas emitted. In the meantime, IBWT system also reduces BOD and COD content in POME for discharge or further polished for reuse in milling processes. It is estimated that the GHG emissions from the palm oil industry could be reduced by 17–20 million tons CO_2 equivalent (CO_{2e}) annually if all POME in Malaysia is treated with such system (Bong et al. 2017). In general, IBWT system consists of several operations, as shown in Fig. 1. Firstly, POME is pre-treated through a series of ponds for cooling, mixing, de-oiling and pH adjustment before digestion processes (Poh and Chong 2009). The pre-treated POME then undergoes anaerobic digestion to produce raw biogas. Technologies such as up-flow anaerobic sludge fixed film (Najafpour et al. 2006), membrane anaerobic system (Abdurahman et al. 2011), up-flow anaerobic sludge blanket (Fang et al. 2011), continuous stir tank reactor (Irvan et al. 2012), covered lagoon (Chin et al. 2013) and expanded granular sludge blanket (Wang et al. 2015) could be used to serve the purpose. Note that each technology has different performance in terms of hydraulic retention time (HRT), CH_4 yield,

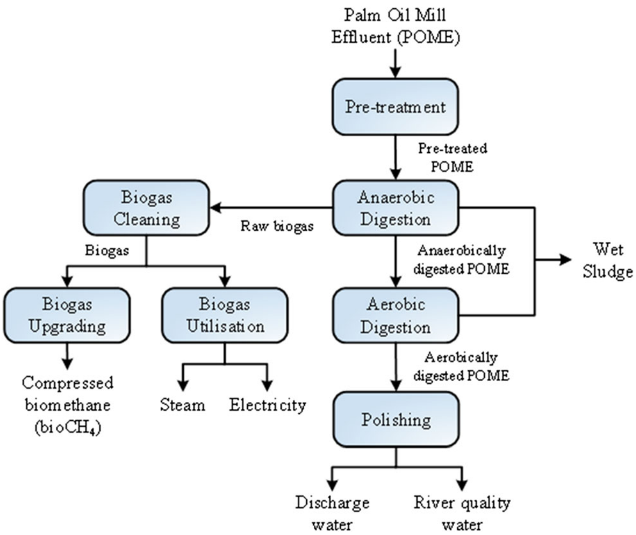

Fig. 1 Integrated biogas and wastewater treatment (IBWT) system unit operations

biogas composition, BOD and COD removal efficiency (Ahmed et al. 2015; Ohimain and Izah 2017). Next, the treated POME from anaerobic digester undergoes aerobic digestion to reduce COD and BOD content. The commonly used aerobic digester includes aerobic lagoon system (Wong 1980), sequencing batch reactor (Chan et al. 2010, 2011), aerobic membrane bioreactor (Damayanti et al. 2011) and extended aeration system (Chan et al. 2012). In the process, both anaerobic and aerobic digestions generate wet sludge as a by-product.

Even though various anaerobic and aerobic digesters are available in the market, the treated POME is unable to fulfil the new discharge limits prescribed (BOD < 20 ppm). In order to further clean up the waste effluent, polishing technologies such as physicochemical treatment and electrocoagulation system are required. Physicochemical treatment consists of coagulation, flocculation and sedimentation processes in which colloidal particles are separated from the digested POME before being released to watercourse as discharge water (Ahmed et al. 2015). On the other hand, the electrocoagulation system uses aluminium electrodes to apply an electrical charge, causing agglomeration of suspended matters in the POME (Kobya et al. 2006; Sontaya et al. 2013). This process generates river quality water (Class IIA), which could be reused as utility water in POM (WEPA 2008).

Meanwhile, raw biogas produced during the anaerobic digestion process contains corrosive and hazardous gas (H_2S), with concentration between 1500 and 3000 ppm (Tong and Jaafar 2004; Hosseini and Wahid 2014). Biological scrubber, activated carbon or metal oxide bed filters are the standard technologies used in biogas cleaning system to remove the H_2S component (Sun et al. 2015; Khan et al. 2017). Following that, biogas could be utilised as a fuel to generate heat, electrical power or both via a boiler, gas engine and steam turbine. Electricity generated can then be feed into the national grid at a premium rate under the feed-in-tariff (FiT) scheme (SEDA Malaysia, 2017). Alternatively, it can be upgraded to compressed biomethane (bioCH_4) at 250 bar$_g$ with more than 98% CH_4 for injection into the natural gas grid (Miltner et al. 2017).

As shown earlier, the Malaysian government has implemented numerous efforts and policies with the increasing awareness of sustainable development. Besides, an extensive amount of scientific studies on POME for biogas utilisation, wastewater treatment and green energy development were reported. However, each technology operates separately with its performance, efficiency and cost requirement. Limited studies to connect and integrate different unit operations for POME processing as a complete system are reported. Besides, the performance of each technology may affect the selection of the surrounding unit operations, changing the overall performance of the entire system. To date, the adoption of POME for biogas utilisation still faces techno-economic challenges and knowledge gaps that hinder deployment.

According to the literature, the area of *process systems engineering* (PSE) has provided quantitative decision support aid using systematic computer-based approaches for simulation, optimisation, control and information processing (Grossmann 2004). Mathematical programming approach has been developed and widely used to address such issues, providing an optimal global solution for problem defined (Grossmann and Guillén-Gosálbez 2010). In order for mathematical models to work, explicit system constraints and optimisation objectives must be specified (Van Beek 2018). Such approach has been successfully applied in various fields, for instance (i) product discovery (de Pablo and Escobedo 2002; Ng et al. 2014; Ooi et al. 2018) and design (Ng and Ng 2013a; Tapia et al. 2018; Foong et al. 2018), (ii) enterprise (Badell and Puigjaner 2001; Shah 2004) and supply chain optimisation (Ng et al. 2012; Foo et al. 2013) and (iii) global life cycle assessment (Tan et al. 2008; Choo et al. 2011; Ramadhan et al. 2014).

Despite the usefulness of the aforementioned works, none of the contributions has focused on the synthesis of the IBWT system and biogas utilisation from POME. Thus, in this research work, the aim is to develop a systematic approach in synthesising an optimum IBWT system with the maximum economic performance to promote biogas utilisation. Besides, the developed system further treats POME to achieve discharge limit or reuse in POM. As shown in the case study, process capacity, costs, power consumptions and productions were considered for technology selection in system development. In order to ensure that the system developed is capable of coping with seasonal changes in POME availability, a multi-period optimisation approach is incorporated. Sensitivity analysis of different parameters to evaluate alternative strategies, ensuring the feasibility of the developed system, is also performed at the end of this study. The proposed approach is illustrated by solving a typical 60 t/h POM case study in Malaysia.

The rest of the paper is organised as follows: Problem Statement section presents the problem statement and a generic superstructure of IBWT system developed in this work. Mathematical Optimisation Formulation section provides a detailed formulation for material balance, utility balance and economic analysis. Next, a Malaysian POM case study adapted from Foong et al. (2018) along with the basis used are presented in Case Study section. The model is then solved and the optimised results are discussed in Discussion section. In this section, two scenarios (with and without national grid connection) are considered, followed by sensitivity analysis to provide strategies to promote biogas utilisation in the industry. The last section concludes this study with the best strategy to encourage biogas utilisation from POME.

Problem Statement

A generic graphical representation for the problem is shown in Fig. 2. The synthesis problem is stated as follows: Given feedstock $i \in \mathrm{I}$ with a flowrate of F_i and its quality q_i is sent to technology $j \in \mathrm{J}$, converted into intermediate product $p \in \mathrm{P}$. Intermediate product p with its quality q_p is further converted into final product $p' \in \mathrm{P}'$ with quality $q_{p'}$ via technology $j' \in \mathrm{J}'$. Apart from intermediate and final products p and p' generated, electricity $e \in \mathrm{E}$ could also be produced in primary technology j and secondary technology j', respectively. Both primary technology j and secondary technology j' are provided with a specific power consumption per unit flowrate (i.e. Y_{ije}, $\mathrm{Y}_{pj'e}$), or per unit equipment (i.e. Y_{je}, $\mathrm{Y}_{j'e}$), respectively. The power consumption rate, P_e^{Con}, is compensated by the on-site power generation, P_e^{Gen}, to ensure a self-sufficient operation. In some scenarios where excess power is generated, it can be sold or exported to the power grid, P_e^{Exp}.

The optimisation objective is to synthesise an IBWT system with maximum economic performance, EP (Eq. 1), given all the process constraints. Based on the fixed design capacities for primary technology j (F_j^{Design}) and secondary technology j' ($F_{j'}^{\mathrm{Design}}$) in the market, the proposed approach will determine the equipment units required, represented by z_j and $z_{j'}$ respectively. Due to the variation in feedstock i supply with time, the model is solved via multi-period optimisation where each season $s \in \mathrm{S}$ is assigned with a fraction of occurrence, α_s.

$$\mathrm{Maximise}\, EP \tag{1}$$

Mathematical Optimisation Formulation

Based on Fig. 1, a detailed mathematical formulation for a proposed multi-period optimisation model is presented. Note that italic mathematical notations represent variables in the model, while non-italic notations are fixed parameters.

Material Balance

As mentioned previously, seasonal variation s in feedstock i supply is considered in this work for the synthesis of an optimal IBWT system. Equation 2 shows the component balance for a total flowrate of feedstock i (F_i), distributed into potential technology j with a flowrate of F_{ij}. F_{ij} distribution into potential primary technology j may change with the variation in F_i for each season s as follows:

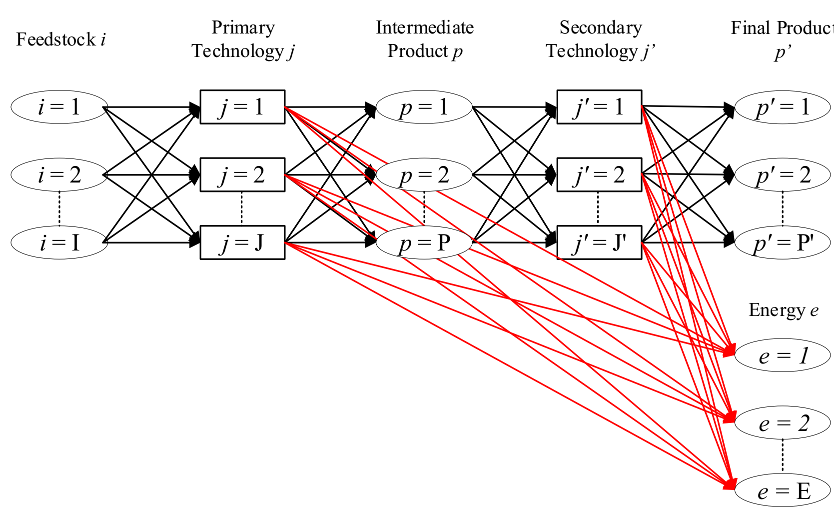

Fig. 2 A generic representation of superstructure

$$(\mathrm{F}_i)_s = \left(\sum_{j=1}^{J} F_{ij} \right)_s \quad \forall i, \forall s \tag{2}$$

In technology j, feedstock i is converted to intermediate product p with conversion X_{ijp}. The total production rate for intermediate product p (F_p) for all technology j is given in Eq. 3.

$$(F_p)_s = \left(\sum_{i=1}^{I} \sum_{j=1}^{J} F_{ij} \mathrm{X}_{ijp} \right)_s \quad \forall p, \forall s \tag{3}$$

Next, the flowrate of intermediate product p (F_p) is distributed to potential technology j' with a flowrate of $F_{pj'}$ for further processing, as shown in Eq. 4.

$$(F_p)_s = \left(\sum_{j'=1}^{J'} F_{pj'} \right)_s \quad \forall p' \forall s \tag{4}$$

Equation 5 shows the conversion of intermediate product p ($F_{pj'}$) to final product p' via technology j' with conversion $X_{pj'p'}$ to give a total production rate for final product p' ($F_{p'}$).

$$(F_{p'})_s = \left(\sum_{p=1}^{P} \sum_{j'=1}^{J'} F_{pj'} \mathrm{X}_{pj'p'} \right)_s \quad \forall p' \forall s \tag{5}$$

In the event where single or no technology is needed to produce the final product p', feedstock i and intermediate product p' can bypass technologies j and j' through a "blank" technology in which conversion does not take place. Besides, the formulation can easily be expanded repetitively for any number of conversion stages required to match the requirements of the case study despite only two steps of conversion technologies j and j' are presented in Fig. 1.

Energy Balance

Apart from material conversions, feedstock i and intermediate product p can be converted into electricity e via primary technology j and secondary technology j' with conversions V_{ije} and $V_{pj'e}$, respectively. Equation 6 calculates the total power generated P_e^{Gen} by the system in kW as follows:

$$(P_e^{\mathrm{Gen}})_s = \frac{1}{\mathrm{AOT}} \left(\sum_{i=1}^{I} \sum_{j=1}^{J} F_{ij} \mathrm{V}_{ije} + \sum_{p=1}^{P} \sum_{j'=1}^{J'} F_{pj'} \mathrm{V}_{pj'e} \right)_s \quad \forall e' \forall s \tag{6}$$

where AOT represents the annual operating time of the process. Meanwhile, electrical power is also consumed in technologies j and j'. Depending on the energy requirement in primary technology j and secondary technology j' selected, the total power consumption P_e^{Con} is calculated with Eq. 7 as follows:

$$(P_e^{\mathrm{Con}})_s = \left(\sum_{i=1}^{I} \sum_{j=1}^{J} F_{ij} \mathrm{Y}_{ije} + \sum_{p=1}^{P} \sum_{j'=1}^{J'} F_{pj'} \mathrm{Y}_{pj'e} + \sum_{j=1}^{J} z_j \mathrm{Y}_{je} + \sum_{j'=1}^{J'} z_{j'} \mathrm{Y}_{j'e} \right)_s \quad \forall e' \forall s \tag{7}$$

where F_{ij} and $F_{pj'}$ are the flowrate of feedstock i and intermediate product p into technology j and j', Y_{ije} and $\mathrm{Y}_{pj'e}$ are the specific power consumption per unit flow of feedstock i and intermediate product p processed, Y_{je} and $\mathrm{Y}_{j'e}$ are the specific power consumption per unit operation, while z_j and $z_{j'}$ are the number of equipment unit needed for technologies j and j', respectively. The required equipment units for primary technology j (z_j) and secondary technology j' ($z_{j'}$) are determined based on the processing throughput, shown in Eqs. 8 and 9.

$$(z_j)_s F_j^{\mathrm{Design}} \geq \left(\sum_{i=1}^{I} \sum_{p=1}^{P} F_{ij} \mathrm{X}_{ijp} + \sum_{i=1}^{I} \sum_{e=1}^{E} F_{ij} \mathrm{V}_{ije} \right)_s \quad \forall j' \forall s \tag{8}$$

$$(z_{j'})_s F_{j'}^{\mathrm{Design}} \geq \left(\sum_{p=1}^{P} \sum_{p'=1}^{J'} F_{pj'} X_{pj'p'} + \sum_{p=1}^{P} \sum_{e=1}^{E} F_{pj'} \mathrm{V}_{pj'e} \right)_s \quad \forall j', \forall s \tag{9}$$

where F_j^{Design} and $F_{j'}^{\mathrm{Design}}$ represent the fixed design capacities for technologies j and j', respectively. z_j and $z_{j'}$ are positive integers that reflect the equipment units of technologies j and j' needed for the given design capacities.

Economic Analysis

In order to perform an economic analysis on the IBWT system developed, the *EP* is evaluated via Eq.10 as follows:

$$\mathrm{EP} = \mathrm{GP} - \mathrm{CRF} \times \mathrm{CAPEX} \tag{10}$$

where *GP*, CRF and *CAPEX* represent the gross profit, capital recovery factor of the system developed and capital costs required, respectively. It is worth mentioning that *EP* shall always be positive with a higher value indicating a greater interest for investment in the developed system. Meanwhile, a negative *EP* value represents a higher investment cost as compared with the *GP* generated, making it an infeasible design. *GP* is calculated using Eq. 11 as follows:

$$\mathrm{GP} = \mathrm{AOT} \sum_{s=1}^{S} \alpha_s \left(\sum_{p'=1}^{P'} \mathrm{F}_{p'} \mathrm{C}_{p'} - \sum_{i=1}^{I} \mathrm{F}_i \mathrm{C}_i + \sum_{e=1}^{E} \mathrm{P}_e^{\mathrm{Exp}} \mathrm{C}_e - \mathrm{OPEX} \right)_s \tag{11}$$

where *OPEX* is the total operating costs of the IBWT system developed. The selling price for final product p' and electricity e are indicated by $\mathrm{C}_{p'}$ and C_e, respectively. Meanwhile, the cost of feedstock i is given as C_i. The *GP* formulation (Eq. 11) is subject to Eq. 12 as follows:

$$\sum_{s=1}^{S} a_s = 1 \tag{12}$$

in which the inclusion of α_s assessed the *GP* of the IBWT system developed for all *s*. Each fraction of occurrence represents the time fraction where season *s* occurs. The summation of these fractions must equal to one as the time fraction is obtained by dividing the duration of season *s* with the total period considered.

CRF is used to annualise *CAPEX* by converting its present value into a stream of equal annual payments over a specified operation lifespan, t_k^{max} and discount rate, r. CRF is determined via Eq. 13.

$$CRF = \frac{r\,(1+r)^{t_k^{max}}}{(1+r)^{t_k^{max}}-1} \quad k\epsilon j' j' \tag{13}$$

CAPEX and *OPEX* are calculated based on the selected technologies *j* and *j'* as well as their equipment unit, z_j and $z_{j'}$ required, as shown in Eqs. 14 and 15 as follows:

$$CAPEX = \left(\sum_{j=1}^{J} z_j CC_j + \sum_{j'=1}^{J'} z_{j'} CC_{j'}\right)_H \tag{14}$$

$$(OPEX)_s = \left(\sum_{j=1}^{J} z_j OC_j + \sum_{j'=1}^{J'} z_{j'} OC_{j'}\right)_s \quad \forall s \tag{15}$$

where OC_j and $OC_{j'}$ are operating costs, while CC_j and $CC_{j'}$ are capital costs, for technologies *j* and *j'*, respectively. z_j and $z_{j'}$ during high crop season with the highest throughput is used to calculate the *CAPEX* of the system developed.

In this model, the effectiveness of investment made through the IBWT system developed is measured in several terms. The net present value at t_k^{max}, $NPV^{t_k^{max}}$ is defined as the summation of discounted *GP* generated by the system, as shown in Eq. 16.

$$NPV^{t_k^{max}} = \left(\sum_{t=1}^{T} \frac{GP}{(1+r)^t}\right) - CAPEX \tag{16}$$

The payback period, *PP*, for the developed system to return its initial investment made before making a profit is then measured via Eq. 17. Following that, the internal rate of return, *IRR*, of the developed system is then assessed using Eq. 18.

$$PP = \ln\left(\frac{1}{1-\left(\frac{CAPEX \times r}{GP}\right)}\right) / \ln(1+r) \tag{17}$$

$$\left(\sum_{t=1}^{T} \frac{GP}{(1+IRR)^t}\right) - CAPEX = 0 \tag{18}$$

Additional Constraints

Although power is being generated (P_e^{Gen}) in the synthesised IBWT, it is also being consumed (P_e^{Con}) in technologies *j* and *j'* to process feedstock *i* and intermediate product *p*. The optimisation objective in this work is to synthesise an independent IBWT system with maximum *EP* (given in Eq. 1), which is independent and self-sufficient to sustain its own operation without relying on external sources for power supply. To achieve this, additional constraint, Eq. 19, is added where the power consumption rate, P_e^{Con}, must be compensated by the power generated on-site, P_e^{Gen} ($P_e^{Gen} > P_e^{Con}$). On the other hand, the excess power, P_e^{Exp}, generated is sold or exported to the power grid.

$$\left(P_e^{Gen}\right)_s \geq \left(P_e^{Con} + P_e^{Exp}\right)_s \quad \forall e' \forall s \tag{19}$$

The quality *q* and *q'* of intermediate product *p* and final product *p'* plays an essential role in the synthesis of an IBWT system. Hence, it is necessary to trace the material quality across the entire process. Equations 20 and 21 show the quality of intermediate product *p* (q_p) and final product *p'* ($q_{p'}$) produced.

Table 2 POM operations throughout a year

Season	Low	Medium	High	Average
Fraction of occurrence, α_s	0.417	0.333	0.250	-
Material flowrates				
Fresh fruit bunch, FFB (kt/year)	195.8	261.0	369.8	261.0
Crude palm oil, CPO (kt/year)	40.5	54.0	76.6	54.0
Palm oil mill effluent, POME (km^3/year)	136.0	181.5	257.0	181.5
Average POME quality				
Biological oxygen demand, BOD (ppm)	35,000			
Chemical oxygen demand, COD (ppm)	74,000			

Table 3 Cost of material and electricity e

Material	Price	Reference
Wet sludge (US$/t)	2	Ng and Ng (2013b), Ng et al. (2013)
River quality water (US$/m^3)	0.5	
Medium pressure steam, MPS (US$/t)	17	
Low-pressure steam, LPS (US$/t)	12	
Electricity to grid (US$/kWh)	0.0796	SEDA Malaysia (2017)
Treated biogas (US$/MJ)	0.003355	Market Watch (2016)
Compressed biomethane, bioCH$_4$ (US$/MJ)	0.005813	Energy Commission Malaysia (2017)
Liquefied CO$_2$ (US$/t)	160	Biofuels Digest (2014)

$$\left(F_p q_p\right)_s = \left(\sum_{i=1}^{I}\sum_{j=1}^{J} F_{ij} \mathrm{q}_i \mathrm{W}_{ijp}\right)_s \quad \forall p' \forall s \tag{20}$$

$$\left(F_{p'} q_{p'}\right)_s = \left(\sum_{p=1}^{P}\sum_{j'=1}^{J'} F_{pj'e}\ q_p \mathrm{W}_{pj'p'}\right)_s \quad \forall p', \forall s \tag{21}$$

where q_i is the quality of feedstock i. Meanwhile, W_{ijp} and $\mathrm{W}_{pj'p'}$ are the conversions of quality in technology j and j', respectively. In order to maintain the quality of final product p' produced ($q_{p'}$), an additional constraint is added to the model.

$$\mathrm{T}_{p'} \geq q_{p'} \quad \forall p' \tag{22}$$

where $\mathrm{T}_{p'}$ is the target of the quality level specified in the case study.

Additionally, the variation in feedstock i supply may result in a change in the selection of primary technology j and secondary technology j'. Hence, different technologies j and j' are invested and operated in an IBWT system under different season s. As a result, huge capital investment is required for such an operation. In order to minimise the *CAPEX* required, the technologies j and j' selected for all season s should remain constant. Hence, Eqs. 23 and 24 are added to restrict the equipment units required, z_j and $z_{j'}$ for technologies j and j' correspondingly.

$$(z_j)_{\mathrm{H}} \geq (z_j)_{\mathrm{M}} \geq (z_j)_{\mathrm{L}} \tag{23}$$

$$(z_j)_{\mathrm{H}} \geq (z_{j'})_{\mathrm{M}} \geq (z_{j'})_{\mathrm{L}} \tag{24}$$

A case study is presented to illustrate the proposed approach. The developed Mixed-Integer Nonlinear Programming (MINLP) model is solved via LINGO version 14 with Global solver (LINDO Systems Inc. 2016) with an Intel® Core™ i5 (2 × 3.20 GHz), 8 GB DDR3 RAM desktop unit.

Case Study

In this study, a potential miller in Malaysia is interested in implementing a new IBWT system to treat the POME generated from a 60 t/h palm oil mill is assumed. Apart from that, the existing mill is assumed to operate in similar behaviour as the POM presented by Foong et al. (2018), with the average POME quality given in Table 2. Note that the fraction of occurrence, α_s, is estimated based on the number of months in which the seasons occur in a year. The α_s value of 0.25, 0.333 and 0.417 represents a duration of 3, 4 and 5 months, correspondingly. Besides, the anaerobic and aerobic digesters are operated in mesophilic conditions (~ 25 °C) where heating is not required. It is also assumed that a typical IBWT system works continuously over the year for 8000 h per annum.

Table 4 Final product p' quality specifications

Final product	Quality	Reference
Discharge water (class B)		Ong (1979), Asis et al. (2016)
Biological oxygen demand, BOD (ppm)	20	
Chemical oxygen demand, COD (ppm)	50	
River quality water (Class IIA)		WEPA (2008)
Biological oxygen demand, BOD (ppm)	3	
Chemical oxygen demand, COD (ppm)	25	
Treated biogas (% CH$_4$)	55	Khan et al. (2017)
Compressed biomethane, bioCH$_4$ (% CH$_4$)	98	Abu Bakar et al. (2017)

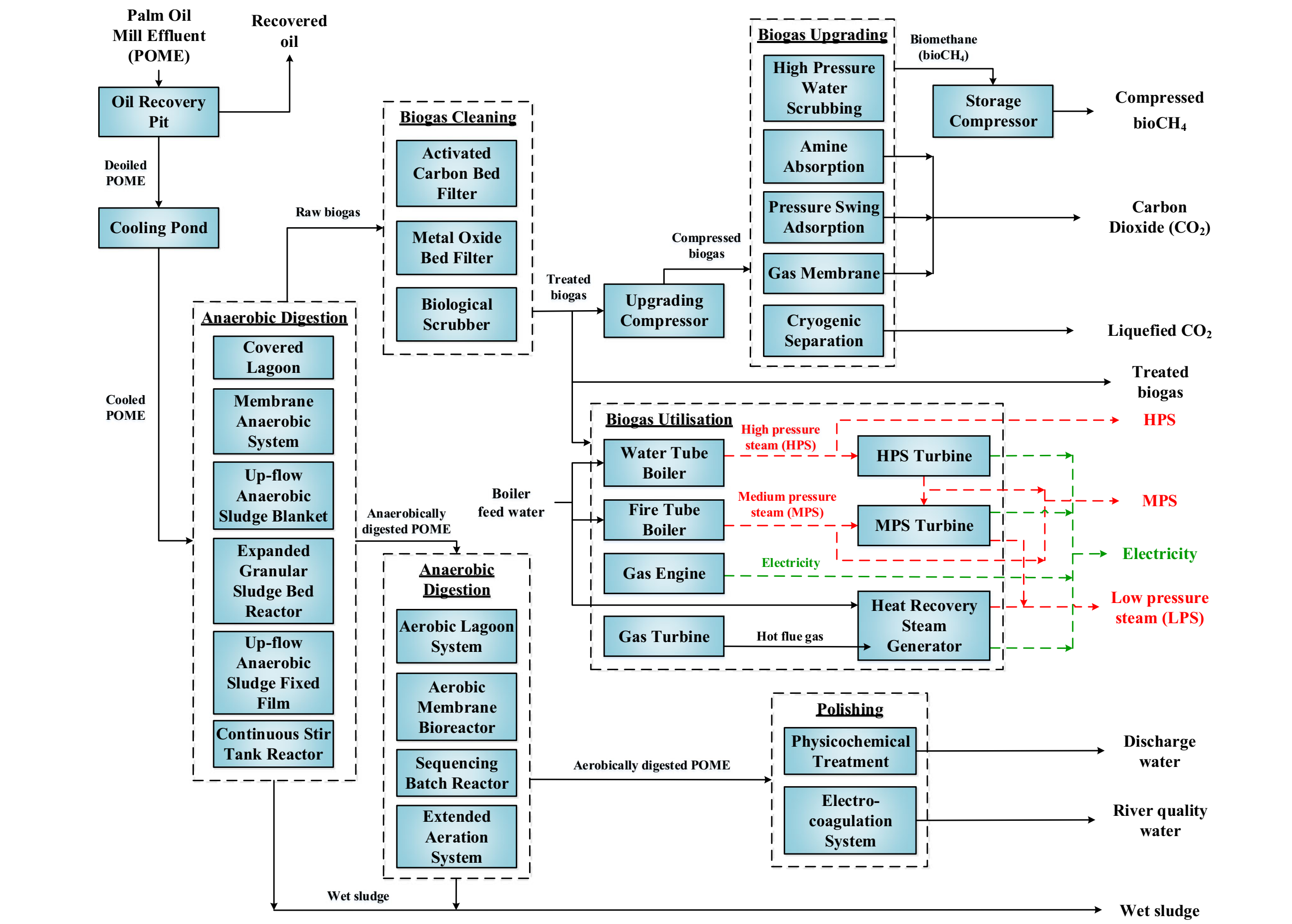

Fig. 3 Superstructure for IBWT system

AsPOMs are not operated continuously, oil recovery pits serve as a buffer tank to normalise the POME supply into the IBWT system. The synthesised system is expected to be built next to the POM with all products and energy sold

Fig. 4 Optimum IBWT system configuration for Scenario 1

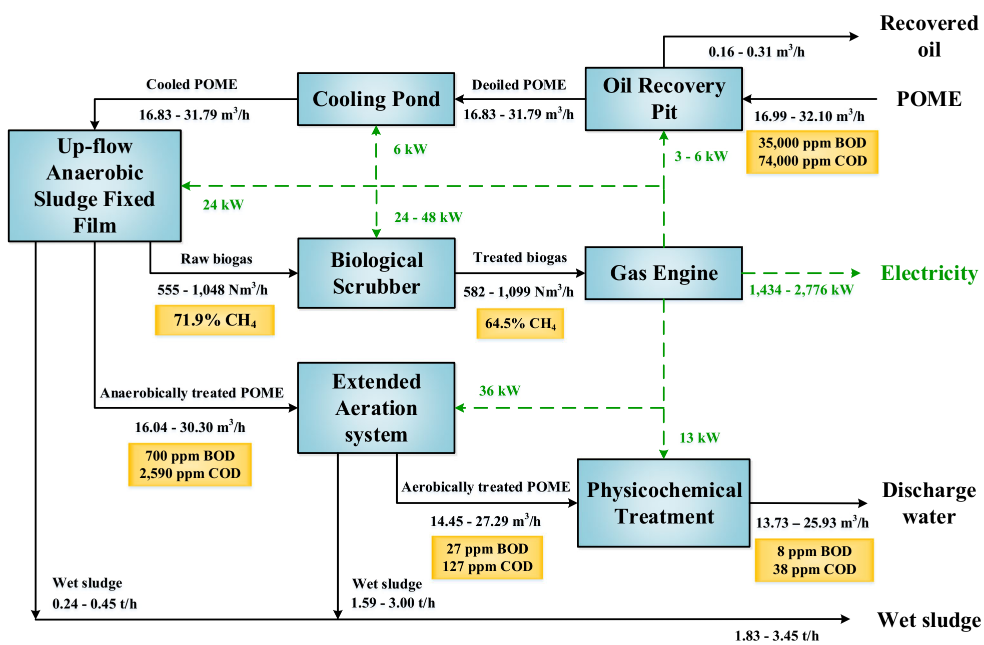

Table 5 Economic parameters for Scenario 1

Economic parameters	Low season	Medium season	High season	Average
Capital cost, *CAPEX* (million US$)	2.94			2.94
Operating cost, *OPEX* (million US$/y)	0.35	0.37	0.42	0.37
Gross profit, *GP* (million US$/y)	0.60	0.87	1.40	0.90
Economic performance, *EP* (million US$/y)	0.38	0.64	1.12	0.61
Net present value, $NPV^{t_k^{max}}$ (million US$)	-			6.30
Payback period, *PP* (y)	-			3.69
Internal rate of return, *IRR* (%)	-			29.7

on the site. In this respect, transportation costs and supply chain issues are neglected in this case study. Furthermore, the site required to build the system is not constrained as most POM in Malaysia is built in a rural area where land availability is not concerned. Table 3 shows the costs of materials and electricity associated with this study. The price of compressed bioCH_4 is assumed to be the same as natural gas due to the absence of market price in the industry. Meanwhile, Table 4 shows the specifications for final products before reuse or discharge to the environment.

A graphical superstructure representation is developed to incorporate all available technologies and configurations in an IBWT system, as shown in Fig. 3. Note that every box presented in the superstructure represents different technology for j and j' which may consist of varying equipment units, z_j and $z_{j'}$, respectively. In the superstructure, POME feedstock is first processed in the oil recovery pit to produce deoiled POME and recovered oil. Deoiled POME (an intermediate product) is processed in the cooling pond to produce cooled POME. Cooled POME from the cooling pond has the option to be processed in various anaerobic digestion technologies such as covered lagoon, membrane anaerobic system and up-flow anaerobic sludge blanket to produce raw biogas, anaerobically treated POME and wet sludge. Raw biogas and anaerobically treated POME are further processed in other technologies to produce final products such as electricity, bioCH_4 and discharge water. Throughout the system, products such as recovered oil, wet sludge and treated biogas which are not processed further will be sold as final products. The list of technologies used and other information such as costs, conversion, material and power consumptions specified are provided in the Supplementary Material (Table S1).

In order to demonstrate the proposed approach, two scenarios are presented to synthesise an IBWT system under a seasonal change in POME availability. In the first scenario, the optimisation objective is set to maximise the *EP* of the IBWT system synthesised. The optimisation objective remains the same in the second scenario, but the IBWT system is optimised under the assumption that the connection to the national grid is not available on the site. Therefore, the excess power generated in this scenario is not saleable under the FiT scheme. Lastly, sensitivity analysis is performed to provide strategies in which biogas utilisation can be promoted in the oil palm industry.

Discussions

Scenario 1: With National Grid Connections

In this scenario, an IBWT system is synthesised to generate biogas while treating the POME from a 60 t/h POM. The objective is set to maximise *EP* (Eq. 1) with the constraints given in Eqs. 2–24. It is assumed that the system has an operation lifespan, t_k^{max}, of 15 years with a discount rate, r, of 5% per annum. The costs of material and electricity given in Table 3 are used to evaluate the performance of the synthesised IBWT system. Meanwhile, the quality specifications for

Table 6 The flowrate of final products and power for Scenario 1

Flowrate	Low season	Medium season	High season	Average
Wet sludge (t/h)	1.83	2.43	3.45	2.43
Discharge water (m^3/h)	15.03	20.04	28.39	20.04
Power generated, P_e^{Gen} (kW)	1540	2000	2909	2035
Power consumed, P_e^{Con} (kW)	106	121	133	118
Power exported, P_e^{Exp} (kW)	1434	1879	2776	1918

Table 7 Chosen and operated technologies for Scenario 1

Equipment	Design capacity	Low season (unit)	Medium season (unit)	High season (unit)
Oil recovery pit	800 m^3	1	2	2
Cooling pond	2400 m^3	1	1	1
Up-flow anaerobic sludge fixed film	2300 m^3	1	1	1
Biological scrubber	310 Nm^3/h	2	3	4
Gas engine	1 MW	2	2	3
Extended aeration system	2300 m^3	1	1	1
Physicochemical treatment	30 m^3/h	1	1	1
Total unit		9	11	13

final products generated given in Table 4 are achieved. The model consists of 821 continuous variables with 123 integer variables and 790 constraints. A global solution is achieved with negligible computational time (less than 1 s). The optimised IBWT system configuration is given in Fig. 4 with the economic parameters, flowrate of materials and power summarised in Tables 5 and 6.

From the optimised result, an average *EP* value of 0.61 million US$/year is achieved over an operational lifespan of 15 years. An average *GP* of 0.90 million US$/y is reported with an $NPV_k^{t_k^{max}}$ of 6.30 million US$ generated. *PP* of 3.69 years are required to return the *CAPEX* of 2.94 million US$ invested with an *IRR* of 29.7%. The corresponding technologies selected and equipment units needed for each season are summarised in Table 7. The up-flow anaerobic sludge fixed film technology is chosen to generate biogas, which is then treated in a biological scrubber before combusted in the gas engine for power generation. On the other hand, anaerobically digested POME from anaerobic sludge fixed film technology is

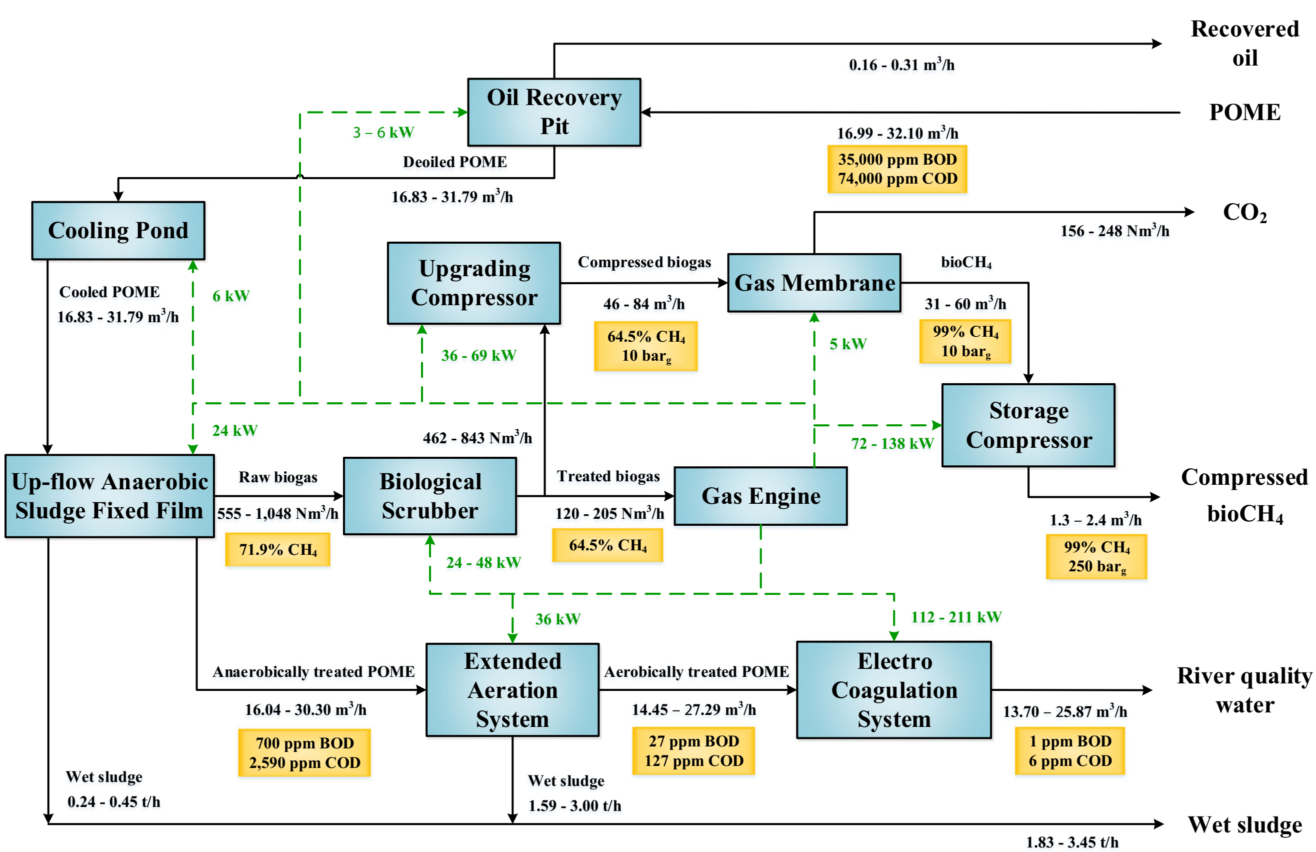

Fig. 5 Optimum IBWT system configuration for Scenario 2

Table 8 Economic parameters for Scenario 2

Economic parameters	Low season	Medium season	High season	Average
Capital cost, *CAPEX* (million US$)	3.03			3.03
Operating cost, *OPEX* (million US$/y)	0.42	0.47	0.53	0.47
Gross profit, *GP* (million US$/y)	0.21	0.39	0.70	0.39
Economic performance, *EP* (million US$/y)	− 0.36	0.11	0.40	0.10
Net present value, $NPV^{t_k^{max}}$ (million US$)	-			1.04
Payback period, *PP* (y)	-			10.01
Internal rate of return, *IRR* (%)	-			9.7

treated in an extended aeration system before polishing via physicochemical treatment to produce discharge water. As shown, the equipment units operated increases as POME feedstock increases from nine units in low crop season (136 km^3 POME/y) to 13 units during high crop season (257 km^3/y). Thus, *OPEX* increases correspondingly at 0.35, 0.37 and 0.42 million US$/year for low, medium and high seasons. However, the increment in *OPEX* is compensated with the raise in generated *GP* (0.60, 0.87 and 1.40 million US$/year for low, medium and high crop season, respectively) due to the increased production and exportation of electrical power. On average, 2.43 and 20.04 t/h of wet sludge and discharge water, respectively, with 2035 kW power are generated by the synthesised IBWT system. At the same time, an average of 118 kW is consumed to operate the system. Hence, an average of 1918 kW electrical power (1434, 1879 and 2776 kW for low, medium and high crop season, respectively) is exported and sold to the national grid under the FiT scheme.

Scenario 2: Without National Grid Connections

In the second scenario, it is assumed that the site is not connected to the national grid, and therefore, excess power generated cannot be exported. This is often the case for Malaysian POMs, which are usually located in the plantation area to reduce logistic costs for FFB. Due to the remote location of POMs, extra charges are required (i.e. 0.2 million US$/km) for power line installation (Electric Light & Power 2013; Vaillancourt 2014). As such, the cost of electricity, C_e, is set to be zero US$/kW, and the calculation for *GP* (Eq. 11) is modified into Eq. 25. Other material price and final product specifications remain the same as provided in Tables 3 and 4.

$$\mathrm{GP} = \mathrm{AOT}\sum_{s} a_s \left(\sum_{p'=1}^{P'} F_{p'} C_{p'} - \sum_{i=1}^{I} F_i C_i - \mathrm{OPEX} \right)_s . \quad (25)$$

The objective remains the same (Eq. 1) with the given constraints in Eqs. 2–10 and 12–25. Similar to the previous scenario, the optimisation problem consists of 821 continuous variables, 123 integer variables and 790 constraints, solved with global solver with negligible computational time (less than 1 s). The optimum IBWT system configuration is shown in Fig. 5, in which, the economic parameters of the system developed under such circumstances are given in Tables 8 with the flowrates of final products and power summarised in Table 9.

An average *EP* value of 0.10 million US$/year is obtained in this scenario (0.61 million US$/y previously) with an operational lifespan of 15 years. *CAPEX* and *OPEX* both increased to 3.03 million US$ and 0.47 million US$/year, respectively, while *GP* reduces to 0.39 million US$/year (from 0.90 million US$/y). As a result, $NPV^{t_k^{max}}$ reduces significantly, from 6.30 to 1.04 million US$ with additional 6.32 years (= 10.01 − 3.69 years) needed to return the investment. Besides, a great fall in *IRR* by 20% (from 29.7 to 9.7%) is also reported. As compared with the previous scenario, technologies in the

Table 9 The flowrate of final products and power for Scenario 2

Flowrate	Low season	Medium season	High season	Average
Wet sludge (t/h)	1.83	2.43	3.45	2.43
Compressed biomethane, bioCH_4 (GJ/h)	10.00	13.50	20.00	13.85
River quality water (m^3/h)	15.03	20.04	28.39	20.04
Power generated, P_e^{Gen} (kW)	317	406	543	403
Power consumed, P_e^{Con} (kW)	317	406	543	403

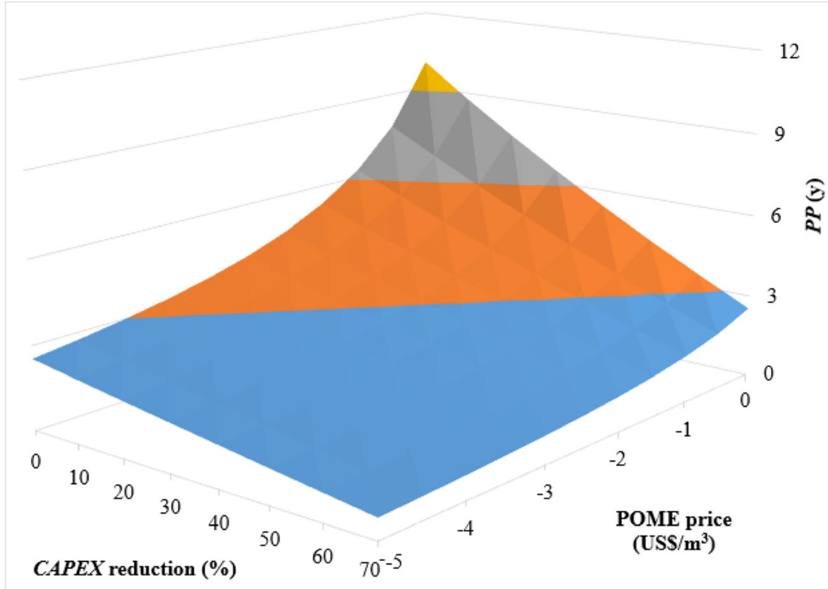

Fig. 6 Sensitivity analysis on POME price and CAPEX reduction to PP of developed IBWT system

synthesised IBWT system remain the same (i.e. up-flow anaerobic sludge fixed film, extended aeration system and biological scrubber) where gas engine is equipped to combust part of the biogas produced, generating power to operate the system. It is noted that an additional 285 kW power (= 403 − 118 kW) is consumed on average to operate the electrocoagulation system to generate river quality water for reuse in the milling process. The generated power is consumed entirely by the system ($P_e^{Gen} = P_e^{Con}$), while the remaining biogas is upgraded into compressed bioCH_4 via gas membrane technology as an alternative product. Compressed bioCH_4 is produced at the rate of 10, 13.5 and 20 GJ/h for low, medium and high season, respectively, yielding a total of 110,800 TJ/year (= 13.85 GJ/h × 8000 h/year).

Sensitivity Analysis

The synthesised IBWT system in Scenario 2 (without grid connection) requires higher costs (i.e. OPEX and CAPEX) but generates lower GP value. It is mainly due to the low price of compressed bioCH_4 in the market, as up to 40% of fossil gas market price is subsidised by the Malaysian government (Energy Commission Malaysia 2014). As compared with scenario 1 where national grid connection is available, additional 6.3 years (from 3.7 to 10 years) is required to return the investment made, causing the industry to lose interest to invest in such a system when grid connection is unavailable on site. To ensure the economic feasibility of the IBWT system developed for compressed bioCH_4 productions, reduction in CAPEX or extra charges for POME treated can be

Table 10 The basis used to calculate GHG emissions from POME

Variable	Value	Note
Annual operating time, AOT (h/year)	8000	From case study
Average POME supply, $POME_{avg}$ (m^3/year)	181,500	
CO_2 conversion from CH_4, X_{comb} (kg/kg)	2.75	Stoichiometric equation: $CH_4 + 2O_2 => CO_2 + 2H_2O$ (complete combustion reaction assumed)
CH_4 production for IBWT system, $CH_{4\ IBWT}$ (kg/m^3)	15.50	Yacob et al. (2006)
CO_2 production for IBWT system, $CO_{2\ IBWT}$ (kg/m^3)	16.71	
CH_4 production for open ponding system, $CH_{4\ OP}$ (kg/m^3)	12.36	Najafpour et al. (2006)
CO_2 production for open ponding system, $CO_{2\ OP}$ (kg/m^3)	28.57	
CH_4 global warming potential as compared to CO_2, GWP_{CH_4}	25	Gardner et al. (1993)
Greenhouse gas emission by IBWT system, GHG_{IBWT} (t CO_{2e}/year)	10,756	Refer to Eq. 26
Greenhouse gas emission by open ponding system, GHG_{OP} (t CO_{2e}/year)	61,187	Refer to Eq. 27

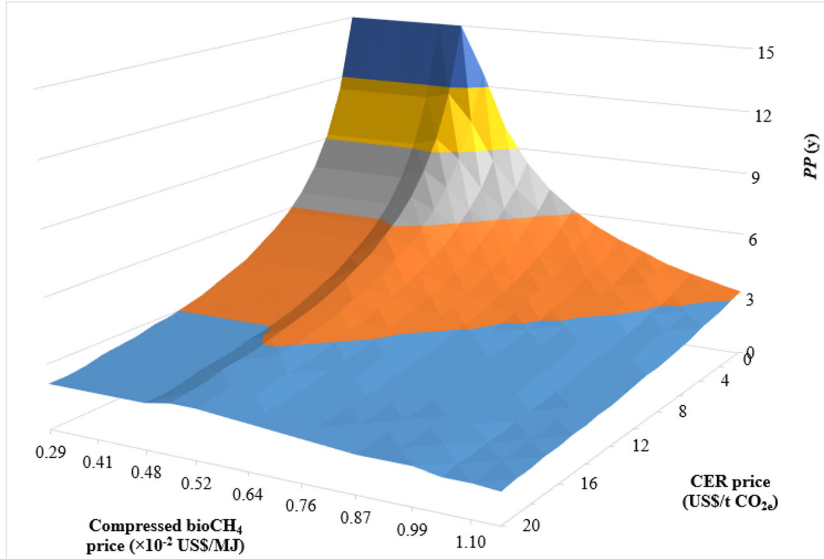

Fig. 7 Sensitivity analysis on compressed bioCH$_4$ and CER prices to PP of developed IBWT system

implemented. In this regard, a sensitivity analysis is performed on the cost of POME feedstock and CAPEX reduction up to −5 US$/m^3 and 70% at −0.5 US$/m^3 and 10% intervals, respectively. The changes in PP with respect to POME price and CAPEX reduction are given in Fig. 6. In order for the synthesised IBWT system to attract the interest of palm oil millers, a PP below 6 years should be achieved. In that case, at least 1.11 US$ should be charged for every m^3 of POME treated (C_{POME} = −1.11 US$/m^3), or 34% reduction in CAPEX (2 million US$), or combination of both are required.

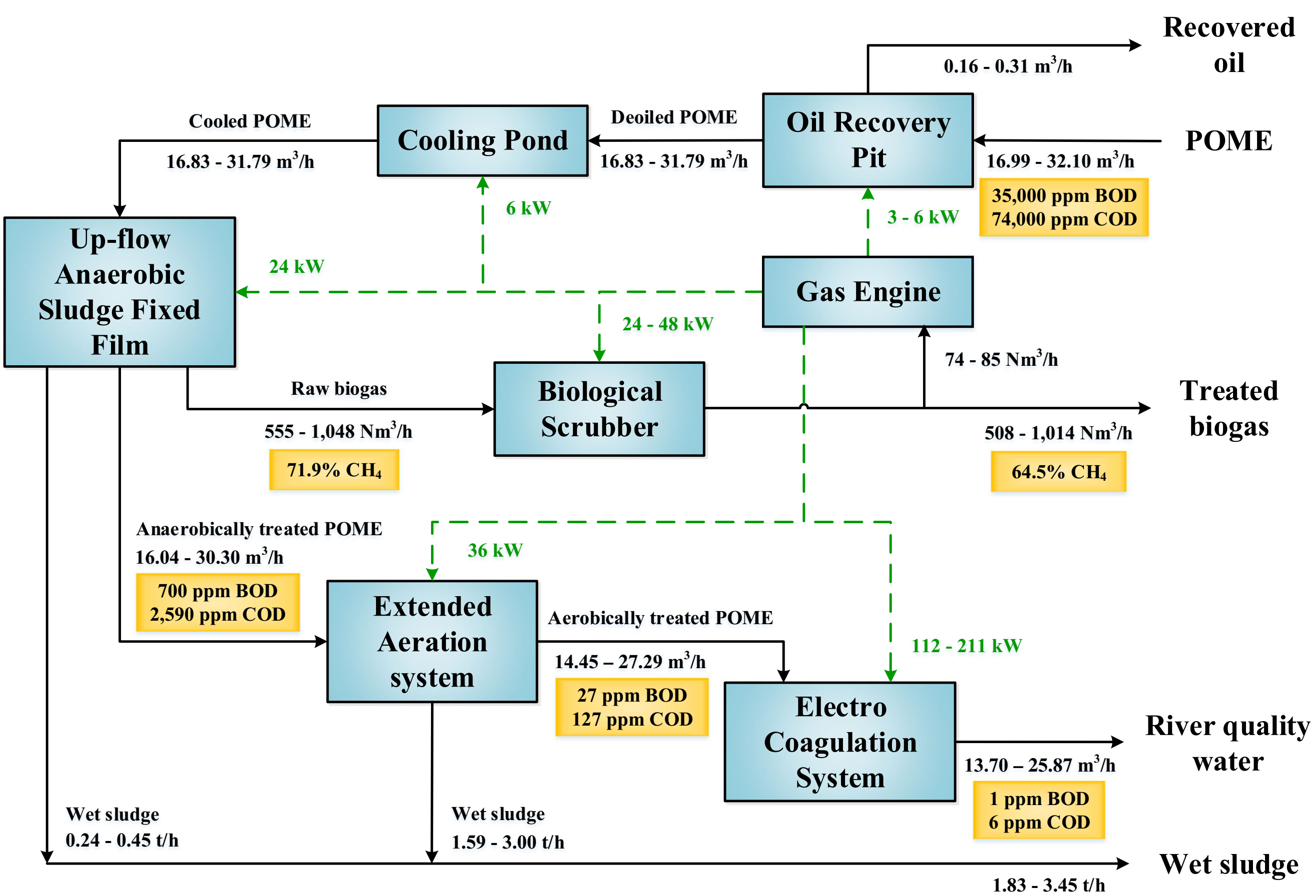

Fig. 8 IBWT system configuration for compressed bioCH$_4$ price below 0.489 × 10^{-2} US$/MJ

Alternatively, it is suggested that subsidies for compressed bioCH_4 and incentives for CER in such a system are needed to promote biogas utilisation in the industry. GHG emissions from POME treated with the IBWT (GHG_{IBWT}) and conventional open ponding systems (GHG_{OP}) can be computed via Eqs. 26 and 27, respectively, with the basis used for calculations given in Table 10. It was found that the implementation of IBWT system in a 60 t/h POM successfully reduces GHG emission by 82% or 50,431 t CO_{2e}/year (= 61,187 − 10,756 t CO_{2e}/year). Figure 7 shows a sensitivity analysis on the changes of PP for the IBWT system developed, based on the price of compressed bioCH_4 and CER. Compressed bioCH_4 price ranges between 50 to 200% of the current price (0.581 × 10^{-2} US$/MJ or 24.55 MYR/mmBtu) at 10% intervals, while CER incentive varies from 0 to 20 US$/t CO_{2e} at 1 US$/t CO_{2e} intervals.

$$GHG_{IBWT} = AOT \times POME_{avg}(X_{comb}CH_{4\ IBWT} + CO_{2\ IBWT}) \quad (26)$$

$$GHG_{OP} = AOT \times POME_{avg}(GWP_{CH_4}CH_{4\ OP} + CO_{2\ OP}) \quad (27)$$

Note that the PP reduces significantly as compressed bioCH_4 and CER prices increase except for the price of compressed bioCH_4 ranging from 0.291 to 0.489 × 10^{-2} US$/MJ where PP remains constant (reduces as CER price increases). In this region, biogas is not upgraded to compressed bioCH_4 but sold for domestic heating with energy price of 0.336 × 10^{-2} US$/MJ (Market Watch 2016) as shown in Fig. 8. CAPEX needed is reduced to 2.61 million US$ due to the removal of biogas upgrading technologies such as compressors and gas membranes from the system. Meanwhile, biogas is upgraded to compressed bioCH_4 when the price is higher than 0.489 × 10^{-2} US$/MJ, as discussed in Scenario 2 (refer to Fig. 5). The increment in CAPEX causes a step increment in PP as compressed bioCH_4 price increases above 0.489 × 10^{-2} US$/MJ, as shown in Fig. 7. In that case, CER incentive of 6 US$/t CO_{2e} is required with the current compressed bioCH_4 price, or 40% subsidy on compressed bioCH_4 price (0.814 × 10^{-2} US$/MJ), or combination of both strategies are needed to promote biogas utilisation from POME in the industry.

Conclusions

IBWT system generates renewable energy in the form of biogas while treating POME to achieve the discharge limit, set by the government. Such a system offers significant benefits to the industry as it generates income from liquid waste produced in POM (i.e. POME) while reducing GHG emission by 82% or 50,431 t CO_{2e}/year. In this work, a systematic approach for synthesis and optimisation of an IBWT system with maximum EP via multi-period optimisation is presented. The case study demonstrated that production of electricity sold to the national grid with a premium price under the FiT scheme is prioritised. On average, the developed IBWT system is capable to export up to 1.9 MW electrical power with a CAPEX of 2.94 million US$ and PP of 3.69 years. In the situation where national grid connection is not applicable, up to 110,800 GJ/year of compressed bioCH_4 can be generated to substitute natural gas in the natural gas grid or vehicle fuels at gas stations. However, the latter process is proven less favourable as a longer payback period of 10 years is required to return the *CAPEX* of 3.03 million US$. In order to achieve a PP of less 6 years for compressed bioCH_4 generation, a treatment cost of − 1.11 US$/$m^3$ POME should be imposed to the miller, or 34% reduction in CAPEX to 2 million US$ is needed. Alternatively, strategies such as compressed bioCH_4 subsidisation up to 0.489 × 10^{-2} US$/MJ and incentivising CER scheme by 6 US$/t CO_{2e} from the Malaysian government are suggested. It is worth mentioning that the model developed can be easily revised and reformulated to suite the applications in other countries where oil palm is cultivated extensively. Future prospects are reflected to consider operational feasibility and development of centralised IBWT system network in the industry.

Acknowledgements Accreditation to Havy's Oil Mill Sdn Bhd for the technical data provided to develop an industrial case study in this work.

Code Availability The developed model is solved via LINGO version 14 with an Intel® Core™ i5 (2 × 3.20 GHz), 8 GB DDR3 RAM desktop unit.

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Writing—original draft preparation: S.Z.Y. Foong
Writing—review and editing: M.F. Chong and D.K.S. Ng
Funding acquisition: D.K.S. Ng
Resources: M.F. Chong and D.K.S. Ng
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Visualisation: S.Z.Y. Foong
Supervision: D.K.S. Ng

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Data Availability Industrial data is obtained from Havy's Oil Mill Sdn Bhd.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Nomenclature *$BioCH_4$,* biomethane; *BOD,* biochemical oxygen demand; *CER,* certified emission reduction; *CH_4,* methane; *CO_2,* carbon dioxide; *CO_{2e},* carbon dioxide equivalent; *COD,* chemical oxygen demand; *CPO,* crude palm oil; *DOS,* Department of Statistics; *FiT,* feed-in-tariff; *GHG,* greenhouse gas; *GHG_{IBWT},* total greenhouse gas emissions from integrated biogas and wastewater system; *GHG_{OP},* total greenhouse gas emissions from open ponding system; *H_2S,* hydrogen sulphide; *HRT,* hydraulic retention time; *IBWT,* integrated biogas and wastewater treatment; *MINLP,* Mixed-Integer Nonlinear Programming; *POM,* palm oil mill; *POME,* palm oil mill effluent; *PSE,* process systems engineering; *SEDA,* Sustainable Energy Development Authority; *USDA,* United States Department of Agriculture; *WEPA,* Water Environment Partnership in Asia; *e,* index for electricity; *i,* index for feedstock; *j,* index for primary technology; *j′,* index for secondary technology; *k,* index for primary or secondary technology; *p,* index for intermediate product; *p′,* index for final product; *s,* index for season; *t,* index for time; *CAPEX,* total capital costs; P_e^{Con}, total power consumption; P_e^{Gen}, total power generated; P_e^{Exp}, total power sold or exported to the grid; *EP,* economic performance; F_{ij}, flowrate of feedstock *i* into primary technology *j*; F_p, flowrate of intermediate product *p*; $F_{p'}$, flowrate of final product *p′*; $F_{pj'}$, flowrate of intermediate product *p* into secondary technology *j′*; *GP,* gross profit; *IRR,* internal rate of return; $\mathrm{NPV}^{t_k^{\max}}$, net present value at $t_k^{\max}$; *OPEX,* total operating costs; *PP,* payback period; q_p, quality of intermediate product *p*; $q_{p'}$, quality of final product *p′*; z_j, number of units of technology selected for primary technologies *j*; $z_{j'}$, number of units of technology selected for secondary technology *j′*; *AOT,* annual operational time; CC_j, capital cost of primary technology *j*; $CC_{j'}$, capital cost of secondary technology *j′*; C_e, cost of electricity *e*; $CH_{4\ IBWT}$, CH_4 generation for integrated biogas and wastewater system; $CH_{4\ OP}$, CH_4 generation for open ponding system; C_i, cost of feedstock *i*; $CO_{2\ IBWT}$, CO_2 generation for integrated biogas and wastewater system; $CO_{2\ OP}$, CO_2 generation for open ponding system; $C_{p'}$, Cost of final product *p′*; *CRF,* capital recovery factor; F_j^{Design}, fixed design capacity for primary technologies *j*; $F_{j'}^{\mathrm{Design}}$, fixed design capacity for secondary technologies *j′*; F_i, flowrate of feedstock i; $\mathrm{GWP}_{\mathrm{CH_4}}$, global warming potential of CH4 as compared to CO_2; OC_j, operating cost for secondary technology *j′*; $OC_{j'}$, operating cost for primary technology *j*; q_i, quality of feedstock *i*; *r,* discount rate; $t_k^{\max}$, maximum operational lifespan for primary technology *j* and secondary technology *j′*; $T_{p'}$, constraint specified for quality of final product *p′*; V_{ije}, electricity conversion for primary technology *j* from feedstock *i*; $V_{pj'e}$, electricity conversion for secondary technology *j′* from intermediate product *p*; W_{ijp}, quality conversion of feedstock *i* in technology *j*; $W_{pj'p'}$, quality conversion of intermediate product *p* in technology *j′*; X_{comb}, conversion of CO_2 from CH_4; X_{ijp}, mass conversion of primary technology *j* from feedstock *i*; $X_{pj'p'}$, mass conversion of secondary technology *j′* from intermediate product *p*; Y_{je}, specific power consumption per unit for primary technology *j′*; $Y_{j'e}$, specific power consumption per unit for secondary technology *j′*; Y_{ije}, specific power consumption per unit of feedstock *i* processed; $Y_{pj'e}$, specific power consumption per unit of intermediate product *p* processed; α_s, fraction of occurrence for season *s*

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