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Introducing a new GHG emission calculation approach for alternative methane reduction measures in the wastewater treatment of a palm oil mill

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Abstract Palm oil mill wastewater treatment is a significant source of greenhouse gas (GHG) emissions. The wastewater, palm oil mill effluent (POME), carries substantial amounts of organic matter: If left in ponds, most of this organic matter would decompose relatively quickly into methane (CH_4) and carbon dioxide. A belt filter press has been introduced as a means to separate organic matter from the wastewater. Solidified organic matter, the belt press cake recovered with a belt filter press, can be further used as organic fertilizer in the plantation. The aim of this study was to confirm that there is a reduction of CH_4 emissions associated with the belt filter press and to find a simple method for determining the reduction at the palm oil mills. CH_4 measurements and total organic carbon (TOC) analysis were conducted in a palm oil mill in Malaysia. The emissions were measured both in ponds with solid separation and in baseline open ponds without any CH_4 reduction measures. TOC was measured in POME and in belt press cake. By removing organic matter, the measured palm oil mill CH_4 emissions of the POME ponds were reduced by 11%. The reduction was as high as 54% in the single pond where the belt filter press was installed. A calculative 13% reduction in methane formation potential was confirmed with TOC measurement. TOC measurement was found to be a simple method worth considering for determining GHG reduction.

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Keywords Palm oil mill effluent · GHG reduction · Methane measurement · Wastewater treatment · Solids separation · Belt filter press

1 Introduction

At palm oil mills, the treatment of wastewater, often called palm oil mill effluent (POME), usually consists of a series of open ponds that are a significant source of greenhouse gas (GHG) emissions (Chin et al. 2013; Taylor et al. 2014), especially of methane, CH_4, which has high global warming potential. The wastewater carries substantial amounts of degradable organic matter in the form of mill process residues. According to Loh et al. (2017), the dry matter content of fresh effluent entering the pond system is approximately 5%. This provides perfect anaerobic conditions and enables highly effective biodynamic processes: The carbon in POME is quickly turned into climate-relevant biogas. Thus, the management of a wastewater treatment plant (WWTP) for palm oil mills plays a substantial role when calculating the life cycle GHG emissions of crude palm oil (CPO).

Originally, the pond system is meant to be dredged of accumulated solid matter at times in order to maintain the water depth at the required level to ensure proper retention times. To avoid the need to shut down the operation and use excavators to do the dredging, palm oil producer Kuala Lumpur Kepong Berhad (KLK) introduced a belt filter press (also known as belt filter or filter belt press) system to continuously remove dry matter from the pond system, see Fig. 1. This system can be run simultaneously with the oil extraction process, and there is no need to use excavators.

The belt filter press is a device used for solid–liquid separation processes, particularly the dewatering of sludges in different industries and water treatment. The process of filtration is primarily obtained by passing a pair of filtering cloths and belts through a system of rollers, as illustrated in Fig. 1. The system takes sludge, effluent, or slurry as feed, often pretreated with flocculant, and separates it into a filtrate and a solid press cake. The filter cake can be used for fertilizer in the plantation, which reduces the need for GHG-intensive synthetic fertilizers.

The belt filter system also has significant potential for reducing GHGs from the wastewater. An installed belt filter system removes the organic matter out of the decaying and methane-producing conditions of open POME ponds. The aim of this study was to

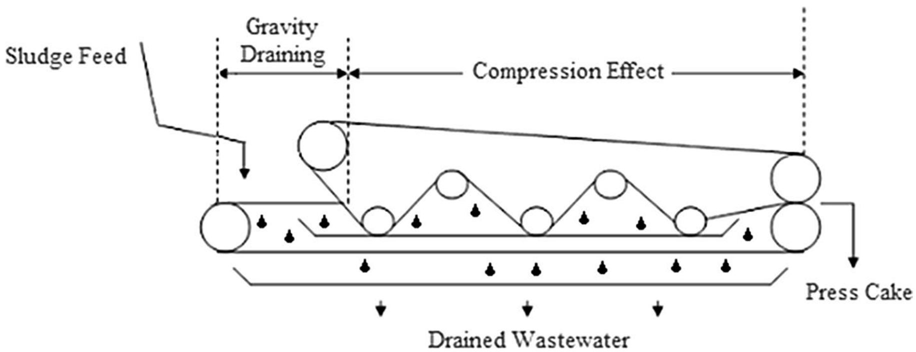

Fig. 1 Simplified picture of belt filter press operating principle

demonstrate that installing a belt filter system leads to reduced GHG emissions and to calculate the emission reduction based on the organic carbon in the belt press cake.

The arrangements for the actual CH_4 emission measurement on the ponds required special equipment and both time and expertise; it was seen as too complicated a method for a palm oil mill to regularly identify the emission level of the wastewater as part of their business as usual: Regular CH_4 measurements or monitoring cannot be integrated into the wastewater management. Therefore, there was a need to find a simple indicator to reliably determine the CH_4 reduction effect of the belt filter system, in addition to confirming the CH_4 reduction confirmation.

Two simple methods related to the assessment of wastewater methane formation potential were considered: chemical oxygen demand (COD) and total organic carbon (TOC). The TOC method was chosen from the perspective of trying to find the simplest method for the mill to analyze the methane reduction potential of their WWTP, without an extensive amount of sampling. The avoided methane formation potential of the belt press cake can be calculated based on its average carbon content.

COD analysis has been used previously for methane formation potential measurement for wastewaters (Yacob et al. 2006; Ahmad et al. 2003); however, the actual dependency may have significant site-specific differences as the method also oxidizes other substances besides carbon, and the methane conversion factor selection may need further wastewater analysis at each palm oil mill where the method is applied. Poh et al. (2010) state that TOC is essential for determining the biodegradability of POME. Also, the belt press cake has a high concentration of solids, which raises the question whether TOC is in fact the more suitable of the two methods for analyzing the emission potential of the belt press cake. COD has been used to assess the potential of a less solid raw effluent flow to form methane (Yacob et al. 2006), and a belt press cake is a much more homogenous sampling point than POME. The literature data available in general for POME and belt press cake TOC are basically nonexistent, and the usability of the indicator was in need of further assessment. In light of this study, TOC analysis appears to be a noteworthy method for analyzing GHG emission reduction potential in POME and belt press cake.

2 Materials and methods

The CH_4 emissions and organic carbon from POME and belt press cake were measured at one palm oil mill in the state of Perak, Malaysia, which is owned by KLK. The criterion for selecting the palm oil mill was to have an installed belt filter system in operation in at least one of the anaerobic wastewater ponds. The study was conducted in January–March and June–July 2017.

The palm oil mill receives its raw material from several decentralized plantation facilities totaling approx. 10,000 ha. The average daily production of the palm oil mill was approx. 156 metric tons (t) of CPO during the measurement period. In this study, the mill's POME discharge to the ponds was approx. 430 m^3 per day, of which the belt filter press treated 100–150 m^3. The production of belt press cake was approx. 27 metric tons per day.

The palm oil mill has five parallel anaerobic POME ponds. The belt filter press pump was installed in pond 1, to which it had been moved from pond 2 3 weeks prior to the measurement period. The belt filter press had been in use in pond 2 from October to December 2016. The remaining ponds 3, 4, and 5 have never had belt filter system in use. The palm oil mill had a system where fresh effluent was pumped permanently on a daily basis into anaerobic ponds and there was no rotation between the ponds. The POME load to each pond was assumed to be similar, and the only difference between the ponds was the belt filter press pump that was installed in pond 1 and that the pump had been in use in pond 2.

2.1 Methane measurement

Measurements were taken for 8 weeks between January and March 2017. Equipment tests and on-site calibration were performed during the week prior to commencement of the actual measurement. Measurements were done 5–6 days per week. CH_4 measurements were carried out in a three-day rotational mode, starting on day 1 in anaerobic pond 1 and covering anaerobic POME pond 2 on the second day. On the third day, the measurements were taken in one of the remaining POME ponds 3, 4, or 5, which served as the baseline measurements with no CH_4 reduction measures in use.

The ponds were measured in four lines each: Four ropes (A, B, C, and D in Fig. 2) were stretched at regular distances across each POME pond as transects in order to have stable and replicable measurement points. In the first half of the measurement period, each rope consisted of two measurement points, resulting in a total of eight points. The CH_4 measurement chamber's closure time was 5 min. In the second half of the measurement period in February, the number of measurement points was increased to three points per rope, in order to obtain more representative results, as it appeared that the pond depth varied significantly from the sides to the middle of the pond, with the deepest point found in the center of the pond (Fig. 2). This resulted in 12 measurement points in total per pond. At the same time, the CH_4 measurement chamber's closure time was decreased to 1 min for reasons of time efficiency. The measurement protocol and the layout of the WWTP are presented in Fig. 3.

Due to the change in measurement points in the second half of the measurement period, and in order to harmonize the measured data, CH_4 emissions were interpolated at five positions. The interpolation of values was calculated on each transect, based on the delta between two points and the according delta of pond depths. Pond depths were measured at all transects of each pond and associated accordingly.

Water temperatures were recorded with logging devices (LogTag) every 30 min at different depths (50, 200, 400, and 600) over several days in each pond. Air temperatures were

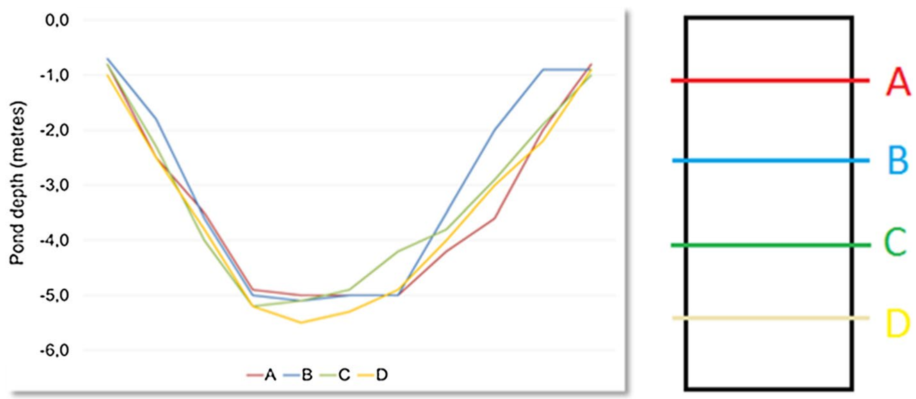

Fig. 2 Profile of the POME ponds and the four transects for measuring

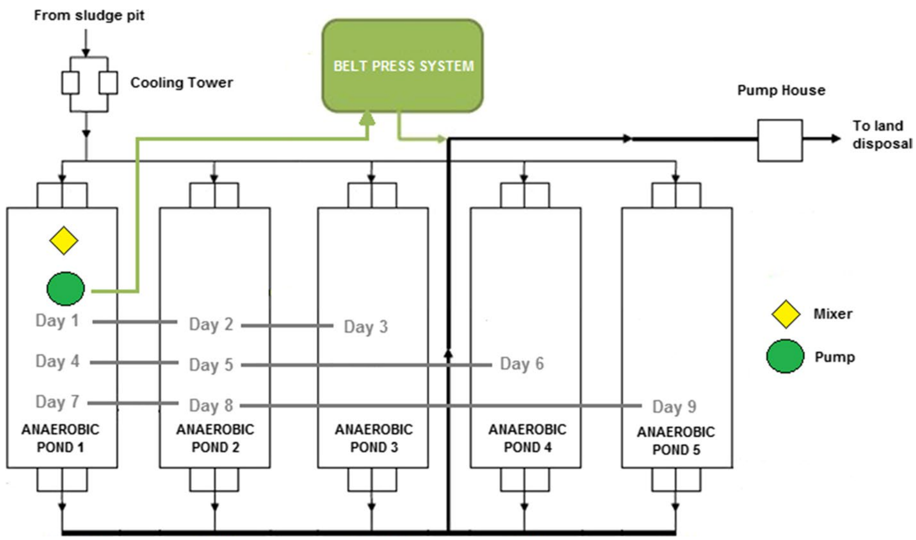

Fig. 3 POME ponds and the rotational measurement at the palm oil mill

recorded in the close vicinity of the POME ponds throughout the whole measurement period. The amounts of daily production of CPO, POME, and belt press cake were received from the mill's own statistics.

2.2 Methane measurement equipment

CH_4 emission measurements were conducted by means of a manual closed-chamber approach (Hoffmann et al. 2017; Pihlatie et al. 2013; Drösler 2005), using a state-of-the-art laser spectroscopy technique. A floatable and airtight chamber (base area 0.071 m^{-2}, volume 0.009 m^{-3}) was used to capture the CH_4 flux from the POME pond surface (Fig. 4). The chamber was connected in a circular pumping system to an LGR^{TM} ultraportable greenhouse gas analyzer (UGGA, Model 915–0011, Los Gatos Research, Palo Alto, CA, USA), typically used in field studies (McEwing et al. 2015). The change in CH_4 concentration inside the chamber was automatically recorded at a one-second frequency, as were site-specific parameters such as temperature and pressure. The chamber placement-related information for each measuring point was recorded manually. In total, approx. 73,440 CH_4 data points and 1224 chamber placements were identified and evaluated.

2.3 Methane measurement emission calculations

The concept of emission calculation using a closed-chamber method is that any gas under observation accumulates under a sealed cover. Thus, the concentration increases over time, as presented in Fig. 4, provided that all other parameters, such as the chamber volume, chamber height, air pressure, and temperature, are regarded as constant. The slope of the gas concentration increase over time is set in relation to the Avogadro gas constant and transformed into a mass increase over time and specific surface, as described by Drösler (2005) in formula (1).

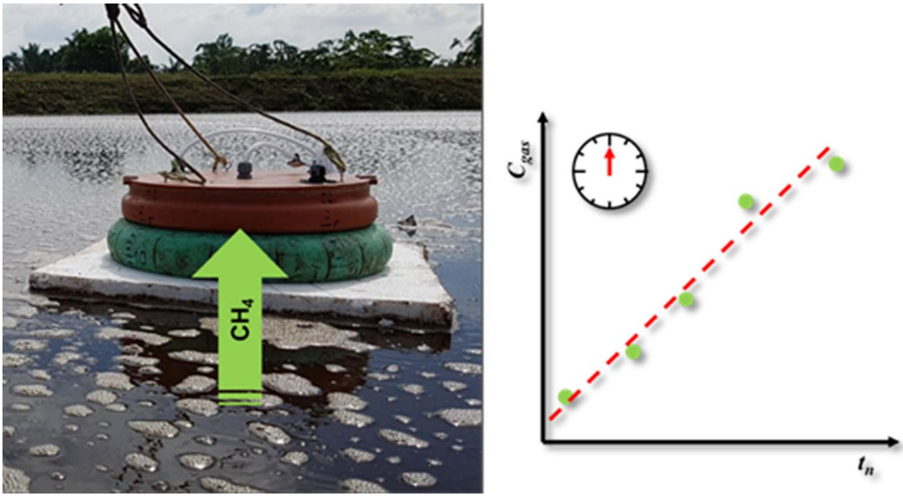

Fig. 4 Concept of accumulating methane under closed chamber

$$r_{CH_4}\left[\mu g\cdot C\cdot m^{-2}\cdot h^{-1}\right] = \frac{M\cdot P\cdot V\cdot \delta v\cdot f_1}{R\left[m^3\cdot Pa\cdot K^{-1}\cdot mol^{-1}\right]\cdot T\cdot t\cdot A} \quad (1)$$

r_{CH4} gas flux (e.g. CH_4), M molar mass g mol^{-1}, P barometric pressure Pa, V chamber headspace volume m^3, δv observed slope of gas concentration C_{gas} over time $t_{n,}$ ppm(v), f_1 elementary part of observed gas molecule, R Avogadro constant, T temperature K, t: time h, A size of observed area m^2

Due to the amount of data produced and in order to avoid human bias in the data evaluation, the final calculation of emissions or fluxes is an automated process capable of presenting a full statistical data evaluation. The calculation was conducted using an automated approach by Hoffmann et al. (2017), which is available within the open-source statistics program R. The final output of the algorithm is the emission (or flux) given as a mass increase of the specific gas over time and surface. Having measured each pond repetitively in a close spatial and temporal grid, and taking into account the specific size of each pond, an average emission value for each pond was generated.

2.4 TOC measurement

TOC measurements were conducted after the actual CH_4 measurement period. TOC was measured in the raw POME in the pond inlet, in the final effluent in the pond outlet, and in the belt press cake. The samples were taken in July and August 2017, and the amount of samples required was assessed based on the aim of the simplest plausible method for the palm oil mill. A total of 12 samples were taken, of which five were of the belt press cake. All 12 samples were analyzed in two commercial laboratories in Penang, Malaysia, using Nelson and Sommers and Walkley–Black titrimetry methods. The dry matter content of the TOC samples was analyzed using ASTM D 2974 and APHA 2540B.

2.5 Correlation between methane and TOC measurements

The theoretical CH4 emissions were calculated for a hypothetical POME treatment with five ponds without solid separation, using the average baseline emission for each pond as detected in the case palm oil mill. This was compared to emissions of another hypothetical mill with four similar average baseline ponds, plus one pond with a belt filter press and emissions equal to emissions from case palm oil mill pond 1. The reduction achieved with this exercise was compared to reduction of CH4 formation potential achieved by the removed organic carbon with a belt filter press. The CH4 formation potential calculation was based on TOC measurement from incoming POME and belt filter press cake.

3 Results

Air temperature measurements showed the typical daily fluctuation of a tropical climate, from 22 °C at night to 34 °C during the day. All records were identical with regard to the hot temperatures, and no significant changes were observed throughout the observation period. The same observation applies for the records of POME temperatures in the ponds, where the temperature remained at the same level for the whole measurement period, the variation being within 1 °C at deeper levels. At the surface level, the total temperature delta is less than 3 °C at a depth of 50 cm below the surface, the variation being caused by sudden precipitation events.

All five ponds showed similar trends with regard to the decrease of CH_4 emissions from the POME inlet to the POME outlet position. Emissions appeared to be highest in the center position of each transect and lower to the edges of the ponds, which was as expected due to the shape of the ponds (Fig. 2).

Figure 5 shows the average CH_4 emission for each POME pond. Anaerobic ponds 3, 4, and 5 can be regarded as “baseline” ponds as they have not been connected with the belt filter system before or during the observation period. The emissions from ponds 3, 4, and 5 range in similar magnitude averaging 315 kg CH_4 per active pond hectare per hour during operational hours. Anaerobic pond 1, the belt filter press pond produced emissions of

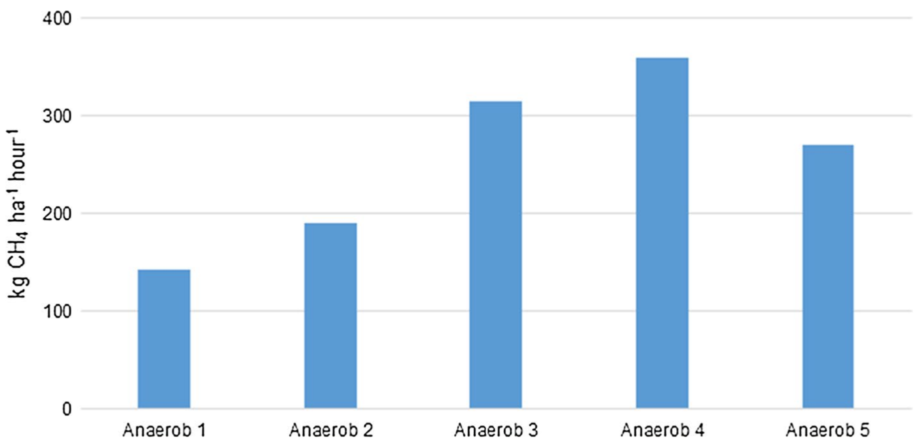

Fig. 5 Overview of averaged CH_4 emissions of all ponds at the palm oil mill

144 kg CH_4 per active pond hectare per hour. Pond 2 which still had a belt filter press pump in use three weeks prior to the observation period from October to December 2016 emitted 191 kg CH_4 per active pond hectare per hour. An average emission value of 1280 kg CH_4 for the whole WWTP facility of the oil mill in question was generated by totaling the average emission for each pond during the observation period.

Figure 6 shows the CH_4 emission reduction in one pond when comparing the average emissions from ponds 3, 4, and 5 without solids separation to pond 1 with a belt filter press. The reduction in CH_4 emissions in a single pond is 54% in the case of the studied palm oil mill. The overall reduction in POME treatment is 11% when reduction with one belt filter press is averaged over a system of five ponds.

POME and belt press cake sample measurements showed averages of 1.6% TOC (variation of 1.26–1.75%) and 5.3% dry matter in raw effluent from the POME inlet; 0.5% TOC (variation of 0.39–0.74%) and 2.5% dry matter in the final POME discharge; and 3.3% TOC (variation of 2.45–3.71%) and 15.5% dry matter in the belt press cake. The averages are weighted per the amount of samples in each measuring month. The concentration of dry matter in the raw effluent is in the range of variation recorded in the literature (Poh et al. 2010; Chin et al. 2013; Loh et al. 2017). The effect of 27 metric tons of removed belt press cake equals 0.89 t of removed carbon per day with a 3.3% carbon content. This equals 13% of the incoming POME carbon content.

The maximum methane formation potential is 1.335 kg CH_4 for every kg of carbon removed. This is based on the molecular weight of both methane (16.04 g mol^{-1}) and carbon (12.01 g mol^{-1}). To take into consideration the fact that not all of the carbon will be converted into methane as some carbon dioxide (CO_2) is also formed, a methane correction factor of 0.8 has been introduced, based on IPCC wastewater methodology, AMS-III H (UNFCCC 2015). To account further for other uncertainties related to, for example, TOC analysis, minimal CH_4 emissions from the belt press cake, or sedimented carbon, an uncertainty factor of 0.94 should also be applied, based on a list of IPCC conservativeness factors for different uncertainty levels (UNFCCC 2003). The methane global warming potential GWP_{100} is 28 according to IPCC AR5 (IPCC 2013). This will result in an *overall methane formation factor of 28.1 kg of carbon dioxide equivalent (CO_{2e}) per each kg of*

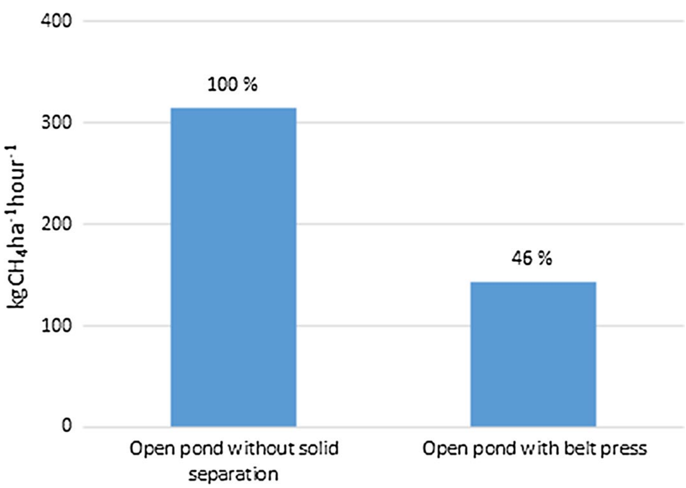

Fig. 6 CH_4 reduction in one pond with belt filter press system

carbon. The complete GHG reduction potential of a belt filter press is calculated with formula (2).

$$\begin{aligned} & CO_{2e}\ \text{emission reduction}_{beltfilterpress}[\text{tons}] \\ & = \text{Carbon content}_{beltpresscake}[\text{tons}] * \frac{16.04}{12.01} * 0.8 * 0.94 * 28 \end{aligned} \quad (2)$$

4 Discussion

There was a significant difference between single-pond CH_4 emissions from pond 1 and the average of ponds 3, 4, and 5 (Fig. 6). Pond 2 also resulted in lower CH_4 emissions than the baseline ponds: It can be assumed from the average CH_4 emissions from pond 2 that it was in some intermediate state between "baseline" conditions and "belt filter press" conditions due to the earlier utilization of the belt filter press prior to the measurement period. However, the emission dynamics were rather high and no temporal or other trends could be read from the data analysis during the observation period. The air and water temperatures were regarded as stable from which no influence on emission changes could have derived, and it is assumed that conditions within the ponds do not follow any daily dynamics.

The 890 kg of total organic carbon per day removed from the POME results in considerable amounts of avoided emissions from the wastewater ponds, as the carbon in the ponds would convert into biogas, including methane, if left in the pond (Yacob et al. 2006; Chin et al. 2013). This confirms the CH_4 measurement results, which gave an indication of a significant reduction of emissions with the belt filter system. The correlation of measured methane reduction (11%) and the reduction in total organic carbon (13%) is shown in Fig. 7.

In the mill in question, the effect of 27 metric tons of removed belt press cake is equal to 0.89 t of removed carbon per day. Further calculated with formula (2) with the IPCC methane global warming potential value of 28, the daily GHG

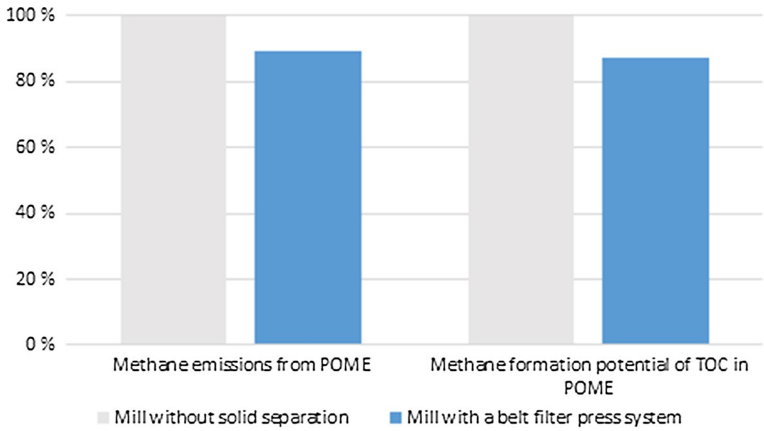

Fig. 7 Correlation of total CH_4 emission reduction and the reduction in CH_4 emission formation potential of TOC. Left-side pillar pair show the CH_4 emissions for a hypothetical POME treatment with five ponds without solid separation were compared to emissions of another hypothetical POME treatment with four similar average baseline ponds plus one pond with a belt filter press. Right-side pillar pair show the CH_4 emission formation potential of TOC in POME ponds without and with solid separation

formation potential of the belt press cake carbon would have been 24.9 t CO_{2e}. Assuming 260 operational days per year, this would result in approx. 6500 t of prevented CO_{2e} annually and a reduction of 0.16 kg CO_{2e} per kg of CPO in this particular palm oil mill with a daily production of 156 metric tons of CPO. When using a global warming potential factor of 23 for methane as defined in the EU renewable energy directive (EC 2009), the reduction amounts to 0.13 kg CO_{2e} per kg of CPO.

The carbon mass balance of all five ponds at the case mill based on TOC measurements of daily POME inlet and outlet and belt press cake flows in the mill's wastewater treatment system indicates that one belt filter of this capacity removes 13% of the carbon from POME and that the POME outlet contains 22% of the organic carbon of POME inlet. This still leaves a theoretical maximum potential of half of the incoming POME to be converted to methane, and approximately 10% to be released as carbon dioxide, when applying the IPCC wastewater methodology for methane and carbon dioxide conversion (UNFCCC 2003, 2015).

There were 445 palm oil mills in Malaysia in 2015 (Loh et al. 2017), of which 246 had a biogas plant either installed, under construction, or being planned. If the remaining 199 mills were of average size and were to install a belt filter press into one of their POME ponds, it would prevent 1.3 million metric tons of annual GHG emissions in Malaysia when using the IPCC emission factor of 28 for methane (IPCC 2013). This represents 7% of Malaysian POME GHG emissions in 2015 (18.15 million t CO_{2e}) (Loh et al. 2017).

5 Conclusions

According to the mill, the belt filter press has played a significant role in improving the wastewater quality and WWTP management practices. The theoretical calculation based on the carbon content of the wastewater shows that a belt filter press also has a significant role in climate change mitigation when removing the carbon from the wastewater. The actual CH4 measurement results give a similar indication with significantly decreased CH4 emissions in the ponds where the belt filter system was, or had been in use. Taking into account the complexity of CH4 measurements and uncertainties related to the measurements, analyzing TOC from belt press cake appears to provide a simple method worth consideration when estimating the GHG formation potential of palm oil mill wastewaters, based on the carbon load.

The methane capture system is more efficient in terms of methane reduction than a belt filter press. However, in cases where the mill is located too far from the electrical grid to feed the excess electricity, or where the mill is not large enough to efficiently utilize methane capture, the belt filter press method is a sensible solution and an excellent plan B for reducing methane emissions. Unlike methane digestion tanks, the belt filter press facility has a net energy requirement to operate, and some chemicals are needed to form good flocs and hence optimize organic matter separation from the POME. Based on KLK's experience, the investment costs of a methane capture system, in contrast, are about 30 times higher than for the belt filter press system. This easily makes up for the moderate operational costs. Also, usage of the carbon-rich filter cake as a soil enhancer reduces fertilizer costs at the plantation.

Both the amount of belt press cake produced per day and its organic carbon content have a significant impact on the palm oil mill GHG emissions. Even further benefits could be achieved by installing more belt filter press capacity and possibly treating more than one of the palm oil mill's anaerobic ponds at a time, so that more of the carbon is removed from the ponds. However, the calculation of the emission factor introduced in this study may only apply with proof of an actively running belt filter facility, including records of belt press cake volumes. In addition, the actual carbon content of the produced belt press cake must be analyzed by an authorized laboratory; TOC should be systematically measured several times per year at the palm oil mill in question, in both high and low crop seasons, for a longer period of time. If TOC level averages remain stable, the sampling frequency may be reduced.

The observations in this study represent small temporal frames and a small fraction of many variations of open POME pond management from KLK, and there are several uncertainties included in the measurements and in the results. Representative sampling is essential in emission calculation. Further comprehensive studies are suggested to investigate whether the findings made here can be further generalized.

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