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COMPARING PHOSPHORUS RECOVERY AND OPTIMUM TIME DIGESTION FROM SINGLE AND MIXING SUBSTRATES BY USING ANAEROBIC MESOPHILIC DIGESTION TECHNIQUE

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ABSTRACT

Phosphorus (P) is considered a limited and non-renewable mineral source that is essential in our daily lives, especially for the agricultural industry to produce fertilizer. Food Waste (FW), Palm Oil Mill Effluent Sludge (POMES), and Water Treatment Sludge (WTS) are wastes that are claimed to contain nutrients such as P. One of the methods that can be used to recover P is through the Anaerobic Mesophilic Digestion (AMD) technique. Therefore, this study was carried out to investigate the highest P recovery and time digestion from single and mixing substrates. The physicochemical and biological properties of raw FW, POMES, and WTS were determined, and it was reported that wastes were suitable to undergo the AMD process. Mesophilic conditions 35^0C (±1) were used as the appropriate conditions for the anaerobic bacteria (AB) to reproduce and grow. Results for single substrates found that POMES recovered the highest P with 57.88% (±1.24), and optimum digestion was at day 12. While FW and WTS recovered P with 31.94% (±0.76) and 26.47% (±1.51), respectively, the optimum digestion times for both wastes were at days 18 (FW) and 21 (WTS), respectively, which were longer than POMES. In mixing substrates, FW-POMES contributed to the highest P recovery value with 68.34% (±1.49), and the optimum time digestion was on day 9. Followed by WTS-POME, FW-WTS, and FW-POMES-WTS with values of 60.42% (±2.12) (day 15), 48.05% (±2.51) (day 8), and 20.85% (±1.33) (day 3), respectively. The better synergetic effect within anaerobic bacteria (AB) in mixing substrates with FW-POMES could eventually influence the highest P removal from the substrate in a short period of time. Moreover, this study also provides information on new strategies used in recovering P.

Keywords: Phosphorus recovery, Food Waste; Palm Oil Mill Effluent Sludge; Water Treatment Sludge; Anaerobic Mesophilic Digestion

Introduction

Despite its existence as a nuisance to the environment, P is reported to be depleted 50-100 years, with the only source of P is from phosphate rock. P is also one of the important components in fertilizer (Witek-Krowiak *et al*., 2022; Zhang *et al.,* 2023). It is used in the agricultural sector to maintain the production of crops. Generally, P plays a role in photosynthesis, respiration, and energy storage and transfer (Cheng *et al.,* 2020). Nowadays, extensive studies have been carried out to recover P from waste as an alternative to phosphate rock. Anaerobic mesophilic digestion (AMD) is one of the favorable techniques for recovering P (Vidal-Antich *et al.,* 2022). This technology earns several points over others as it is a natural biological process that uses microorganisms to degrade organic waste under mesophilic conditions. Besides that, a study by Rabii *et al.* (2019) has identified this recovery system as technically and economically feasible for various waste feedstock for recovering nutrients such as P. In recent years, AMD from mixing substrates has been considered, as the technique can improve digestion efficiency and directly increase product output compared to single substrates (Meegoda *et al.,* 2028; Mohammed Kelif *et al.,* 2022). According to Agnieska *et al*. (2023), mixing substrates in one digestion process could help increase the synergetic effects between the bacteria as the co-substrates supply the missing nutrients in the digestion medium. Food waste (FW) contains high moisture content and is a readily biodegradable in nature hence, it is the most challenging type of waste for disposal management. According to Xu *et al.* (2018), FW containing high phosphorus (P) (4.0 g P/Kg TS) content makes it appropriate to be used as a resource for P recovery. Palm oil mill effluent sludge (POMES) refers to the sludge that forms in the open dumping pond. Generally, the oil palm industry produces about 60% of raw POME, which is then dumped into the open pond system. It is a cheap treatment method compared with other treatments (Islam *et al.,* 2018). A study of POMES by Mohammad *et al.* (2021) has mentioned using POMES as organic fertilizer as it contains micronutrients such as P. Besides that, the study lists the existence of anaerobic digestion (AD) bacteria, such as acidogenic bacteria. These bacteria are important in the AD process, which is, in fact used for the recovery of P. Water Treatment Sludge (WTS) is a waste or residue that is produced in water treatment plants during the purification of raw water and is usually dumped directly into sea or river. Nevertheless, this approach could lead to the formation of undesirable mud and affect the source of water through the contamination of chemicals used in water treatment. A Previous study by Selaman *et al.* (2019) reported that WTS contains micronutrients such as P and microorganisms that could help in the degradation of the nutrient. Therefore, this study aims to identify the highest P recovery and the optimum time of digestion from single and mixed waste.

Methodology

Analytical methods

The standard procedure for determining the physicochemical and biological properties of the raw materials was done according to Selaman (2021). Determination of the volatile solid (VS) content, total carbon (TC), total nitrogen (TN),total volatile fatty acid (TVFA), and total anaerobic bacteria (AB).

Table 1: Physicochemical and biological properties of raw FW, POMES, and WTS.

Parameters	FW	POMES	WTS
Volatile solid (VS) (%)	98.56± 0.04	85.20 ± 0.08	13.04± 0.04
Carbon to Nitrogen (C:N) ratio	13.72	18.54	9.16
Total volatile fatty acids (TVFAs) (mg CH_3COOH/L)	415.43 ± 0.93	4156.78 ± 3.05	200.24 ± 4.98
Total anaerobic bacteria (AB) (CFU/g)	3.10 $x10^2$	7.25 x 10^7	8.10 $x10^4$

Anaerobic mesophilic digestion of single and mixing substrates

The experimental work was performed using a Duran Bottle with a working volume of 400 mL. The schematic diagram of a simple batch mesophilic reactor can be found in Figure 1. Digestion tests were performed in a mechanical incubator shaker. The substrates to distilled water ratio were fixed at 1.5:1.0. While the temperature was set up at mesophilic conditions 35^0C (±1), and the mixing speed was 80 rpm. The Duran bottle was charged with FW, and pH was controlled at 6.0 by using 1.0 M HCl and 1.0 M NaOH. The digestion time for each digester was set up for 30 days, as suggested by a previous study by Selaman (2021). During the experiment, a small sample was taken out once every three days to determine the P recovery. The concentration of P was determined by using a Cary 60 UV-visible spectrophotometer at a wavelength of 880nm. The procedure was repeated for single substrates (POMES and WTS) and mixing substrates (FW-POMES, FW-WTS, WTS-POMES, and FW-POMES-WTS).

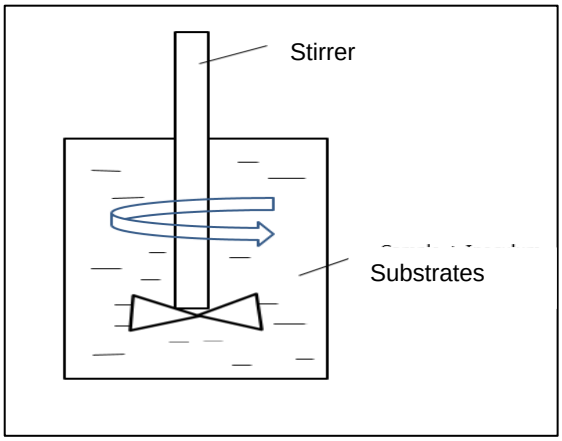

Figure 1: Schematic diagram of simple batch mesophilic reactor

Results and Discussion

P recovery in single substrates

Figure 2 presents the results obtained from the analysis of each substrate after 30 days of digestion. The data for POMES showed the highest P recovery with 57.88 % (±1.24). The P recovery increased from day one until day 12 digestion and then significantly decreased until

day 30. This is followed by FW with a P recovery of 31.94 % (±0.76). During the digestion process, P recovery started to increase from day one digestion until day 18 and then continued to decrease until day 30. While the lowest P recovery is shown in WTS with 26.47% (±1.51). The highest P recovery was shown on day 21, and from then on, it decreased until day 30 of digestion.

Based on the figure, POMES showed the highest P recovery value. This could be due to the fact that the VS value of POMES is higher compared to FW and WTS (Table 1). Total VS indicates the content of organic content in the substrates; a higher VS value indicates higher nutrient recovery (Mohammad *et al.,* 2021). Aside from that, this could also be due to the better carbon to nitrogen (C:N) ratio in POMES (Table 1). As mentioned by Maria *et al.* (2022), C:N ratio is an important parameter that influences the digestion process since it helps in building positive synergism in the digestion medium, which can contribute to the highest recovery of nutrients such as P. Moreover, the characteristic of POMES, which had already undergone fermentation during the long retention time (40-60 days) in treatment ponds, enabled it to contain a high total AB, which would help in degrading the structure and directly remove the P in the form of ortho-P. Therefore, this could also be the reason for the higher P recovery in POMES compared to the other substrates.

Surprisingly, the highest P recovery for POMES digestion was shorter (day 12) compared to FW. This is likely due to the higher initial TVFAs values of POMES (Table 1), which could promote the production of TVFAs at early digestion and contribute to higher P recovery. The optimum digestion day of 12 days for POMES also suggests that POME has a higher digestion rate compared to FW and WTS, in which the optimum time was 18 and 21 days, respectively. The decrease in P recovery in all single substrate digestions could be due to the accumulation of TVFAs (Choi *et al*., 2023).

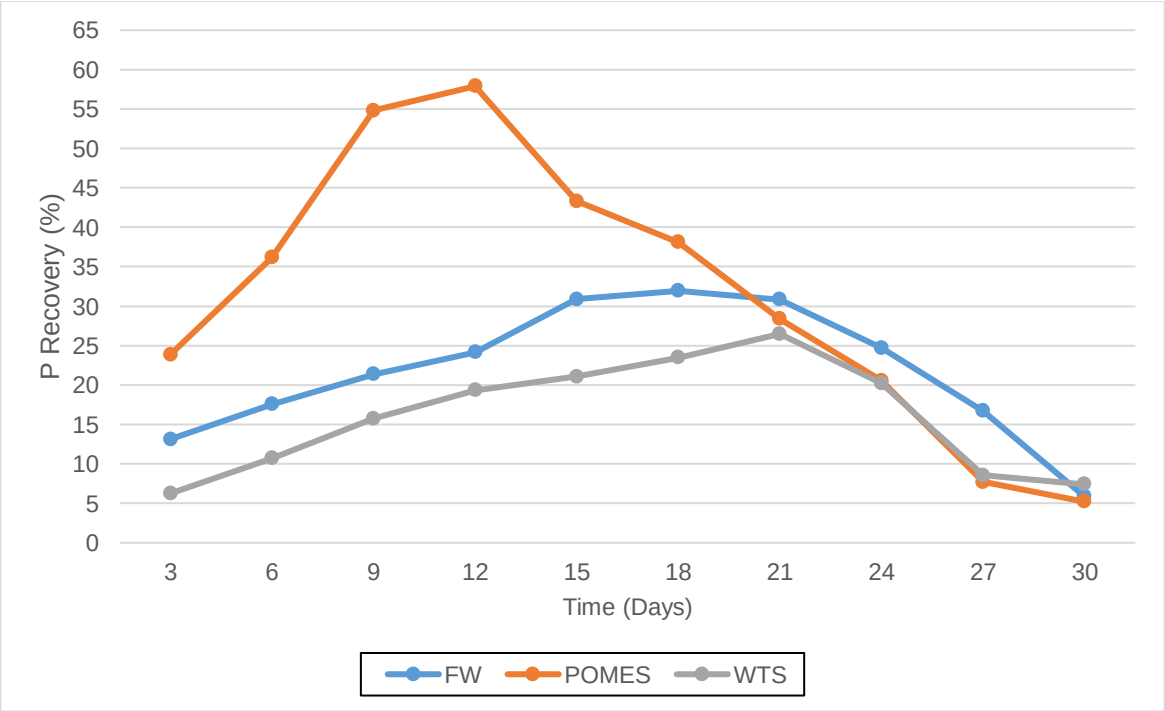

Figure 2: AMD of FW, POMES and WTS at 30 days of digestion time

P recovery in mixing substrates

Figure 3 shows the results from mixing substrates. From the results, it showed that the mixing substrates between FW-POMES contributed to the highest P recovery value with 68.34% (±1.49). From the graph, it showed that P gradually increased starting from day 1 until day 9 of digestion and then significantly decreased until day 30 of digestion. This was followed by mixing substrates WTS-POMES with a P recovery value of 60.42% (±2.12). During the digestion process, P removal from the substrate slightly increased from day 1 until day 15, and then continued to decrease until day 30. While mixing substrate, the FW-WTS value was 48.05 % (±2.51). The highest P recovery was shown at day 18 and slightly decreased until day 30 of digestion. While mixing substrates between FW-POMES-WTS showed a decreasing value of P starting from day 3 until day 30 of digestion. The accumulation of acid would be the cause of the P decline. A higher value of TVFA will lead to the instability in digestion performance and acidogenesis bacteria activity; therefore, mixing these three substrates in one reactor is not recommended.

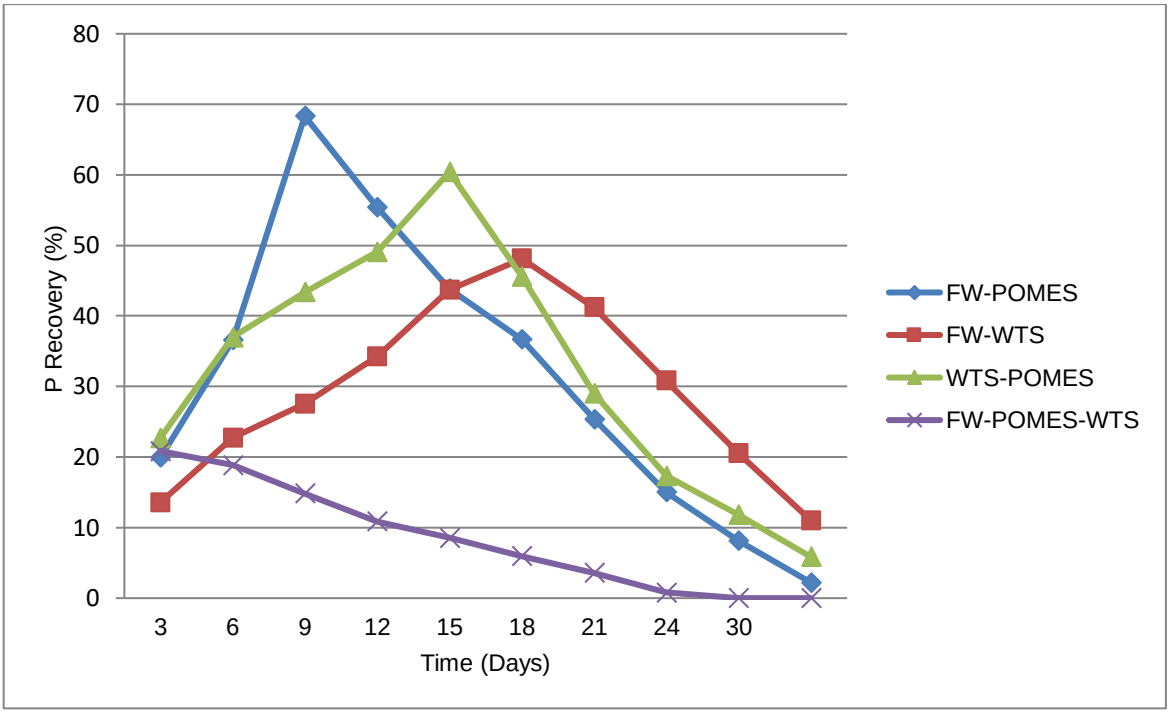

Figure 3: AMD of FW-POMES, WTS-POMES, FW-WTS, and FW-POMES-WTS at 30 days of digestion time

In this study, mixing substrates between FW and POMES shows the highest P recovery compared to the others (Figure 3). The total VS of both FW and POMES in Table 1 could explain the higher value of P recovery by mixing both in one reactor. Total VS indicates the organic content in the substrates (Agnieska et al., 2023). In addition, mixing FW and POMES could form a better C:N ratio compared to other mixing substrates, thus affecting product recovery during the AD process, which explains the highest value of P recovery (Zhang et al., 2023). Moreover, the P recovery value was also higher compared to the results of single substrate digestion of both substrates (Figure 1). This might be due to the combination of FW and POMES that have better synergetic effects between both substrates' bacteria during the AD process, which in turn help in enhancing P removal from the substrates (Mohammed Kelif et al., 2022). Besides that, Rabii et al., (2019) also mentioned that mixing substrates in one AD

process could help in increasing the efficiency of the process as the co-substrates will help to supply the missing nutrients in the digestion medium. This finding suggests that a mixture of FW and POMES can greatly be used to increase the AD product, which is P. Interestingly,the results also showed that the optimal days of P recovery during the digestion process for all mixing substrate became shorter as compared to single substrates digestion (Table 2). This finding showed that the appropriate composition of organic matter in one reactor would affect the growth and performance of bacteria in increasing P recovery.

Table 2: Comparison of P recovery and optimization time using single and mixing substrates

	Single Substrates			Mixing substrates			
	FW	POMES	WTS	FW & POMES	FW & WTS	WTS & POMES	FW, POMES & WTS
P Recovery (%)	31.94 (±0.76)	57.88 (±1.24).	26.47 (±2.51).	68.34 (±1.49).	48.05 (±2.51).	60.42 (±2.12).	20.85 (1.33).
Optimum digestion time (day)	18	12	21	9	18	15	3

According to Choi *et al.* (2022), the higher TVFAs value would eventually help in increase the P removal from the substrates. However, the increasing in the concentration value could lead to the accumulation of TVFAs. A similar report by Abraham *et al.* (2023), stated that a higher TVFAs concentration leads to decrease in P values. Therefore, TVFAs are considered one of the key factors that can influence P removal from the substrates. This may also be due to the high nitrogen value, which could lead to an increase in pH (Eq. 2.6). According to Wid *et al.* (2017), increasing pH causes the inhibition of acidogenic bacteria's performance and, as a result, decreases the P removal from the cell.

Conclusions

This study suggests that in single substrate digestion, POMES can recover the highest P value with 57.88 % (±1.24) and the optimum time was shorter (Day 12) compared with FW and WTS substrates. This could be due to the initial highest values of VS, C:N ratio, and TVFAs in POMES, which promote a better synergetic effect within the AB and hence influence the highest P removal from the substrate. While mixing substrates, digestion between FW and POMES recovered the highest P value with 68.34% (±1.49), and optimum time was shorter (Day 9) compared with other mixing substrates. This may be due to the fact that the co-substrates supplied the missing nutrients in the digestion process and promoted a better synergetic effect in the digestion medium. Eventually, these results show that mixing substrates can enhance P recovery compared to others. Ultimately, the data show other substrates also contained P that can be recovered through the AMD process.

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