

## CO-DIGESTION OF FOOD WASTE AND RUBBER SLUDGE FOR BIOGAS PRODUCTION

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### Abstract

Food waste (FW) constitutes nearly one-third of all food produced globally and is rich in carbohydrates, proteins, and lipids, making it a suitable substrate for anaerobic digestion (AD) to produce biogas. However, the variable organic content in FW often causes instability in the AD process, leading to low biogas yields. This study explores the potential of using rubber sludge (RS) as a co-substrate in the co-digestion of FW to enhance system stability and increase biogas production. The characteristics of RS were characterised using SEM-EDX, BET surface area analysis, and CHNS elemental analysis. The study evaluated different feedstock ratios (FW:RS), retention times, and pH levels towards cumulative biogas yield. The porous structure and high carbon content of RS has supported microbial activity, thereby improving process stability. Moreover, trace mineral elements (TMEs) in RS contribute positively to the process, and inclusion of RS helps optimise the carbon-to-nitrogen (C/N) ratio of the substrate. However, the surface area of RS did not directly correlate with higher biogas yield. The co-digestion process showed an increase in cumulative biogas yield from 632 ml to 845 ml at FW:RS of 100:0 to 70:30. The yield further improved to 1320 ml at an optimal retention time of 28 days and rise to 1725 ml at pH 8. These findings highlight the potential of RS in stabilising AD systems and enhancing biogas production, providing a practical approach for improving AD of FW.

Keywords: Biogas, Co-digestion, Food waste, Rubber sludge.

## 1. Introduction

It is well known that the utilisation of energy by the world is dependent on fossil fuels, such as coal, petroleum, and natural gas. Tragically, the broad reliance on these conventional energy sources may lead to various serious environmental issues including climate change, global warming and greenhouse gases. Besides that, those types of energy sources create an energy crisis due to their progressive depletion over time. To curb energy crisis, one of the leading solutions is by substitution of biomass that can be claimed as renewable energy source and a means of environmental protection. Hence, the substitution of fossil fuels with biomass represents a viable renewable energy strategy to mitigate resource depletion while reducing adverse environmental impacts [1].

Biogas is one of the renewable energy sources produced from the anaerobic digestion (AD) of organic matter and consists of specially 55-65% of methane, 35-45% of carbon dioxide and other different impurities which might be found in hint quantities together with hydrogen, oxygen, nitrogen, hydrogen sulphide and water [2, 3]. Food waste (FW) which consists of carbohydrates, protein and lipids is one of the promising feedstocks for biogas production due to its capability substrate withinside the AD technique to provide methane. By utilisation of FW as feedstocks for biogas production, it can bring out serials of environmental problems if it is not being disposed or treated properly, since FW has high organic content, high moisture content, high fat, and high salt [4]. Hence, these dual attributes will lead to resource utilisation and the solution of environmental pollution.

However, problems related to instability of organic contents in FW, low biogas yield and even process failure continue to occur when FW is digested as the only substrate in long-term operation. Several researchers have performed the AD of FW and concluded that due to the buildup of total ammonia nitrogen (TAN) and volatile fatty acids (VFAs), low pH value, imbalance of carbon-to-nitrogen (C/N) ratio and inadequate trace elements withinside the AD technique of the FW has run to low methane degradation for biogas yield [5]. To overcome these shortcomings, co-digestion of FW and co-substrate appears to be among promising approaches for inconsistency of organic content in FW which end up with inhibitory compounds, acidification of substrate, inappropriate amounts of inorganic substance, and absence of trace elements compare to single FW substrate in AD [6].

Malaysia, Thailand, Indonesia, Vietnam, China and India are among the main rubber producers globally as those figuring to over 90% of total rubber production in the world [7, 8]. Consequently, the enormous amounts of wastewater reported have been released from the rubber industry into the environment as the processes deal with the latex concentrate and standard block rubber.

Therefore, rubber industry wastewater must be treated before discharge into common water bodies. At last part of the treatment process, rubber sludge (RS) was produced, and it can be converted to another valuable product to facilitate energy and environmental issues with minimal operation cost. Previous studies have shown the potential and performance of RS as carbonaceous materials for enhancing biogas production and adsorbent in removing contaminants in wastewater [9-12].

Although anaerobic co-digestion has been widely applied to overcome the operational instability associated with FW mono-digestion, persistent challenges such

as rapid acidification, nutrient imbalance, and unfavourable C/N ratio continue to limit process efficiency and methane recovery. Existing studies have primarily focused on conventional agricultural and municipal co-substrates, while the potential utilisation of industrial wastewater treatment residues remains largely underexplored. RS generated from rubber processing wastewater treatment plants represents an abundant yet underutilised biomass with potential buffering capacity and micronutrient availability, but its applicability in AD systems has not been previously reported.

Therefore, this study investigates the feasibility of employing RS as a co-substrate for the anaerobic co-digestion of FW to improve digestion stability and biogas production performance. The novelty of this work lies in valorising rubber industry sludge as a functional co-substrate capable of regulating substrate acidification, optimising nutrient balance, and enhancing microbial activity, thereby establishing a novel waste-to-energy pathway that promotes synergistic integration between industrial sludge management and organic waste treatment.

## 2. Experimental

### 2.1. Materials and chemical

The FW was collected in the recycle bin from cafeteria at Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Kuantan, Pahang. Then it was meshed and stored in a container and refrigerated at 4 °C prior to characterisation (Fig. 1(a)). Meanwhile, the RS as a co-substrate was acquired directly from wastewater treatment plant at FGV Rubber Industries Sdn Bhd, Chenor, Pahang (Fig. 1(b)). A primary sludge sampling point was identified and selected for sample collection. These sampling points were chosen to obtain well-mixed samples and representative cross-sections of the entire flow. The collected co-substrate was also stored in a refrigerator set at 4 °C prior to characterisation. Hydrochloric acid (HCl, 99%) and sodium hydroxide (NaOH, solid pellets) were supplied by Merck and used for pH adjustment during the study.



**Fig. 1. (a) Meshed FW, (b) Rubber sludge collection, (c) Collected rubber sludge.**

### 2.2. Characterisation of food waste

The characterisation of FW was done by following the methods from Bayrakçeken et al. [13] without any adjustment.

#### 2.2.1. Determination of moisture content in food waste

The moisture content in FW was measured by thermogravimetric method. The principle of determining moisture content was based on the loss of mass that occurs

when the material is heated. The mass of the sample substance was measured before and after the drying process to determine the final moisture content on a percentage basis (Eq. 1).

$$\% \text{ Moisture} = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

where,  $W_1$  = Weigh of sample before drying (g) and  $W_2$  = Weigh of sample after drying (g).

### 2.2.2. Determination of total carbohydrates in food waste

Carbohydrate content in FW was calculated using equation in Eq. (2).

$$\% \text{ Carbohydrates} = 100 - (\text{Moisture} + \text{Protein} + \text{Ash} + \text{Fat}) \text{ in g} \quad (2)$$

### 2.2.3. Determination of protein content in food waste

Protein content was measured by Kjeldahl method. Hot acid digestion was used to break down the protein into ammonia, which was then distilled into a standardised acid and the excess acid back-titrated to obtain the estimated value. A catalyst is required for the conversion of organic nitrogen to ammonium sulphate. The calculation is shown in Eq. (3).

$$\% \text{ Protein} = (A-B) \times N \times 14.007 \times \frac{6.25}{w} \quad (3)$$

where, A = Sample titration was conducted with volume of 0.2 N HCl (ml); B = Blank titration was conducted with volume of 0.2 N HCl (ml); N = Normality of HCl; W = Sample weight (g); 14.007 = Atomic weight of nitrogen; 6.25 = Conversion factor of protein nitrogen.

### 2.2.4. Determination of lipids in food waste

Lipids in FW were measured through gravimetry methods. A lipophilic solvent was used to extract the prepared sample. After extraction the solvent was expelled, and the dry residue was weighed. The equations used to determine the lipid content are shown Eq. (4).

$$\% \text{ Lipids} = \frac{\text{Weight of extracted lipids (g)}}{\text{Initial sample weight (g)}} \times 100\% \quad (4)$$

## 2.3. Characterisation of rubber sludge

To examine the surface morphology and element distribution of RS, scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX, Hitachi, Japan) was used. Whereas, to compute the specific surface area, The Brunauer-Emmett-Teller (BET) model (TriStar 3000, Micro-Metrics, USA) was employed. Next, a Carbon Hydrogen Nitrogen Sulphur (CHNS) analyser was used to measure the composition of C, H, N, S in RS.

## 2.4. Co-digestion of food waste and rubber sludge

The co-digestion experiments were conducted using 500 ml Scott bottles as anaerobic digesters. FW and RS were mixed at designated ratios, with deionised water added to achieve a final working volume of 250 ml. Deionised water is used

to ensure high purity in experimental processes. By using deionised water, the presence of organic and inorganic contaminants can be minimised, and contributes to a quality standard in experimental procedures, further supporting sustainable and reliable research practices [14]. To ensure anaerobic conditions, nitrogen gas was flushed into each digester for one minute before sealing with airtight stoppers. All digesters were incubated under mesophilic conditions at 37 °C and gently agitated twice daily to enhance substrate-microorganism contact.

A blank control containing only FW and deionised water was prepared to compare the effect of co-substrate addition. In this study, FW was considered the main substrate, while RS was incorporated as a co-substrate to improve digestion stability and biogas yield. A RS-only control was not included, as the scope of the work was to investigate its synergistic effect rather than its independent potential. The experiments were performed in three sequential batches under a one-factor-at-a-time (OFAT) design. In the first batch, different FW:RS feedstock ratios (100:0, 70:30, 50:50, 30:70 and 10:90) were tested to determine the most efficient combination for biogas generation. Using the optimal ratio obtained, the second batch evaluated the effect of initial pH (4, 5, 6, 7, and 8) on biogas yield. In the final batch, the effect of retention time (7-35 days) was studied, while feedstock ratio and pH were maintained at previously optimised conditions. The reactors were run in duplicate to ensure the reliability of the results. The experimental design is summarised in Table 1.

**Table 1. Parameter study for co-digestion of food waste and rubber sludge.**

Parameter	Description	Parameter
Feedstock ratio (FW:RS)	100:0, 70:30, 50:50, 30:70 and 10:90	Feedstock ratio (FW:RS)
pH	4, 5, 6, 7 and 8	pH
Retention time (Days)	7, 14, 21, 28 and 35	Retention time (Days)

## 2.5. Biogas measurement and composition analysis

The cumulative biogas yield was quantified using the water displacement method, where the volume of displaced water in ml was recorded as the corresponding volume of biogas generated in ml (normalised to standard temperature and pressure conditions (273.15 K and 101.325 kPa)). Initially, the initial volume of water in a container was measured. Then, the sample was submerged in the water, triggering the water level to rise, and then the final volume of water was recorded. In addition, the volume of the sample is determined by subtracting the initial water volume from the final water volume.

## 3. Result and Discussion

### 3.1. Characteristics of food waste

The characteristics of FW are tabulated in Table 2. The amount of moisture content in FW is 89.9% which is perfectly suitable for AD that necessary for degradation processes, microbial activity and metabolism [15]. In this study, AD is carried out in submerged (wet) settings based on the moisture content. The condition for this study occurs at solid concentrations lower than 15%. Submerged processes provide benefits including a smaller inoculum demand, shorter retention times, and more volatile solid

reduction [16]. Therefore, the higher moisture content may have contributed to a higher biogas output because of this circumstance in a short period of time.

The three main organic components of FW are carbohydrates, proteins, and lipids which have varying potential in methane degradation for biogas production [17]. The composition of FW in Table 2 revealed a significant amount of carbohydrates in FW of this present study. Carbohydrates are made up of easily hydrolysed and fermentable sugars viably to produce hydrogen acetate and CO<sub>2</sub> which are converted to methane. Being rich in carbohydrates making FW can serve as suitable substrates for microbial growth leading to enzyme production which contributed to a shorter retention time during AD [18].

The presence of proteins in FW should not be higher than carbohydrates to avoid process inefficiencies since protein degrades more slowly than carbohydrates under anaerobic conditions, which can restrain the overall AD process [19, 20]. Moreover, higher percentage of protein may convert to high amino acids content and lead to Volatile Fatty Acids (VFAs) inhibition in AD process (Fig. 2). The occurrence of this inhibitory cause to relatively longer start-up period during AD than expected [21]. Hence, the composition of protein in this study (Table 2) is ideal for successful AD processes [22].

A high lipids content exists in FW also resulting in a slow degradation rate during AD since it can also inhibit the process due to the accumulation of VFAs (Fig. 2) and can cause system failure [23-25]. A lower lipids concentration can prevent scum flotation and clogging during microbial activity. In this study, the percentage of lipids in FW is also lower and there is no necessary pretreatment required to degrade lipids for AD. This should reduce the instability digestion process and potentially lead to a more consistent and higher biogas yield necessarily. It can be expected that the addition of co-substrates during the process should be lower.

**Table 2 Characteristics of food waste.**

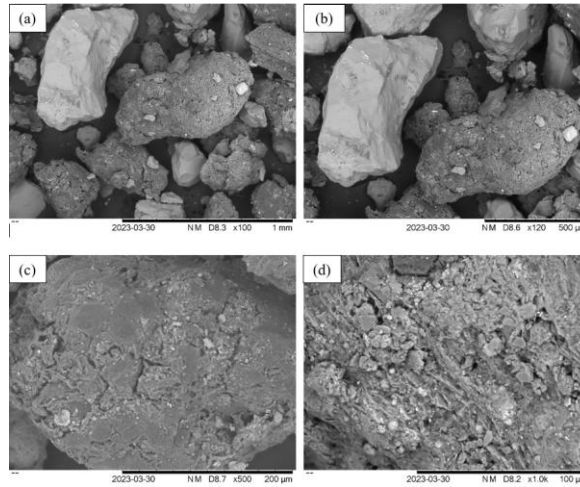
<b>Element</b>	<b>Unit</b>	<b>Result</b>
<b>Moisture content</b>	%	89.9
<b>Carbohydrate</b>	g/100 g	8.1
<b>Protein</b>	%	1.6
<b>Lipids</b>	%	0.1

## 3.2. Characteristics of rubber sludge

### 3.2.1. Morphology analysis

The SEM micrograph (Fig. 2) of RS as co-substrate at various magnification shows that the sludge particles possess highly irregular morphologies with a heterogeneous distribution of shapes and sizes. The particles appear as loosely bound aggregates composed of both coarse fragments and finer granules. The surfaces of many particles are rough and porous, which may facilitate better mass transfer and substrate availability, which are crucial for microbial activity [26] as well as can improve the overall stability of the AD process [27]. This stability is essential for maintaining consistent microbial activity and preventing process failures [28]. The porous structure might contribute from the carbon content in the RS as detected in Table 3. Besides that, some regions display relative cracks, voids,

and embedded smaller particles, suggesting high degrees of heterogeneity which may contribute from the reveal traces of elements in RS.



**Fig. 2. SEM images of rubber sludge (a) 100x magnification, (b) 120x magnification, (c) 500x magnification and (d) 1000x magnification.**

Energy-dispersive X-ray spectroscopy (EDX) was employed to analyse the outcomes from the revealed traces of elements mentioned as in Table 3. The presence and balance of nutrients and trace elements in the co-substrate are crucial because anaerobic bacteria and archaea require both macro and micronutrients to grow and maintain metabolic activities. The absence or deficiency of these elements can significantly inhibit the anaerobic process. Furthermore, trace elements act as cofactors for key enzymes involved in the metabolic pathways of anaerobic microorganisms. These elements are essential for the proper functioning of enzymes that facilitate the breakdown of organic matter and the production of methane [29]. Particularly, those trace elements are important to enhance the conversion of VFAs to methane, thus preventing VFA accumulation and ensuring process stability.

As shown in Table 3, RS is considerably impacted by the small amount of trace metal elements (TMEs) including Mg, Al, Si, P, S, Ca and Fe which are crucial for sustaining the activity of microorganisms and stimulating microbial metabolism. This makes RS a viable co-substrate for food waste during AD process which contributes to methanogenic activity. This is because, if the amount of TMEs is higher, the concentrations will introduce to toxicity and prevent methanogenic bacteria from growing, which reduces methane generation [30]. Moreover, high levels of certain trace elements can alter the chemical equilibrium within the digester [31]. Excessive trace elements also can lead to process instability, characterised by pH drops and reduced biogas production. For example, reactors without optimal trace element balance experienced significant pH drops and biogas production decline, indicating process failure [29].

Apart from that, RS consists of carbon and oxygen. Adding carbon-rich materials like RS to the substrate can significantly increase biogas production. This is due to the improvement in C/N ratio to an optimal value which increased the biogas production [32]. Furthermore, carbon content can help mitigate the

accumulation of VFAs and ammonia, which are common inhibitors in AD [33]. Oxygen supply at the initial stage can accelerate the hydrolysis of substrates, leading to faster degradation of volatile solids. This is crucial for breaking complex organic matter into simpler compounds that can be further processed by anaerobic microorganisms. Introducing oxygen (microaeration) into the anaerobic digester can improve methane yield and volatile solids removal efficiency. This is due to the enhanced activity of certain microbial communities that thrive under microaerobic conditions [34, 35].

**Table 3 Properties of rubber sludge as determined by SEM-EDX analysis.**

Element	Weight %	Atomic %
Carbon	44.483	53.802
Oxygen	46.153	41.908
Magnesium	0.253	0.151
Aluminium	1.508	0.812
Silicon	4.386	2.269
Phosphorus	0.258	0.121
Sulphur	0.356	0.161
Calcium	0.965	0.350
Iron	1.638	0.426

### 3.2.2. Surface area analysis

In anaerobic co-digestion processes, the surface area of co-substrates plays a critical role in influencing microbial activity and substrate biodegradability [36]. When the surface area of the substrate is not high, it can limit the accessibility of hydrolytic enzymes to organic material, reducing the hydrolysis rate, often the rate-limiting step of the digestion process [37]. This low surface area is commonly associated with substrates having dense structures, where compact biomass hinders microbial interaction and enzymatic breakdown, resulting in less effective contribution to overall methane yield despite the organic content.

However, co-digestion with co-substrates possessing complementary properties can mitigate these limitations by improving nutrient availability and buffering capacity, thus enhancing digestion stability and biogas production even when individual substrates exhibit low surface area [38]. Generally, co-digestion tends to yield higher biogas volumes than mono-digestion due in part to increased surface area provided by the co-substrate, allowing better microbial colonisation, nutrient balance, and inhibitor dilution.

Nevertheless, in this study, RS displayed a relatively small surface area of 3.3677 m<sup>2</sup>/g and an average pore diameter of 29.7431 Å, classifying its pores as mesopores (20-500 Å). Adsorption capabilities through these mesopores depend on the unique structure of the RS, with liquid-solid adsorption mechanics influenced by pore characteristics. Interestingly, larger surface area and pore volume did not correlate with higher biogas and methane yields in this case. The relatively low surface area of RS may be attributed to greater graphitisation of carbon in the presence of elements such as magnesium, silicon, and iron found within the sludge, which likely affected its structural properties and adsorption behaviour. This reveals that while surface area is important, other physicochemical factors also significantly impact biogas production efficiency from co-substrates like RS.

### 3.2.3. Elemental analysis

The production of biogas through co-digestion is influenced significantly by the chemical composition of the co-substrates to improve the stability of the system for enhancing the biogas yield due to the inconsistency of the organic content in the substrate. In the present study, CHNS composition analysis was done to quantify the weight percentages of carbon, hydrogen, nitrogen, and sulphur (C, H, N, S) in RS. Carbon is a fundamental element in biogas production, primarily contributing to the formation of methane.

The carbon content in RS is crucial to promote microbial processes that convert organic matter into biogas. Besides that, the carbon content in RS will contribute to the C/N ratio of the substrates. An optimal C/N ratio ensures efficient microbial activity and maximises biogas production. Among all the compositions in Table 4, carbon led the highest percentage, and this finding is aligned with the porous structure present in SEM micrograph.

Besides that, hydrogen is important during methanogenesis stage, where hydrogenotrophic methanogens convert hydrogen and carbon dioxide into methane [39]. However, the composition should be controlled as it can cause the existence of inhibitory compound thereby disturb the microbial processes [40, 41].

Nitrogen is also essential for microbial growth yet must be balanced with carbon as it affects the C/N ratio in overall substrates. The excess nitrogen in the substrates can lead to ammonia inhibition which reduces the biogas yield. In this study, C/N ratio of RS is 58:1 showing there is insufficient nitrogen to maintain microbial biomass. This may lead to rapid nitrogen depletion and reduced microbial growth. Hence, by combining this high C/N ratio with FW, it can help maintain the desired balance.

Apart from that, sulphur has two sides when it comes to producing biogas. While it is necessary for certain microbial processes, its presence as hydrogen sulphide can be unfavourable. In conclusion, the elements C, H, N, and S play significant roles in biogas production. Optimising their levels through co-digestion and other techniques can enhance biogas yields and quality, making the process more efficient and sustainable.

**Table 4 Properties of rubber sludge as determined by C, H, N and S analysis.**

Parameter	Average Results %
Carbon	22.58
Hydrogen	6.17
Nitrogen	0.39
Sulphur	1.76

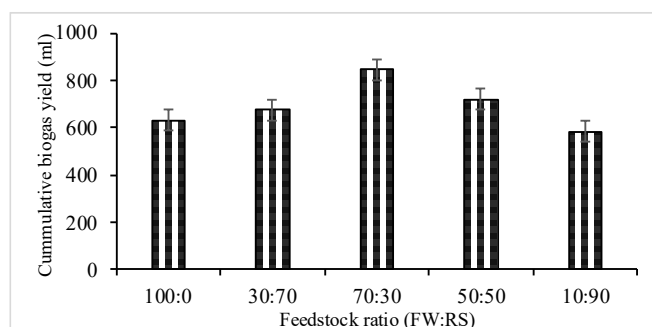
## 3.3. Parametric study of co-digestion process

### 3.3.1. Effect of feedstock ratio

The fundamentals for a steady process performance include an improved nutrient balance and a greater C/N ratio in organic wastes, both of which are produced by the co-digestion of FW with RS. In other words, the nutrient deficiency in FW might be made up for by the addition of RS which has raised the low C/N ratio of

the FW. Since there is a better nutrient balance and C/N ratio with the inclusion of co-substrate, the process performance and biogas yield may be improved. As calculated from Table 4, the C/N ratio of RS used can contribute to the C/N ratios of the FW leading to improving the stability of the substrate.

Figure 3 displays the cumulative biogas yield in ml for the co-digestion of various FW and RS ratios. After 14 days of the process, the extended dataset of feedstock ratios revealed that the cumulative biogas yield increased progressively from 100:0 to 70:30, peaking at 845 ml. Beyond this ratio, the yield began to decline gradually with increasing RS proportion. This indicates that the presence of RS at moderate levels supplies essential trace elements and balances the C/N ratio, enhancing microbial activity which contributes to stability of the system as well as the process. However, excessive inclusion of RS (>30%) reduced the yield due to concentrated nutrients and potential inhibitory effects.



**Fig. 3. Cumulative biogas yield based on feedstock ratio.**

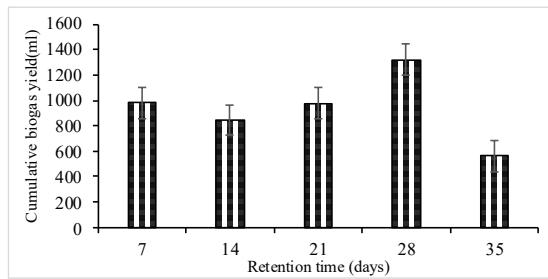
### 3.3.2. Effect of retention time

Figure 4 explains the variation of cumulative biogas yield in ml with respect to retention time in days. Sufficient retention time is required by microorganisms to digest organic materials into biogas [42]. During methanogenic stage, the variation of biogas generation of FW and RS as co-substance with mixing ratio (70:30) is dependent on the methanogenic microorganism activity, where the microbial growth and the conversion process are significantly impacted by the retention time.

Since this study was conducted under mesophilic conditions, a retention time of 14-40 days was required for effective organic waste treatment. In this study, the retention time was set between 7 and 35 days, reflecting the commonly reported duration ranges in mesophilic batch digestion research for biogas kinetics. This range aligns with standard weekly sampling standard and typical assessments of digesters over periods of 30 to 40 days [43].

The observation was conducted a bit earlier to see if there were any changes in the digestion. For the first seven days the cumulative biogas yield increases and gradually decreases till the 14th day. According to reports, methanogenic bacteria quickly absorb volatile fatty acids when the digestion process lasts more than five days, increasing the supply of biogas and decrease after microbial activity becomes slower. The cumulative biogas yield then uniformly increases until day 28, after which the system has stabilised, confirming this as the optimum retention time. Thereafter, yields declined to almost half of the previous volume likely due to

substrate depletion and methanogen decline. This dataset reinforces the conclusion that 28 days is the ideal retention time under the tested mesophilic conditions.

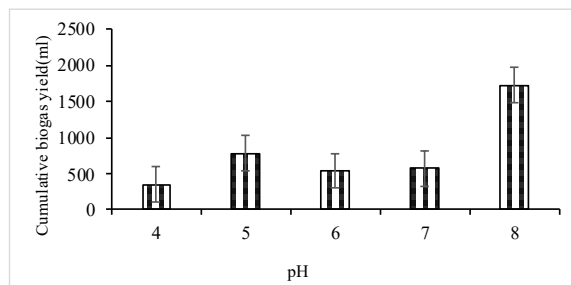


**Fig. 4. Cumulative biogas yield based on retention time.**

### 3.3.3. Effect of pH

Figure 5 demonstrates the effect of the pH value on the cumulative biogas yield. pH value is one of the important parameters in co-digestion process as it directly affects the organic compound digestion. Besides that, the metabolic activity of the entire biogas generating process is significantly influenced by the pH level. As seen in the figure, the cumulative biogas yield is the lowest at pH 4 as the hydrolysis is compromised at acidic pH value, limiting the conversion of protein to total ammonia nitrogen (TAN) and lipids to volatile fatty acids (VFAs) [44, 45].

Subsequently, it is tremendously growing at pH 5 showing the microbial activity might start being active for the degradation of available nutrients and drastically decline at pH 6 and 7 which might be due to the inhibition in methanogenic bacteria activity. The peak value was obtained at pH 8, where the effectively functioning methanogens promoted the activity, where it was comfortable for bacterial activity in co-digestion of FW and RS. Yet it contributes to the increase in cumulative biogas yield.



**Fig. 5. Cumulative biogas yield based on pH.**

## 4. Conclusion

This study explores the potential of RS as a co-substrate for the co-digestion of FW. The addition of RS to FW contributed to system stability by addressing the inconsistency of organic content in FW, which had previously led to low biogas production. The characteristics of RS significantly improved the digestion process. Specifically, the porosity of RS which attributed to its carbon content has enhanced the substrate availability for microbial activity, thereby improving

process stability. Additionally, the TMEs present in RS played an important role in the co-digestion process.

The inclusion of RS also improved the C/N ratio of the substrate. However, the surface area of RS did not result in a higher cumulative biogas yield. In parametric study, the cumulative biogas yield increased from 632 ml to 845 ml when the feedstock ratio changed from 100:0 to 70:30. The yield further increased to 1320 ml at the optimum retention time of 28 days. Further, at the optimal pH value of 8, the highest cumulative biogas yield of 1725 ml was achieved. Overall, these results demonstrate that co-digestion of FW and RS offers significant advantages for AD of FW and enhances biogas production.

### Acknowledgements

The authors would like to thank Ministry of Higher Education, Malaysia for their generous financial support under Fundamental Research Grant Scheme (FRGS), contract number: FRGS/1/2024/TK08/UMP/02/15. The authors would like to express their sincere gratitude for the financial support received from Universiti Malaysia Pahang Al-Sultan Abdullah under the Fundamental Research Grant Scheme through research project RDU223302. The support for the laboratory used from Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah was equally acknowledged and appreciated.

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