

Biochemical methane potential of kitchen waste amended with different biochar's: Experimental and kinetic studies

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ABSTRACT

The objective of this study was to investigate the impact of six kinds of biochar on the anaerobic digestion (AD) for kitchen waste. The utilized types were agricultural waste biochar (BC-AW) and sewage sludge biochar (BC-S) chemically activated in acid (H_3PO_4) and base (KOH). The results indicated that all biochar products promoted the shortening of stasis, weakening acidification and accelerating organic matter degradation, as well as increasing the activity of methanogenic bacteria. The agro-wastes-derived biochar activated with base (BC-AW-KOH) had the greatest cumulative gas production (2250 mL/gVS and 72% methane yield), attributed to having the highest surface area (2111.9 m²/g) and an improved pore structure. Inactivated sludge biochar (BC-S) showed the least performance and productivity. The Transport Function model was also found to be the best statistical description of the experimental data, as revealed by kinetic modelling. According to these observations, treatment of biochar by chemical activation is a promising approach for improving the stability of the anaerobic digestion system and energy recovery from organic waste.

Keywords: anaerobic digestion, biochar, KOH modification, H_3PO_4 modification, kinetic models.

INTRODUCTION

With the increase in restaurants, the amount of waste generated from their kitchens is also increasing, leading to environmental pollution and numerous health problems stemming from kitchen food scraps (Luo et al., 2015). This harm has caused public concern. With the worsening global energy and environmental problems, efficient anaerobic digestion of food waste is considered one of the best technological methods for reducing environmental pollution and recovering energy (Rajagopal et al., 2017). However, food waste has a complex composition, causing problems such as the instability of the anaerobic digestion system, rapid acidification, and low activity of beneficial bacteria (Sinervo, 2017). All local and international research relies primarily on external additives, which complicates the preparation process and increases production costs.

Biochar is a stable, slightly soluble aromatic compound produced as a residue from carbonisation or the phytochemical decomposition of

biomass in the absence or scarcity of oxygen (Gul et al., 2015). Biochar is inexpensive and can be widely used for soil improvement, environmental pollution control, and pollution remediation (Paz-Ferreiro et al., 2014). For example, Fagbohunge et al. used the anaerobic digestion of citrus peels to study the effect of different biochar addition levels on anaerobic digestion (Fagbohunge et al., 2017). Another study reported using bread scraps as substrates for anaerobic digestion, investigating the effect of biochar on two-phase anaerobic digestion. An increase in microbial growth and metabolic processes was observed, which maintained pH stability during biogas production (Sunyoto et al. 2016). This stability plays an important protective role. Wang Li et al. (2009) have shown that adding biochar effectively regulates the carbon-to-nitrogen ratio in the system, reduces ammonia nitrogen stress, significantly increases microbial activity, improves system stability, and enhances digestion gas production under unstable conditions. Therefore, biochar can be considered an important

additive in the anaerobic digestion of organic waste without posing environmental risks.

However, despite the aforementioned experiments, recent scientific studies addressing biochar in anaerobic digestion remain limited, and its engineering applications in solid waste treatment are even fewer. Xu et al. (2015) and Zhang et al. (2019) found that biochar has a positive and effective impact on anaerobic digestion as well as synthetic wastewater. Mumme et al. (2014a) and Abudi (2018) found that the added value of biochar in methane production during the digestion of agricultural waste is negligible.

In this research, the dynamics of biochar in AD were the subject of investigation. Digestion trials were performed using kitchen waste amended with six biochar materials. The influence and role of biochar addition in the anaerobic digestion of food waste were studied by quantifying several parameters at different stages of the AD process. Additional purposes were to assess the effects biochar had on biogas production and viability of anaerobic decomposition, characterizing its impact on microbial communities, and to evaluate organic waste co-digested with biochar.

MATERIALS AND METHODS

Inoculum

Activated sludge was collected at 37 °C from the wastewater treatment plant of the old Karkh project, located in the Al-Bitha area. This wastewater treatment plant constructed in 1980 with a capacity of 205000 m³/d. Measurements were taken as shown in Table 1.

Substrate (organic solid waste – food waste)

Kitchen (household) waste, consisting mainly of leftovers from three meals (breakfast, lunch, and dinner), was collected and ground. The waste was then placed in a transparent polyethylene bag and kept frozen at -20 °C. The organic food waste used in anaerobic digestion was analysed, and the results showed that its pH was acidic (pH 5.9, as shown in Table 2). The total solids content was 23.04%, and the volatile solids content was 0.23%.

The carbon and nitrogen values were 48,640 and 1.396, respectively, for a C:N ratio in the 20–30 food waste.

Table 1. Characteristics of inoculant

Parameter	Inoculant
pH	6.8
T.D.S.(ppm)	1250
S.S(ppm)	33
NO ₃ (mg/L)	4.7
T.S(%)	0.03
V.S(%)	0.012

Biochar

Collection and preparation

Six types of biochar were used in the conducted research, including agricultural waste biochar (BC-AW), acid-activated agricultural waste biochar (BC-AW- H₃PO₄), alkali-activated plant waste biochar (BC-AW-KOH), sludge biochar (BC-S), acid-activated sewage sludge biochar (BC-S- H₃PO₄), and alkali-treated sewage sludge biochar (BC-S-KOH). Agricultural waste was collected from the grounds of the College of Engineering/Al-Mustansiriya University, while sewage sludge was collected from the old Al-Karkh project in the Al-Bitha area. The biochar was prepared through pyrolysis, acid activation, and alkali activation.

Preparation of biochar from conocarpus leaves

Leaves of conocarpus collected from tree pruning waste were carefully washed with tap and distilled water to remove dust, followed by oven drying at 105 °C for 24 hours. The leaves were then air-dried, ground and passed through a 150 micrometre sieve.

Biochar was prepared using pyrolysis, 500 g of the leaf powder were kept in an alufoil and a metal box inside temperature controlled oven (Carbolite CWF1200/UK). The temperature was raised to 360 °C at the rate of 10 °C min⁻¹ and held there for one hour. The obtained biochar was cooled to room temperature, ground and stored in airtight plastic bags (Figure 1) (Qasim et al., 2023).

Preparation of biochar from sewage sludge

The sewage sludge was obtained from the old Al-Karkh plant in Bu'aitha. It was subsequently disseminated on particular trays and oven-dried at 105 °C during 24 h.

Table 2. Characterisation of organic waste

Parameter	Organic waste
TOC(mg/l)	48640
TN(mg/l)	1396
TS%	23.04
VS%	0.23
pH	5.9

The dried sludge was then ground in a grinder and sieved through a 150-micrometer sieve. The biomass was pyrolyzed to biochar at a temperature of 500 °C.

For biochar production, 500 g of leaf powder were enclosed with thick sheets of aluminium foil and inserted into a custom made metal box, which was sealed tightly. The metal box was kept in a thermostatic oven (Carbolite CWF1200/UK). The oven was slowly heated to 500 °C with a rise rate of 10 °C/minute and kept at the desired temperature for 1 hour. The metal container was cooled at room temperature. The product was sealed in an airtight container (Figure 2) (Qasim et al., 2023).

Activation of H_3PO_4 biochars (BC-S- H_3PO_4 and BC-AW- H_3PO_4)

The biochar prepared from agricultural residues and sewage sludge was activated using phosphoric acid. Activation was achieved by soaking the biochar in a 17.5% phosphoric acid (H_3PO_4) solution for 24 hours at room temperature. The acid-to-biochar ratio was 1:1. On the basis of previous research, a 1:3 ratio is considered optimal, as it is the most cost-effective and environmentally friendly.

The biochar absorbent material was dried at 60 °C and then thermally decomposed in a nitrogen

atmosphere at up to 600 °C for 1 hour. After cooling, the modified biochar was washed with deionized water to remove excess phosphoric acid. The pH of the resulting biochar solution was approximately 5.5. The washed samples were dried and ground into a fine powder using a sieve with a mesh size of less than 1 mm (Budinova et al., 2009).

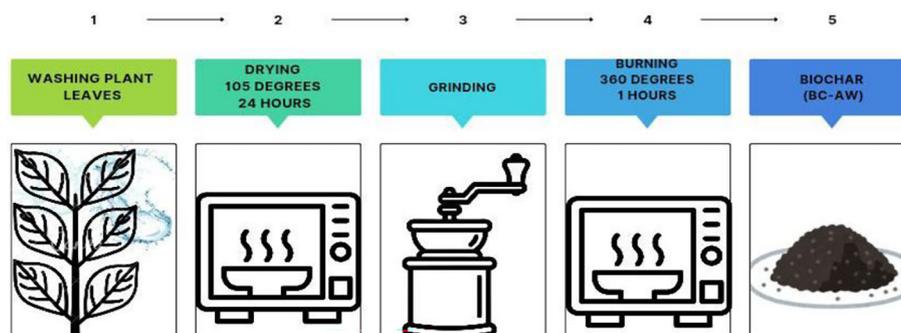
Activating biochar with KOH (BC-S-KOH and BC-AW-KOH)

Biochar was prepared from dried leaves and sewage sludge; the raw biochar obtained was activated by potassium hydroxide as an activating agent. 45 g potassium hydroxide, 45 g of biochar, and 150 ml deionized water were mixed well in a glass bottle (500 ml). The bottle was sealed and set on a shaker with a mixing speed of 100 rpm for 24 h. The activated biochar underneath was dried at 80 °C for 24 h.

After the treatment, the biochar was thermally treated by heat-treating it in a ceramic container (sealed lab beaker) inside a kiln at 700 °C for two hours with nitrogen gas. The container was cooled, washed with fresh water three times until the pH of the rinsing water became neutral. Finally, the biochar was dried further for 24 hours at 105 °C (Liu et al., 2019; Lu et al., 2025).

Characterisation techniques

Biochar morphology and specific surface area have to be characterised using scanning electron microscopy (SEM) and specific surface area measurement by BET is required for biochar. Their significance is associated with the good environment for the microbes colonisation and biochemical reactions due to porosity and surface roughness. They are also important for monitoring activation effectiveness, conducting the electron transport in the best manner and stabilising the arrangement

**Figure 1.** Preparation of biochar (BC-AW)

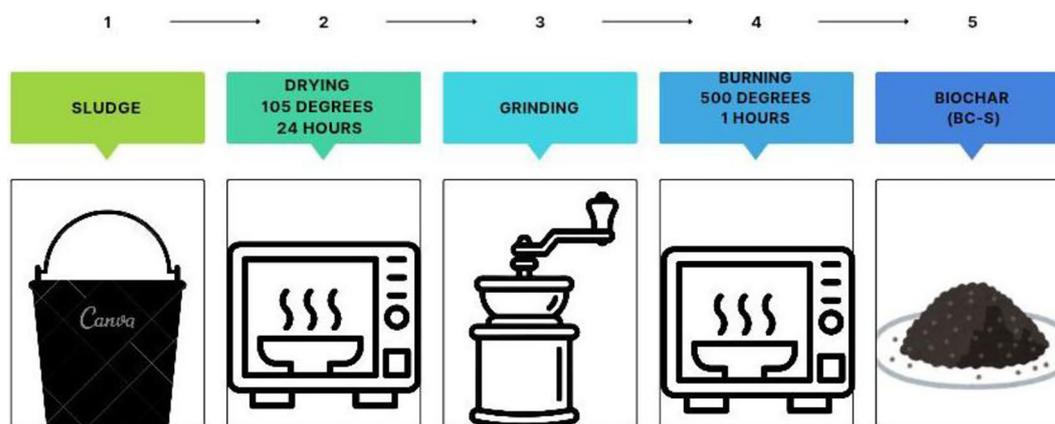


Figure 2. Preparation of biochar (BC-S)

of the system to attain better methane generation. Thus, the obtained findings may provide a useful tool for biochar selection in organic waste applications and energy production.

Experimental design and setup

All assays were carried out in glass bottles of 250 ml with butyl rubber stoppers, which were made gas-tight. Each bottle was supplemented with 200 mL working substrate and 150 mL anaerobic inoculated biomass. For each bottle, 5 g of biochar was mixed with 20 g of organic food waste. The bottles were then purged with nitrogen gas from a cylinder for 2 min to induce an anaerobic condition and remove air, and subsequently sealed. The bottles were integrated into the gas storage bag with rubber tubing. The bottles, containing the bacteria and substrate, were incubated in a suspension at 100 rpm at 35 ± 1 °C using a G-25 controlled-environment bath shaker. Biogas production was monitored daily. Gas storage bags were transported daily to the Scientific Research Authority (formerly the Ministry of Science and Technology) in the Renewable Energy Department, where the volume of gas produced by the system was measured using a gas analyser specifically designed to measure the biogas composition. The components of the biogas (methane and carbon dioxide) were continuously measured until day 35 of the experiment. The experiments concluded when biogas production rates approached their lowest levels (Hu et al., 2023).

Kinetic modelling

Anaerobic digestion is one of the most sustainable and resource-efficient modern technologies

for treating organic waste, especially food waste, to produce renewable energy in the form of biogas. However, this process faces some technical limitations regarding system stability (accumulation of volatile fatty acids and inhibition of bacterial activity due to the complex composition of the waste). Therefore, biochar has been used as a strategic additive to improve the performance of anaerobic digestion, as it enhances direct electron transfer between species, provides a large surface area for microorganisms, and modifies the pH (Zhu et al., 2025a; Tiong et al., 2025).

There are already experimental results; however, it is difficult to predict system performance and optimise operating parameters without kinetic modelling. Kinetic modelling is an essential mathematical tool to analyse the biogas production dynamics, from which it can be estimated the values of relevant parameters such as hydrolysis rate, maximum potential methane production (M_{max}) and lag phase (λ). The advantages of these models are not limited to simulating published experimental data, but also that the scaling-up/development of industrial bioreactors on a large scale and de-bottlenecking operations facing performance losses due to unstable conditions can be avoided (Kelif Ibro et al., 2024).

The kinetic models employed in anaerobic digestion studies vary, ranging from the first-order models that assume hydrolysis under specific rate conditions to more complete sigmoidal curves, including the modified Gompertz curve and the logistic curve. These models are known to accurately represent the stages of microbial growth and gas production, particularly when the addition of enhancers such as biochar alters the nature of the biochemical reactions occurring within the reactor (Basinas et al., 2024).

Moreover, the Transference Function model is also an enhanced model that offers more understanding relative to the system response when its operating conditions change. The significance of comparing these models is to determine the most statistically fit model (R^2 and RMSE values) that will help in a detailed interpretation on how the physical and chemical characteristics of biochar, such as surface area and porosity due to chemical activation, influence methane production kinetics (Table 3).

Biogas production and composition

The composition of biogas was analysed utilizing a gas analyses (Gas board-3200 plus). Calibrations were performed using the standard gases (H_2 , O_2 , N_2 and CH_4 or CO_2 ; purity >99.9%). The daily volumetric biogas volume was determined using the water displacement method and further converted to STP (standard pressure and temperature, i.e., 273 K) as well as to ideal gas volume using independent variables in the ideal gas law. The pH was determined by a pH meter.

RESULTS

Characteristics of biochar

It is observed from Table 4 that the specific surface area and total pore volume of all materials are significantly enhanced as a consequence of chemical activation compared to those of raw biochar. The BET surface of the BC-AW was 100 m^2/g , whereas that of BC-S was very low, 22 m^2/g^{-1} thus showing a poorly porous structure of the raw agro-industrial wastewater-derived materials (Thakur, 2024).

The surface area of BC-AW and BC-S increased 11- and 36-times, respectively, after acidic activation (1100 and 800 m^2/g). This

homogenisation results from desiccation of phosphoric acid, which is able to inhibit the shrinkage of the carbon skeleton and induce pore with its dehydrating capacity (Abudi et al., 2022).

Alkaline activation by alkaline potassium hydroxide (KOH) action was found to be much more efficient. The surface area and total pore volume of BC-AW-KOH biochar were the largest, up to 2111.9 m^2/g , and 1.43 cm^3/g among all tested samples, due to an alkaline activation mechanism where KOH reacts with carbon, which is then soluble carbon compounds formed. This attacks the “pitting” and expansion of pores, especially in microspores (Basinas et al., 2024).

This conclusion is further verified by the BET results that biochar BC-AW-KOH, with the largest surface area and the greatest pore structure development, had the maximum CH_4 production rate (72%). This is consistent with the concept that surface characteristics are the major controlling factor of biochar performance in anaerobic digestion (Xu et al., 2025).

The BET isotherm data can be used for an accurate interpretation of what the image (Figure 3) would show in this study. In contrast to raw biochar BC-AW and BC-S images being more selective medium based on a less rough/less porous surface. First pores may form, but they will be disordered and partly sealed, explaining the low surface area (100–22 m^2/g).

Acid Activation H_3PO_4 Images are likely to reveal that pores have just been generated and clearly observable channels are present in the porous structure when compared with the as-received material, which implies an increase of pore size (Hassan et al., 2023).

Alkaline Activation KOH: The sponge-like alkali activated images of BC-AW-KOH and BC-S-KOH would be porous with a huge amount of open and connected pores. This structure is the clear visual evidence of the capability of alkaline activation to produce advanced porosity, as also

Table 3. Models used to calculate kinetic parameters for the anaerobic digestion

Model	Equation	Parameters	Number
First-order kinetic	$M(t) = M_{max}(1 - e^{-kt})$	Mmax, k	2
Modified Gompertz	$M(t) = M_{max} \exp \left\{ -\exp \left[\frac{R_{max}e}{M_{max}} (\lambda - t) + 1 \right] \right\}$	Mmax, Rmax, λ	3
Logistic function	$M(t) = \frac{M_{max}}{\left\{ 1 + \exp \left(\frac{4R_{max}e(\lambda - t)}{M_{max}} + 2 \right) \right\}}$	Mmax, Rmax, λ	3
Transference function	$M(t) = M_{max} \left\{ 1 - \exp \left(-\frac{R_{max}e(t - \lambda)}{M_{max}} \right) \right\}$	Mmax, Rmax, λ	3

shown by the BET value higher than 2000 m²/g. Recent findings confirm that biochar-induced enhancement in anaerobic digestion occurs mainly via its surface and porosity features. Very large surface area, such as in BC-AW-KOH is a good substrate for adhesion and proliferation of microorganisms, especially methanogens. Such “microbial colonies” are shielded, thus raising a concentration of the effective biomass in a reactor. The conductive carbon backbone of biochar, in particular if highly porous, is assumed to support direct interspecies electron transfer. This bypass electron transport pathway expedites the metabolism of VFAs to CH₄ at a faster rate, which decreases the possibility of self-fermentation and system acidification. The large total pore volume can effectively absorb inhibitors, such as free ammonia and surplus VFAs, as a buffer to stabilise the system (Xu et al., 2025).

BET results (and (predicted) SEM images), reveal that chemical activation with KOH is the best approach to obtaining biochar of a higher surface quality. The ultra-high specific surface area and large pore size of BC-AW-KOH biochar provide an excellent catalysis, a good matrix for the growth of methane-producing microorganisms, as well as electron transfer modes that is

conducive to promoting the efficiency of high performing methane production and system stability; which coincides with the current frontier research direction in this field (Vayena et al., 2024).

Variation of pH

Figure 4 shows the changes in pH in each experimental group during anaerobic digestion of kitchen waste. As it is shown in Figure 4, the readily assimilated organic fraction from kitchen waste decays very rapidly. In the initial 3 days in the process of anaerobic digestion, the pH value declines dramatically and an evident acidification can be observed. A slight drop in the pH values (the experimental groups) was shown at both the 12-day and 16-day; this may be caused by the decomposition probability of hardly degradable substances from kitchen waste. After that, the pH of all groups increased gradually to a steady state in slightly alkaline ranges of 7–8. The observed elevation of the pH levels could be due to increased ammonia concentration in the system. One of the reasons may be that the applied biochar itself has basic properties (Huang et al., 2015). Alkaline substances can also enhance the ability of the anaerobic digestive system to

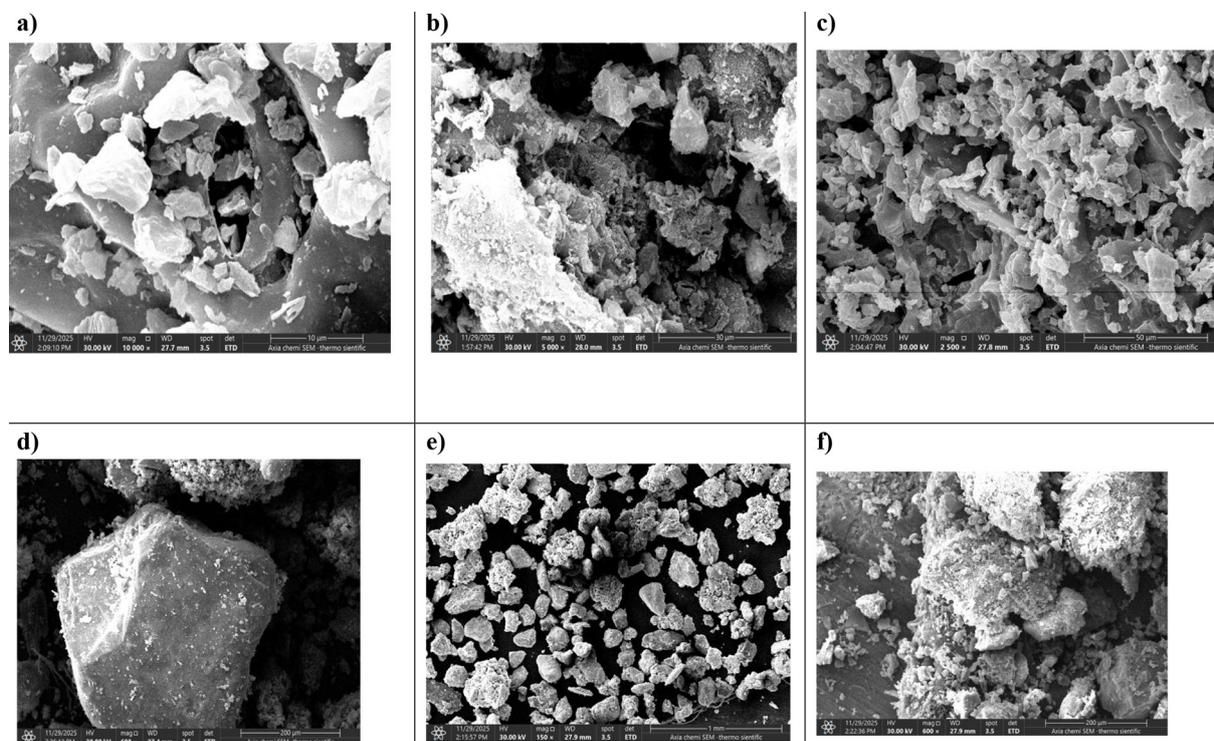


Figure 3. (a) SEM BC-AW, (b) SEM BC-AW-H₃PO₄, (c) SEM BC-AW-KOH, (d) SEM BC-S, (e) SEM BC-S-H₃PO₄, (f) SEM BC-S-KOH

Table 4. Characteristics of different biochars

No	Property	Biochar					
		BC-AW	BC-AW-H ₃ PO ₄	BC-AW-KOH	BC-S	BC-S- H ₃ PO ₄	BC-S-KOH
1	Surface area (BET) (m ² /g)	100	1100	2111.9	22	800	1211.3
2	Total pore volume (cm ³ /g)	0.1	1.2	1.43	0.08	0.7	1.01
3	Average pore diameter (nm)	886.8	579.4	702.0	366.5	754.1	554.5

regulate pH. The pH of the biochar used in the experiments was alkaline, as was the biochar itself. This improves the pH regulation ranges within the digestive tract. Lu and colleagues used the anaerobic digestion of glucose as a testing platform, comparing anaerobic digestion with and without the addition of biochar. Tests indicated that the addition of biochar can significantly reduce the duration of digestion stagnation and delay system acidification (Luo et al., 2015). The average concentration of AD and BC-S samples in the experimental group at the middle and end of the experiment was lower than their average concentration at the middle and end of the experiment for all other groups, such as BC-AW, BC-AW-KOH, BC-AW-H₃PO₄, BC-S-KOH, and BC-S-H₃PO₄. The pH value also increased in the experimental group to which biochar was added at the end of the experiment, compared to the group that did not have biochar added.

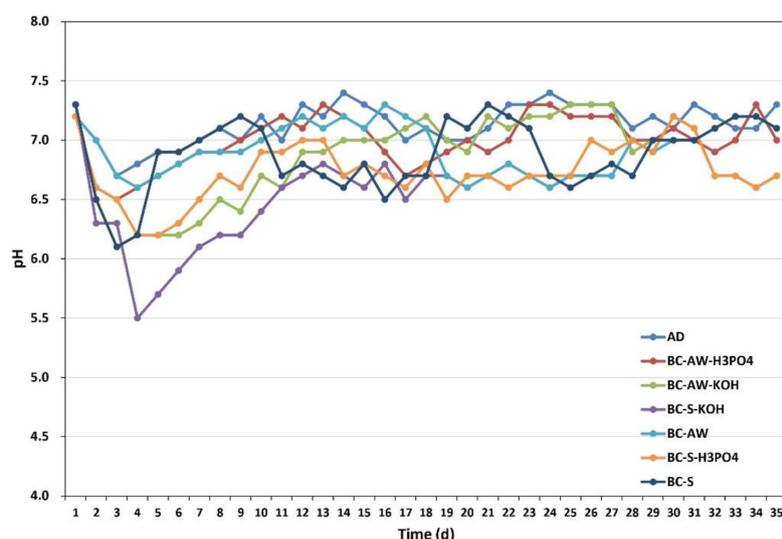
Biogas production

Figure 5 shows the daily biogas production (ml/g of volatile solids per day) for six different

experimental groups plus the control group (AD) over 35 days. It is evident that the addition of different types of biochar (Biochar-BC) has a significant effect on anaerobic digestion and gas production.

Phase I: Period of rapid onset and rapid worsening (days 1–10)

The early phase of the first days of the experiment: most groups with biochar showed an exaggeratedly high initial gas production, and then a steep drop. Notably, the BC-AW-KOH sample (biochar from agricultural residues was activated with KOH) demonstrated the highest gas production on day 1 (~170 ml/gVS.d) The BC-S-KOH (biochar from sewage sludge activated with KOH) was the second highest group, up to about 145 ml/gVS.d on day 1. These early high yields can be explained by the fact that activated biochar has a large surface area and porosity, which is an ideal habitat for growing and replicating methanogens, so it speeds up the decomposition rate of rapidly biodegradable organic matters at the initial stage (He et al., 2024; Xiao et al., 2021). After the first peak, most groups underwent a rapid

**Figure 4.** pH variation during anaerobic digestion of kitchen waste

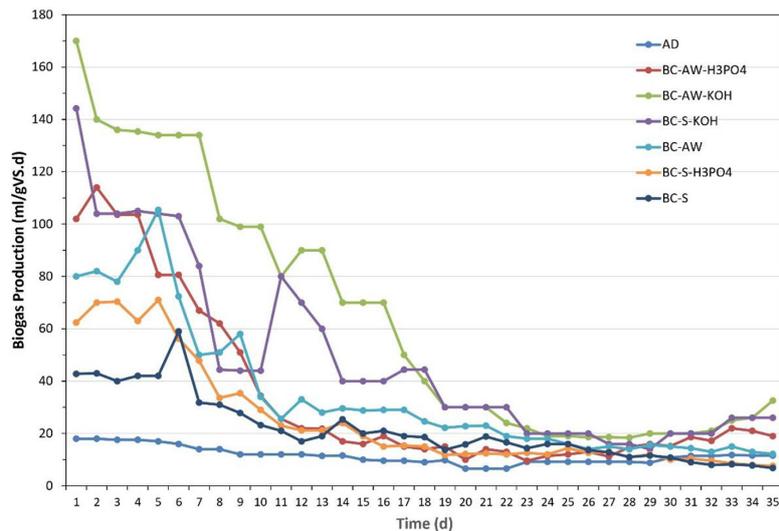


Figure 5. Daily biogas production

decrease. The production of BC-AW-KOH, for instance, rapidly decreased from 170 ml/gVS.d to approximately 100 ml/gVS.d by day 8. In comparison, the AD control (anaerobic digestion without biochar) showed an initial low and constant CH_4 over the experiment quality with values under 20 ml/gVS.d, indicating the highly positive influence of BC application.

Phase II: Stagnation periods and secondary peaks (days 11–25)

After the first decline, a few groups experienced occasions of little production or some kind of “stale stage”. BC-S-KOH and so on showed a clear stagnation period from days 9–11, during this period the production of approximately 45 ml/gVS.d was obtained before peaking on day 12 (approximately, 80 ml/gVS.d). The latter secondary peaks might be related to the breakdown of more complex organic compounds and a shift in the bacterial populations between species (mostly lysates and methanogens) that are present in the reactor (Fagbohunge et al., 2017). Remarkably, the (KOH)-treated groups displayed significant fluctuations and higher peaks than those of the unactivated control or that of the (H_3PO_4)-group. For instance, the BC-AW-KOH group retained a relatively high yield compared to other groups during this duration.

Phase III: Plateau and decline (from day 25 onwards)

With the exception of the last period of production, most lines met at low yields (10–30 ml/gVS.d), which signified the consumption of the

majority of the biodegradable organic material. Nevertheless, it is surprising that the production of CO_2 in both BC-AW-KOH and BC-S-KOH had a slight increase during the last few days (33–35), which could suggest they have a role on enhancing long-term decomposition of resistant organic products (Basinas et al., 2024).

Figure 6 shows the cumulative biogas production (ml/g of volatile solids) across 35 days of anaerobic digestion. High and rapid cumulative biogas volume in all the biochar-amended groups of the first ten days group to a rapid initial gas production rate. Thereafter, the slope of increase diminished somewhat, but production still increased nearly linearly until day 35 when the experiment was terminated. This behaviour corresponds to the consumption of readily available organic matter at first, and different kinetic constants for slower degradation of material are more complex (Pan JunTing et al., 2014; Zhu et al., 2025b).

After experiment termination (day 35), the final values clearly demonstrated a difference among the standard portions, including all groups. The group BC-AW-KOH (agricultural residue activated carbon with KOH) obtained the highest cumulative amount of 2250 ml/gVS among the other treatment groups (400 ml/gVS), whereas the AD control (anaerobic digestion without additives) showed the lowest cumulative production, approximately 400 ml/gVS (Basinas et al., 2024; Yan et al., 2022).

The maximum cumulative biogas production (2250 mL/gVS) was obtained in the group added with BC-AW-KOH and it was significantly greater than that of other experimental groups.

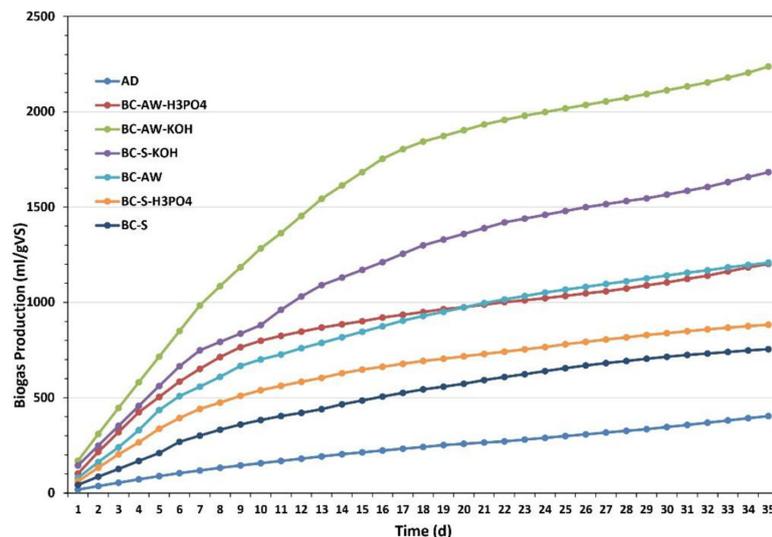


Figure 6. Accumulative biogas production

In particular, the amount of produced BC-AW-KOH was about 1.32 times that of BC-S-KOH (1700 mL/g), while it was approximately 1.88-fold more than the yield from BC-AW (1200 mL/g), and 1.91-fold higher compared to BC-AW-H₃PO₄ (1180 mL/g), as well as higher with 2.56 and three times with respect to that obtained for BC-S-H₃PO₄ (880 mL/g) and inactivated sludge biochar BC-S (750 mL/g), respectively.

These findings proved a beneficial impact of activated biochar (KOH) on the stimulation of total biogas production. It is also consistent with the findings from previous studies, where the porous structure of biochar promotes a digestion environment for anaerobic digestion systems by serving as a colonisation site for microbes and facilitating interspecies electron transfer, which may enhance the efficiency of methane production (Hassan et al., 2023).

Biogas composition

The graphical results (Figure 7) indicate the variations of methane concentration dynamically under seven treatments during 35 days. The results can be distinguished into three predominant time phases, which are indicative of the microbial response to the introduction process of diverse types of biochar:

Phase 1: Onset and adaptation phase (days 1–10)

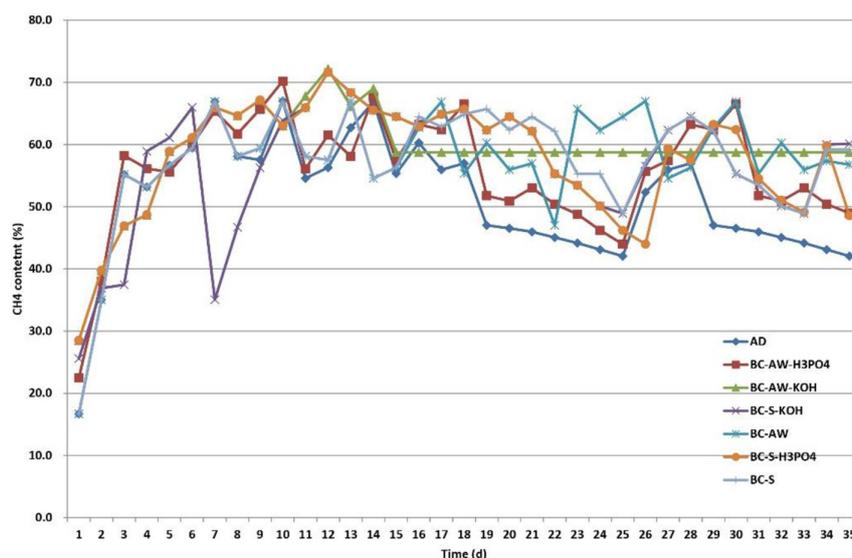
All reactors exhibited a fast and high accumulation of methane in the first 3 days, while it

went from barely detectable to very high (15–25% up to >55%). The sudden surge indicates that the lag phase was abbreviated and methanogenesis was stimulated immediately after the addition of biochar. At day 7, BC-S-KOH decreased firmly and abruptly toward below 35% compared with BC, which was at 65%. Such behaviour may be considered as a “microbial shock” caused by the severe chemical characteristics of such a carbon (for instance, high residual alkalinity or release of inhibitory compounds from the sludge), resulting in transient accumulation of abiogenic bacteria over methanogens.

Phase II: Crest and agitation-active period (days 11–25)

This stage would likely represent the most active period within this study (15 minutes) as the highest values were recorded for much of the treatments containing activated biochar, the BC-AW-H₃PO₄ and BC-S-H₃PO₄ groups reached close to 72% of methane production around day 12. This superiority can be assigned to the function of acid activation for generating microspores whose capacity for microbial flocculation is higher and promoting the transportation of electrons.

Very stable behaviour was seen in the case of the BC-AW-KOH curve whereas great fluctuation between up and down was observed in the rest of the other curves. Such stability is evidence that alkaline-activated biochar derived from a leaf has good buffering capacity that helps in preventing the system instability due to fluctuation of volatile fatty acids.

Figure 7. CH₄ content

Phase 3: Sustainability and end (days 26–35)

Control group (AD) – the AD curve was kept on a downward trajectory and fell down to almost 42% at the end of the experiment – obviously due to the exhaustion of the regulatory capacity and accumulation of inhibitors.

Biochar performance sustainability – all biochars (except AD-BC-S at a certain time) maintained CH₄ levels > 50%. The BC-AW-KOH was also the most noticeable for remaining nearly constant at 59% up to the last point monitored, thus showing that this biochar not only improves production efficiency, but it also keeps a high microbial activity until a long time.

The visual quality results indicated that the chemically activated biochar, i.e., plant base biochar, had significantly improved the anaerobic digestion. Activation with H₃PO₄ gave very high production peaks, while activation either by KOH was observed for operational stability. This difference allows for the choice of biochar type according to the desired goal (higher production or more stable system); this is consistent with recent publications which demonstrated that surface and porosity properties of biochar are crucial features to bypass problems encountered during conventional anaerobic treatment (Mumme et al., 2014b; Luo et al., 2015; Abudi et al., 2022), which confirmed the effect of chemically treated biochar in promoting methane production and improving the operation of anaerobic systems.

Kinetics studies

Table 5 shows that the applied kinetic models are capable of characterising the methane production produced from organic and solid waste co-digestion. However, their prediction of quality and accuracy are not uniform for all models and criteria of evaluation. For all models, it was observed that the maximum value of expected methane production (M) raised notably in function of the solid waste fraction in the substrate mixtures. This suggests that co-digestion can improve the biodegradability of organic matter and the stability of the reactor. This increment is assumed to be due to a better attenuation of nutrients available and the C:N-ratio balance, as well as the inhibition occurring effects decrease, in agreement with the other observations (Angelikaki et al., 2009; Mumme et al., 2014a).

For the first-order kinetic model, *k* values increased from 0.028 to 0.0547 d⁻¹, corresponding with enhanced mixing ratios, suggesting a speed up of the hydrolysis phase, which reaction is the limiting-step in anaerobic digestion. This model, however, is too simple and easy to apply, as mentioned, but lacks of the ability to simulate the dynamic behaviour of microbial growth (Meng et al., 2022; Donoso-Bravo et al., 2011).

Other power models, such as modified Gompertz, logistic and transport function models, showed an increase in the maximum methane production rate *R*_{max} (from 18 mL CH₄). The ability to produce higher amounts of methane showed enhanced methanogenic activity and a

higher speed of generating methane inside the reactor. These models provide a better representation of various biological stages, such as lag and generation time, a reading tool for describing the temporal evolution of biogas production, as it was demonstrated (Zwietering et al., 1990).

Examination of the statistical quality indicators, such as R^2 , RMSE and AIC, indicates that

some models with lower percentage differences are not necessarily those providing the best fits by using experimental data. The model with the smallest AIC value (where AIC is a measure that exchanges, in an optimal way, goodness of fit and model complexity) is the best-fitting and most reliable (Hassan et al., 2023). Therefore, on one hand, the transport functions model can provide

Table 5. Estimated parameters of the kinetic models

Model	Parameters	AD	AD-BC-AW- H_3PO_4	AD-BC-AW-KOH	AD-BC-S-KOH	AD-BC-AW	AD-BC-S- H_3PO_4	AD-BC-S
First-order kinetics	Total Biogas _{Exp.} (mL)	403.6	1202.2	2237.6	1683.4	1208.6	882.8	754.6
	B_{max} (mL)	383.558	1112.559	2211.895	1638.701	1176.126	851.670	749.421
	Total Biogas _{Theo.} (mL)	383.558	1112.559	2211.895	1638.701	1176.126	851.670	749.421
	Diff. (%)	5.2	8.1	1.2	2.7	2.8	3.7	0.7
	K (1/d)	0.028	0.112	0.079	0.072	0.077	0.087	0.054
	R^2	0.994	0.984	0.997	0.998	0.996	0.993	0.998
	rMSPE(%)	2.065	3.075	1.441	1.049	1.584	1.91297	1.243
AIC	105.702	229.137	214.62	148.750	144.307	160.336	69.887	
Modified Gompertz	B_{max} (mL)	388.466	1201.301	2233.189	1682.063	1207.755	881.584	745.586
	Total Biogas _{Theo.} (mL)	388.466	1201.301	2233.189	1682.063	1207.755	881.5842	745.586
	Diff. (%)	3.9	0.1	0.2	0.1	0.1	0.1	1.2
	R_{max} (mL)	18	103.6	170	144	105	70.4	43
	λ (d)	0	0	0	0	0	0	0
	R^2	0.983	0.981	0.989	0.965	0.968	0.980	0.987
	rMSPE(%)	9.960	11.4444	9.2608	14.902	14.622	11.106	7.9705
AIC	250.849	350.173	365.34	365.510	324.336	285.650	236.764	
Logistic model	B_{max} (mL)	397.889	1202.1847	2237.2028	1683.321	1208.553	882.701	752.692
	Total Biogas _{Theo.} (mL)	397.889	1202.184	2237.202	1683.321	1208.553	882.701	752.692
	Diff. (%)	1.4	0.0	0.0	0.0	0.0	0.0	0.3
	R_{max} (mL)	18	144	2237.600	144	105	70	43
	λ (d)	0	0	0.000	0	0	0	0
	R^2	0.979	0.968	0.982	0.952	0.955	0.971	0.981
	rMSPE(%)	12.523	14.783	11.5278	17.0113	16.795	13.2690	10.704
AIC	281.007	353.488	374.68	369.245	328.229	292.620	272.947	
Transference model	B_{max} (mL)	318.869	1158.689	2080.942	1599.079	1150.827	827.772	651.906
	Total Biogas _{Theo.} (mL)	318.869	1158.689	2080.942	1599.079	1150.827	827.772	651.906
	Diff. (%)	26.6	3.8	7.5	5.3	5.0	6.6	15.8
	R_{max} (mL)	18	144	170	144	105	70	43
	λ (d)	0.1	0	0	0	0.000	0.100	0.000
	R^2	0.993	0.992	0.998	0.997	0.997	0.997	0.999
	rMSPE(%)	10.385	3.723	5.658	2.354	1.985	4.364	10.070
AIC	281.881	251.567	353.16	209.119	218.001	255.9760	340.485	

optimal comprehensive statistical performances; on the other hand, the modified Gompertz model has more powerful predictive capacity when explaining the biological characteristics of methane production.

It concludes that co-digestion is an effective method to enhance gas amount and rate for biogas, as well as all the kinetic models should be examined by a series of statistical and biological indicators rather than simply a single one to select the best one that is capable of simulating the process accurately and realistically.

CONCLUSIONS

The authors of this study found that the application of biochar is a promising alternative to improve anaerobic digestion efficiency (the quantity of biogas produced, methane quality and process stability) for organic waste treatment. The stasis time decreasing, acidification mitigating degree and reaction medium conditioning effect of the different kinds of biochar applied were (to different extents) higher than in a non-treated anaerobic digestion system. This was probably owing to the physicochemical characteristics of biochar, such as its large specific surface area, porous structure, and formation of appropriate sites for providing stabilisation in microbial communities and promising electron transfer conduits among microorganisms.

It was also found that co-digestion supplemented with biochar increased the maximum production and production rate of methane, while significant increments were observed in the parameter value of different kinetic models. The modified Gompertz model, logistic growth function and the transport-function fitted better to the temporal pattern of methane production than the first-order model, as revealed by lower AIC values and RMSEs, with the transport gas function presenting the best statistical performance. These findings also highlight the importance of assessing kinetic models by various statistical parameters instead of relying on a single criterion.

In general, the results have successfully shown that alkali-activated carbon, in this case, the plant residue derived alkali-activated carbon is a superior choice as a pretreatment material to support anaerobic digestion and improve methane production, followed by sludge derived alkali-activated carbon. These types are practical for

use in organic waste biotreatment and bioenergy recovery systems of biochar that will be applicable for practical use in the future.

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