

Potential production of struvite from the anaerobic digestion of food waste: analysis in one-phase and two-phase configurations

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ABSTRACT

Anaerobic digestion (AD) of food waste (FW) has been gaining more interest as it has potential for the production of organic amendments with high struvite ($\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O}$) content, which is a nutrient of great interest in sustainable agriculture. In this study, the influence of AD of FW in one- and two-phase configurations on methane production and the potential for struvite formation using digestate was evaluated. It was found that the two-phase is more efficient as its organic loading rate is 18% higher than that of one-phase configuration. In addition, the two-phase yielded a higher methane content in biogas (>60%) and a higher organic matter transformation in each of the AD stages (>20%); further, the digestate complied with the regulatory requirements for the use of organic amendments, thereby being deemed as a Type-B material with a struvite precipitation potential, exceeding 80%, as opposed to the digestate from one-phase configuration, which may represent a revenue of up to US\$ 26,505 per year.

Key words: biogas, digestates, hydrolysis, mass balance, methane

HIGHLIGHTS

- Two-phase anaerobic digestion of food waste (AD-FW) is an alternative for the generation of struvite.
- The presence of struvite helps the sanitization of the digestate obtained in the AD-FW.
- Two-phase AD has potential for the treatment as well as energy and agricultural use of FW in small communities.

1. INTRODUCTION

In Latin America, municipal solid waste (MSW) is commonly managed through disposal (36% in sanitary landfills, 33% in uncontrolled open dump sites, and 25% in controlled open dump sites), which costs US\$10–\$20 per ton of MSW (Rojas & Flórez 2019). However, these landfills and dump sites often lack adequate techniques for the management and treatment of leachates, which are one of the main sources of greenhouse gases (Margallo *et al.* 2019). In addition, there are other concerns associated with these practices, such as the reduction or depletion of disposal sites, which has also become a serious issue in urban planning (Manyoma-Velásquez *et al.* 2020).

In the physical composition of MSW, food waste (FW) represents the largest constituent, especially in developing countries (>50%), wherein FW production will likely increase from 1,300 million tons per year reported in 2012 to 2,200 million tons per year by 2025. The FW is characterized by its organic matter, nitrogen, phosphorus, and trace element contents, which can be potentially recovered and used in the generation of value-added byproducts.

One of the strategies for the processing of organic substrates is the implementation of biotechnological processes, such as anaerobic digestion (AD). In AD, biodegradable organic matter is transformed into biogas (mostly methane), which has economic value as a source for renewable energy and as a biomass mixture component (a digested material or digestate, which is the source of organic fertilizers); moreover, biodegradable organic matter has large agricultural potential owing to its bio-fertilizing power (Ma *et al.* 2018).

Further, AD technology for the treatment of solid waste exhibits lower implementation rates across Latin America compared to other regions of the world (Margallo *et al.* 2019).

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FW-treating AD plants usually employ a one-phase configuration, in which all the process stages (from hydrolysis to methanogenesis) occur within a single reactor, with extended solid retention times of up to 20–30 days (Jo *et al.* 2018). However, to achieve better process management conditions in terms of maximizing the methane production, a two-phase configuration is recommended for rapidly acidifiable substrates exhibiting high organic matter content and heterogeneous composition, such as FW, as it guarantees a more stable operation at higher organic loading rates (Aslanzadeh *et al.* 2014; Parra-Orobio *et al.* 2020a, 2020b).

Given that food security at a global level depends on a regular supply of soil nutrients, such as nitrogen (N) and phosphorus (P), the demand for chemical fertilizers has been steadily increasing for the last 100 years. For these purposes, N is largely synthesized through the energy-demanding Haber–Bosch process, while much of the P is extracted from finite mineral reserves (phosphate rock) (Lorick *et al.* 2020). The excessive demand for these elements has not only led to water resource eutrophication but also raised concerns regarding the future supply of fertilizers and food production (Cordell & White 2014).

Despite ~199 million tons of fertilizers being used around the world in 2018 (Thant Zin & Kim 2021), significant P deficiencies are reported in farming soils in many regions, particularly in tropical and subtropical regions (including Colombia) due to soil erosion (IDEAM-MADS 2015; Thant Zin & Kim 2021).

One of the alternatives to chemical or inorganic fertilization is using biofertilizers, such as struvite, which naturally precipitate as crystals whenever the Mg:NH₄:PO₄ concentration ratios exceed 1:1:1 (Castro *et al.* 2017). Unlike other fertilizers, struvite is characterized by low water solubility, which increases its performance by reducing uncontrolled nutrient insertion in the soil and contributes significantly to the protection of the environment (Lorick *et al.* 2020).

In this context, some authors have documented the generation of struvite through AD processes. For example, in their FW codigestion study, Kjerstadius *et al.* (2015) reported that this technology can generate 229 mg of struvite per kg of FW present in the digestate. Further, Wid & Ayut (2019), in their anaerobic process FW valorization study, obtained 136 g of struvite per kg of FW. In both cases, the corresponding research was mainly conducted in one-phase reactors. Vinardell *et al.* (2021) theoretically analyzed the production of struvite from the AD of FW (AD-FW) in one-phase configuration. Finally, Lorick *et al.* (2020) performed a systematic review of struvite production from organic waste, mainly sludge and animal manure; similarly, the present study focused on the production of this biofertilizer in one-phase configuration. For this reason, many authors, such as Ma *et al.* (2018), assert the need to explore alternatives that can be used to recover valuable nutrients from AD-FW as these nutrients represent an important biofertilizer source.

The present study focuses on showing the influence of the configuration of one- and two-phase semicontinuous anaerobic reactors treating FW on the production of renewable energy in the form of methane, and on obtaining biofertilizers such as struvite. Much of the research till date has focused on struvite production in single-phase configuration, and few studies have investigated two-phase reactors that treat FW.

2. MATERIALS AND METHODS

2.1. One and two-phase anaerobic reactor configurations

The semicontinuous reactors used for AD of FW were operated under mesophilic conditions (35 °C ± 1 °C) and fed with FW from a university restaurant serving 3,000 students daily, generating 86.6 kg of FW per day. The composition of the FW used in this study is based on previous studies by Oviedo-Ocaña *et al.* (2015) and Parra-Orobio *et al.* (2018) in small communities that perform separation at the source and selective collection of MSW. The composition of FW used was as follows: banana and potato peels (56%), citrus fruits (25%), non-citrus fruit (8%), fibers and minerals (8%), and herbs (3%).

The inoculum used in the reactors was a mixture of flocculent and granular anaerobic sludge in a 75:25 ratio established according to previous research (Parra-Orobio *et al.* 2020a, 2020b). The flocculent sludge came from an anaerobic sludge digester from a municipal wastewater treatment plant with advanced primary treatment (75%). The granular sludge was taken from an upflow anaerobic sludge blanket (UASB) reactor that treats wastewater generated in pig and bovine slaughter processes (25%).

According to previous studies, such as Parra-Orobio *et al.* (2021), the one-phase configuration (R1) corresponded to a 9.2-L reactor with an organic loading rate (OLR) of 6 kgVS/m³·d, while the OLRs for the two-phase configuration were as follows: an OLR of 15 kgVS/m³·d for the acidogenic reactor (R2, 5.75 L) and an OLR of 7.3 kgVS/m³·d for the methanogenic reactor (R3, 9.2 L). Both configurations were monitored and operated under these conditions for 50 days (Figure 1) (Parra-Orobio *et al.* 2020a, 2020b).

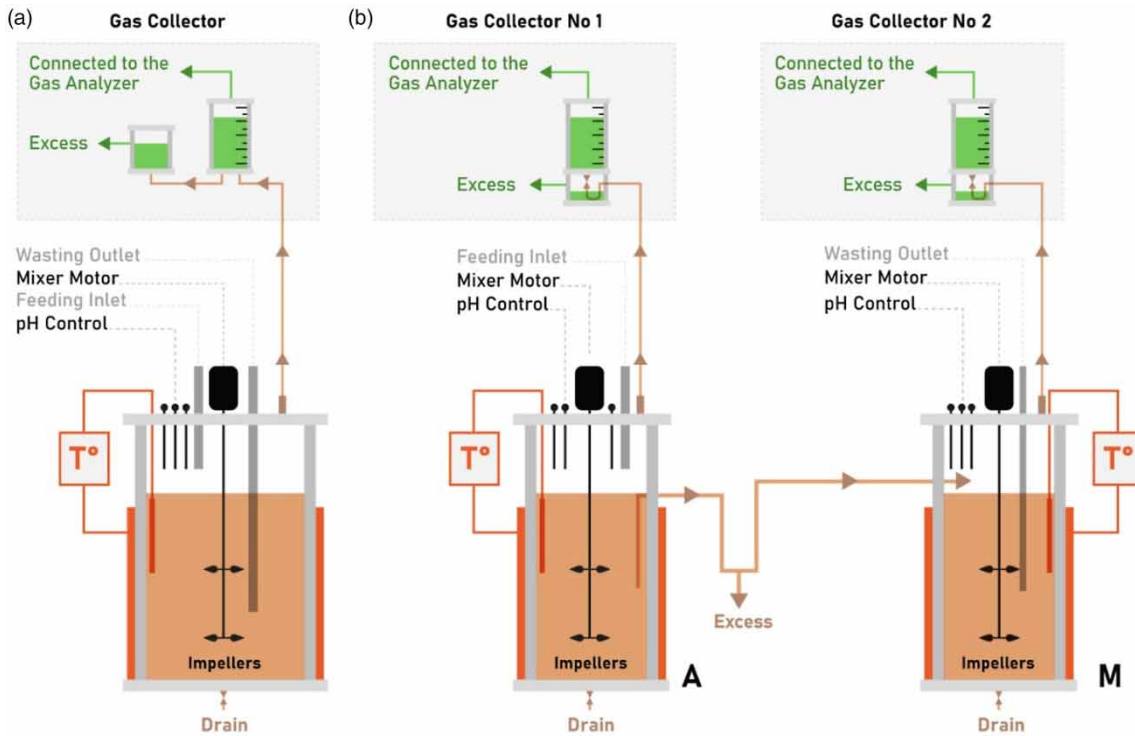


Figure 1 | Anaerobic reactors scheme a. one-phase reactor b. two-phase reactor. A: acidogenic reactor. M: methanogenic reactor.

The biogas volume was quantified through the displacement method and normalized to standard conditions ($T = 273.15 \text{ K}$, $P = 1 \text{ atm}$). The biogas composition was determined via gas chromatography using a GC2014 chromatograph (Shimadzu Corporation, Kyoto, Japan), and a thermal conductivity detector was used to analysis the composition of the biogas and provide the methane and carbon dioxide content as a percentage value (carrier gas: helium; carrier gas flow: 25 mL/min ; column: molecular sieve; column temperature: $70 \text{ }^\circ\text{C}$; injection temperature: $120 \text{ }^\circ\text{C}$; current: 170 mA). The biogas samples were taken once a day during all the days of operation of the reactors.

The affluent and effluent from each of the reactors were sampled every five days in terms of pH (potentiometric in a 50-mL extract of distilled water and a 10-g sample), total alkalinity and bicarbonate alkalinity (titration method), volatile fatty acids (VFAs) (titration method), and total ($\text{COD}_{\text{total}}$) and soluble chemical oxygen demand ($\text{COD}_{\text{soluble}}$) (closed reflux and spectrophotometry-DR 500 spectrophotometer) (APHA 2005). The alpha index (α_1), was determined for each of the reactors as suggested by Ripley *et al.* (1986).

2.2. Chemical oxygen demand (COD) fragmentation at each anaerobic process stage

To assess the equilibrium and reactions of the different AD stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis), the mass balance was analyzed in terms of COD in each of the reactors, as per the recommendations from Wu *et al.* (2016) for one-phase and two-phase reactors, using Equations (1)–(12).

$$\text{Hydrolysis } \% = \frac{(\text{TCOD} - \text{SCOD})_{\text{affluent}} - (\text{TCOD} - \text{SCOD})_{\text{effluent}}}{(\text{TCOD} - \text{SCOD})_{\text{affluent}}} * 100 \quad (1)$$

$$\text{Acidogenesis } \% = \frac{(\text{COD}_{\text{AGV}} + \text{COD}_{\text{CH}_4})_{\text{Reactor}} - (\text{COD}_{\text{VFA}})_{\text{effluent}}}{(\text{TCOD} - \text{COD}_{\text{VFA}})_{\text{affluent}}} * 100 \quad (2)$$

$$\text{Acetogenesis } \% = \frac{(\text{COD}_{\text{HAc}} + \text{COD}_{\text{CH}_4})_{\text{Reactor}} - (\text{COD}_{\text{HAc}})_{\text{effluent}}}{(\text{TCOD} - \text{COD}_{\text{HAc}})_{\text{effluent}}} * 100 \quad (3)$$

$$\text{Methanogenesis } \% = \frac{(\text{COD}_{\text{CH}_4})_{\text{Reactor}}}{\text{TCOD}_{\text{effluent}}} * 100 \quad (4)$$

$$\text{Hydrolysis rate (HR: gCOD/L*d)} = \frac{Q*(\text{TCOD} - \text{SCOD})_{\text{effluent}} - Q*(\text{TCOD} - \text{SCOD})_{\text{effluent}}}{V} \quad (5)$$

$$\text{Acidogenesis rate (AR: gCOD/L*d)} = \frac{Q*(\text{COD}_{\text{VFA}})_{\text{effluent}} + V*(\text{COD}_{\text{CH}_4})_{\text{Reactor}} - Q*(\text{COD}_{\text{VFA}})_{\text{effluent}}}{V} \quad (6)$$

$$\text{Acetogenesis rate (AcR: gCOD/L*d)} = \frac{Q*(\text{COD}_{\text{HAc}})_{\text{effluent}} + V*(\text{COD}_{\text{CH}_4})_{\text{Reactor}} - Q*(\text{COD}_{\text{HAc}})_{\text{effluent}}}{V} \quad (7)$$

$$\text{Methanogenesis rate (MR: gCOD/L*d)} = (\text{COD}_{\text{CH}_4})_{\text{Reactor}} \quad (8)$$

$$\text{Specific hydrolysis rate (SHR: gCOD/gVS*d)} = \frac{Q*(\text{TCOD} - \text{SCOD})_{\text{effluent}} - Q*(\text{TCOD} - \text{SCOD})_{\text{effluent}}}{\text{VS}_{\text{Reactor}}*V} \quad (9)$$

$$\text{Specific acidogenesis rate (SAR: gCOD/gVS*d)} = \frac{Q*(\text{COD}_{\text{VFA}})_{\text{effluent}} + V*(\text{COD}_{\text{CH}_4})_{\text{Reactor}} - Q*(\text{COD}_{\text{VFA}})_{\text{effluent}}}{\text{VS}_{\text{Reactor}}*V} \quad (10)$$

$$\text{Specific acetogenesis rate (SAcR: gCOD/gVS*d)} = \frac{Q*(\text{COD}_{\text{HAc}})_{\text{effluent}} + V*(\text{COD}_{\text{CH}_4})_{\text{Reactor}} - Q*(\text{COD}_{\text{HAc}})_{\text{effluent}}}{\text{VS}_{\text{Reactor}}*V} \quad (11)$$

$$\text{Specific methanogenesis rate (SMR: gCOD/gVS*d)} = \frac{(\text{COD}_{\text{CH}_4})_{\text{Reactor}}}{\text{VS}_{\text{Reactor}}} \quad (12)$$

where TCOD is the total chemical oxygen demand (COD) of the FW (g/L), SCOD is the $\text{COD}_{\text{soluble}}$ of the FW (g/L), COD_{VFA} is the VFA present in the FW in terms of COD (g/L), COD_{HAc} is the acetic acid present in the FW as COD (g/L), COD_{CH_4} is the equivalent amount of methane produced in COD (g/L), and $\text{VS}_{\text{Reactor}}$ is the volatile solids from FW present in the reactor (g/L).

2.3. Digestate characterization and potential struvite determination

The digestate collection process involved collecting the liquid and solid portions of the material digested in the anaerobic process, wherein samples were taken after the operation of the R1 (Digestate 1: C1) and R3 (Digestate 2: C2) reactors. Then, the samples were stored at 4 °C until their characterization was in accordance with the Agricultural Application Standards from the Colombian Standards for Organic Products used as fertilizers (Colombian Technical Standard-NTC 5167-ICONTEC (2011) and Executive Order 1287 of 2014 (MVCT 2014)), in addition to elements from the US EPA Standard No. 503 of 1994 (USEPA 1995).

The parameters were measured by following the protocols established by APHA (2005) and ICONTEC (2011): cation exchange capacity (CEC) (in an extract containing 50 mL of distilled water and 10 g of sample), total organic carbon (TOC) (spectrophotometric method), total nitrogen (Kjeldahl Titration method), total phosphorus (spectrophotometric method), and metals (Cu, Cd, Cr, Mg, Zn, Hg, Mo, Ni, Pb, and Se) (via atomic absorption). Microbiological and parasitological parameters characterized were fecal coliforms (FC), *Salmonella spp.*, and viable Helminth Eggs (HE), as suggested by Bailenger (1979), USEPA (1995), and Boost & Poon (1998). All physicochemical, microbiological, and parasitological parameters were measured in triplicate.

To estimate the potential struvite precipitation (PSP), Mg, NH_4^+ , and PO_4^{3-} contents present both in the substrate and in the digestate were considered. The maximum amount of struvite was determined according to the stoichiometry from its formation reaction (Equations 13 and 14) (Castro *et al.* 2017). Finally, an economic approximation of the PSP was

conducted as suggested by Castro *et al.* (2017).



$$\text{PPE} = ([\text{PO}_4^{3-}]_{\text{digestate}} \left[\frac{\text{g}}{\text{kg}} \right] * \frac{245 \text{g struvite}}{95 \text{g PO}_4^{3-}} * \frac{\text{quantity of digestate (kg)}}{\text{quantity of substrate added (kg)}} \quad (14)$$

2.4. Statistical analysis

Considering the nonlinear trend of the parameters evaluated herein, the differences in the behavior of the configurations were evaluated by adjusting generalized semiparametric additive models. Similarly, correlation indicators between the parameters were determined using Pearson's (low normality) or Spearman coefficients (under noncompliance with the assumption of normality of the data) (Montgomery 2004).

3. RESULTS AND DISCUSSION

3.1. Biogas production behavior and process stability

Figure 2 shows the behavior of the reactors in terms of the production of biogas, methane, and carbon dioxide (2a, b and c); the behavior of pH and VFAs during the operating period of the reactors (2d, e and f); and the corresponding alpha index (2g, h and i).

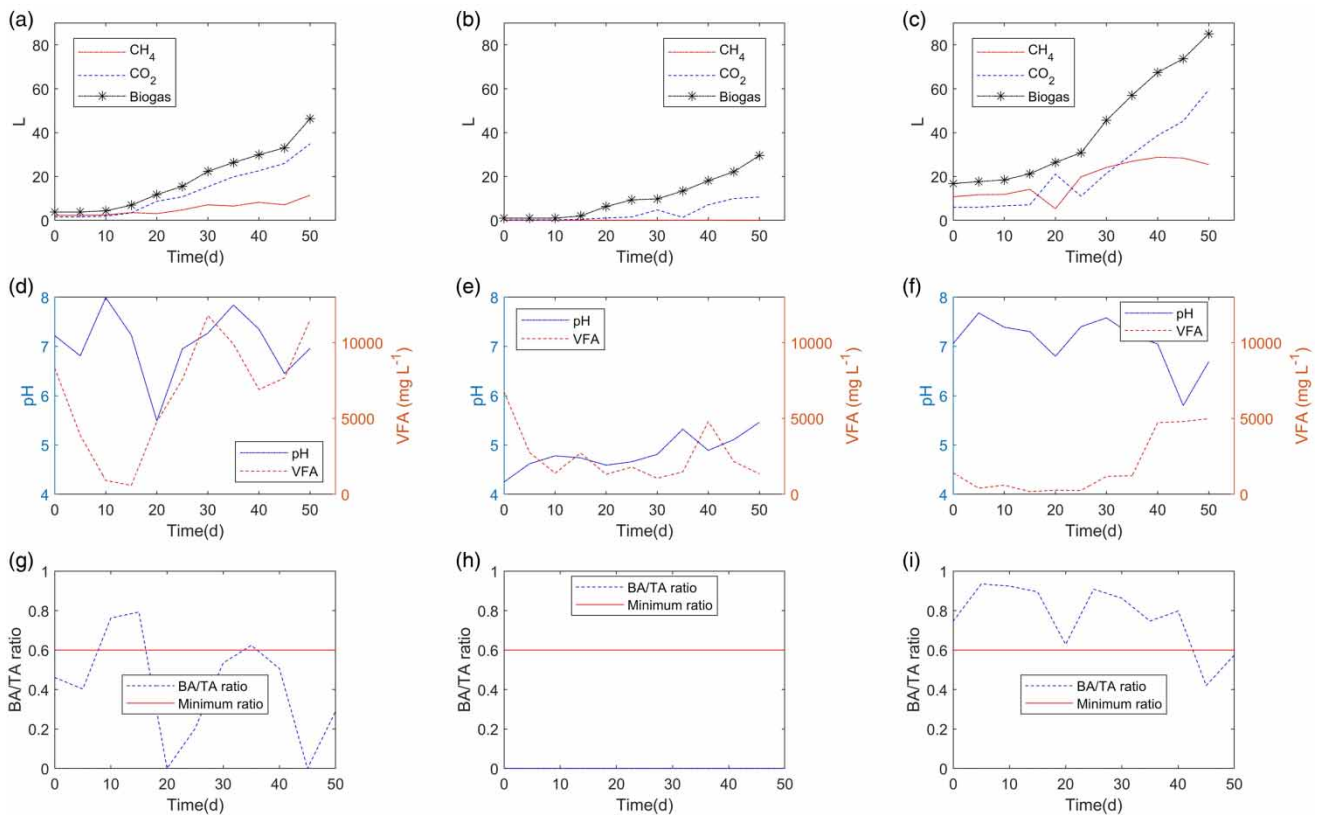


Figure 2 | (a) biogas quality and quantity for the one-phase configuration (R1), (b) biogas quality and quantity the two-phase configuration (R2: acidogenic reactor), (c) biogas quality and quantity for the two-phase configuration (R3: methanogenic reactor), (d) pH level and volatile fatty acids behavior for the one-phase configuration (R1), (e) pH level and volatile fatty acids behavior for the configuration two-phase (R2: acidogenic reactor), (f) pH level and volatile fatty acids behavior for the two-phase configuration (R3: methanogenic reactor), (g) alpha index for the one-phase configuration (R1), (h) alpha index for the two-phase configuration (R2: acidogenic reactor), (i) alpha index for the two-phase configuration (R3: methanogenic reactor).

Therein, we can observe differences in the configurations in terms of the quantity and quality of the biogas. Here, the two-phase configuration (R2 and R3) is more stable than the one-phase configuration (R1), which coincides with the findings reported by authors such as *Aslanzadeh et al. (2014)* and *Xiao et al. (2018)*. The stability in the two-phase reactor is due to the fact that the phase separation allows the consolidation of microbial consortia that facilitate the degradation of complex and heterogeneous organic matter, such as FW, and that, in turn, is observed in the quantity and quality of the biogas generated using this type of configuration.

In the two-phase configuration, the amount of biogas produced in the reactor was minimal; a large percentage of carbon dioxide and a low percentage of methane were generated (R2: acidogenic reactor). Hydrogen accounted for the remaining percentage as this gas is produced by bacteria within the pH ranges in which this reactor was maintained (4.5–6.0). This is consistent with the results reported by authors such as *Mañunga et al. (2019)*, who stated that this pH range favors the metabolism of these microorganisms and of carbohydrate-rich substrates such as FW.

The biomass in the case of R3 reached a greater adaptability, which was reflected in the larger biogas quantities (volume) and better biogas quality (methane content) than in R1. This may be due to high VFA concentrations present in the one-phase reactor, associated with disturbance scenarios due to OLR (*Figure 2(g)*), which was not observed in the two-phase reactor. This could be due to the type of inoculum used and the metabolic pathways that were established as a result of the phase separation. Authors such as *Parra-Orobio et al. (2018)* state that the inoculum can have an important impact on the buffer capacity of the system as, depending on its origin, these can provide alkalinity temporarily, mainly in the start-up stage. However, by varying the operation conditions of the reactor, this period of alkalinity can be prolonged (*Xiao et al. 2018*; *Parra-Orobio et al. 2021*).

In short, the two-phase configuration yielded an 18%-OLR increase compared to R1. In addition, in the two-phase configuration, the AD process did not show extended disturbance periods, reaching methane contents of >60% and better buffer capacity conditions (*Figure 2(i)*) than R1, which also confirms that this configuration restricts the amount of substrate to be treated. The aforementioned results are consistent with the results reported by *Aslanzadeh et al. (2014)* and *Jo et al. (2018)*, who stated that the two-phase configuration generates a higher methane content and achieves a higher system operational stability.

3.2. Chemical oxygen demand (COD) fraction in the anaerobic process stages for each configuration

Figure 3(a) shows the organic matter transformation that took place in each stage, *Figure 3(b)* shows the reaction rates in each stage, and *Figure 3(c)* shows the biomass growth throughout the different AD phases. In the case of the one-phase reactor

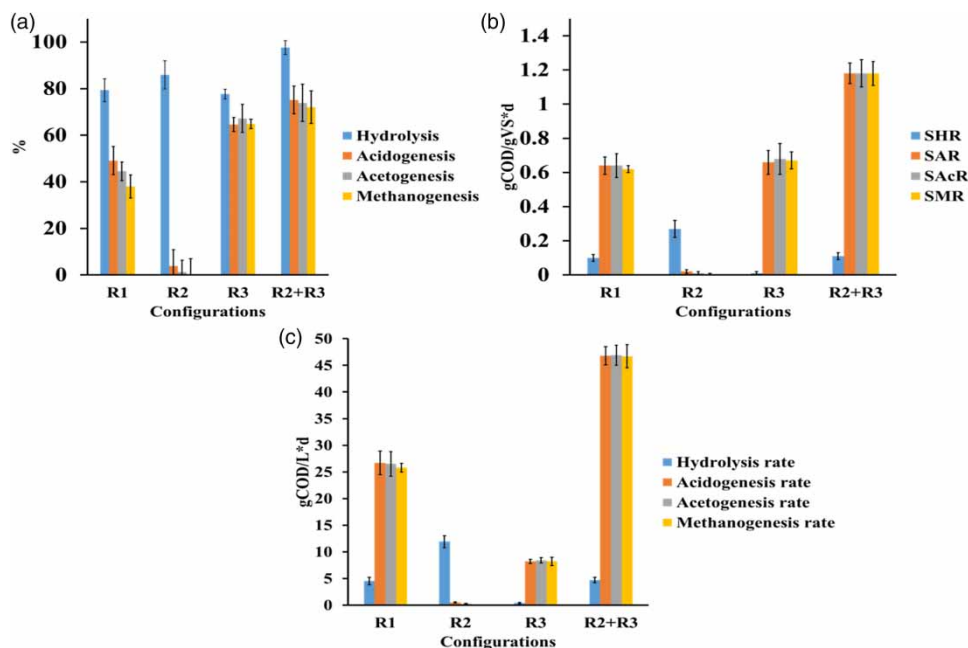


Figure 3 | Chemical oxygen demand mass balance in the different anaerobic digestion stages. (a) Organic matter transformation percentages by stage, (b) reaction rates, (c) biomass growth.

(R1), the used OLR generated a significant destabilization of the hydrolytic process as we only observed a 79% fragmentation compared to the 97.7% observed in the two-phase configuration (R2 + R3). This also exerts a negative effect on the other process stages as reflected in a lower biogas production and quality, where only 38% of the organic matter introduced into the reactor (R1) was transformed into methane.

The previously described phenomenon may be due to the fact that the organic substances present in the FW are disintegrated and hydrolyzed in the hydrolytic reactor, where the acidification process also occurs; in this stage, the released proteins are metamorphosed into peptides and amino acids; the amino acids, in turn, convert into organic acid, NH_3 , and CO_2 (Kavitha *et al.* 2016). In addition, carbohydrates are transformed into polysaccharides, or even reducing sugar, a source of carbon and energy for microbial consortia that is more solidly established in the two-phase configuration, which reaffirms the results obtained.

On the contrary, the values are similar to those reported in the studies by Wu *et al.* (2015a, 2015b). Although these studies used a lower OLR, which can have a considerable impact on the consolidation of microbial consortia capable of adapting to the loading disturbances in the single-phase reactor, the reaction rates (HR, AR, AcR, and MR) and the specific biomass rates (SHR, SAR, SAcR, and SMR) in the present study were higher than those reported in these previous studies, which can be attributed to the microbial diversity of the mixed inoculum (Xiao *et al.* 2018; Parra-Orobio *et al.* 2020a, 2020b).

In general terms, the two-phase configuration achieved higher COD transformations than the one-phase reactor, both in terms of the conversion for each stage and the reaction and specific biomass rates. Results from this configuration increased by 18%–45.2, 9–26%, 11.5%–29.4%, and 12.3%–34.1% in the hydrolysis, acidogenesis, acetogenesis, and methanogenesis stages, respectively. These values are similar to those reported by Xiao *et al.* (2018).

As per the foregoing, phase separation favors substrate hydrolyzation (more than 90% of the substrate is hydrolyzed), which translates into a higher methane production. In this case, the methanogenesis reaction rate was 20% higher. Similarly, the specific methanogenesis rate associated with substrate assimilation during biomass growth in each stage exceeded 30%, which is consistent with the values reported by Wu *et al.* (2015a). Hence, phase separation also facilitates the growth of microbial consortia that treat such heterogeneous and complex wastes as FW.

3.3. Digestate characterization and potential struvite precipitation for each configuration

In addition to the favorable effects of the two-phase configuration on methane production, we also observed its effects on digestate characterization. Table 1 presents the physicochemical, microbiological, and parasitological characterization results for the C1 and C2 digestates from the two configurations assessed and the suggested values from the different standards used as benchmarks.

The CEC is associated with the gradual release of nutrients to crops and the retention of potential pollutants within the soil (Greenberg *et al.* 2019). Some authors, such as Gusiatin *et al.* (2016), claim that CEC values are linked to the organic matter and hydroxide content as they interact with the exchangeable cations present in the soil. In the present study, C1 yielded a lower CEC than the minimum value defined by Colombian Technical Standard-NTC 5167 (ICONTEC 2011), while C2 fully complied with this value. The low CEC in the case of C1 can be associated with the operating OLR used in the reactor, which led to an excess of unmineralized organic matter, as proven by the high VFA concentrations obtained (Aslanzadeh *et al.* 2014).

Overall, these nutrient variables meet the minimum requirements for organic fertilizers used in crops established in NTC 5167 (ICONTEC 2011), wherein the potential contribution from digestates in terms of organic matter and nutrients is emphasized. Along these lines, C2 yielded the highest N and P concentrations. The values found herein are also similar to other digestates obtained through anaerobic FW digestion, such as those reported by Bhogal *et al.* (2016) (4.67 gN/kg and 0.61 gP/kg) and Möller (2016) (7.53 gN/kg and 1.76 gP/kg).

Regarding heavy metal content, the digestates comply with the provisions listed in Colombian Executive Order 2187 of 2014 (MVCT 2014) and EPA Part 503 (USEPA 1995). In terms of pathogenicity, the absence of both FC and *Salmonella* sp is probably due to the bactericidal effects from VFAs (Samaniego & Pedroza-Sandoval 2013). C1 also exhibited a higher HE level than C2 (total inactivation), which may be due to the antiparasitic effects from VFAs and the double exposure experienced by the digested material to these compounds in the two-phase configuration – conditions that may completely destroy the protective layer of these pathogens (Samaniego & Pedroza-Sandoval 2013; Ambrose *et al.* 2020).

To obtain struvite, a biofertilizer with a high agronomic value, NH_4^+ , phosphorus, and Mg are required (Castro *et al.* 2017). When assessing the content of these compounds in the digestates, the superiority of C2 is evident, wherein the increase in NH_4^+ content in R3 may be caused by the degradation of nitrogenous organic compounds, such as the proteins present in the substrate. In fact, their digestion favors the occurrence of ammonification processes (Ma *et al.* 2018), which in turn

Table 1 | Physicochemical, microbiological, and parasitological characterization of digestates for the one- and two-phase configurations

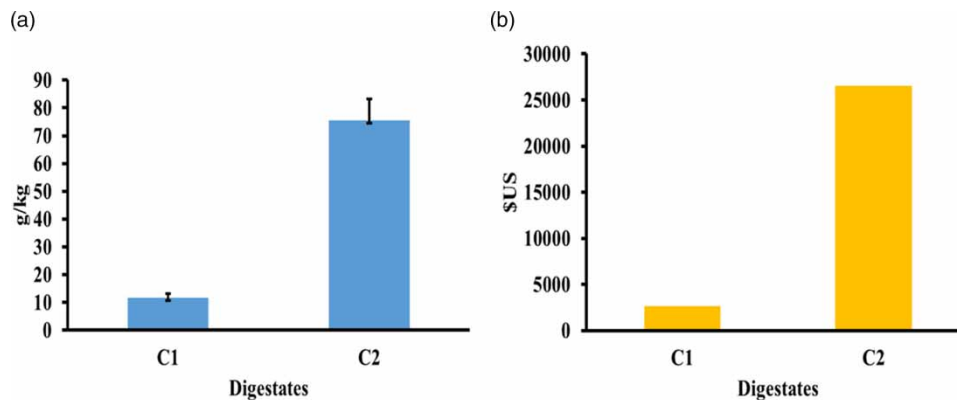
Parameters	Substrate	C1	C2	Executive order 1287/14 ^a	USEPA (1995)
Physicochemical characterization					
CEC (cmol/kg)	N.E.	20.75	51.80	N.E.	N.E.
TOC (g/kg)	39.46	37.18	39.47	N.E.	N.E.
TN (g/kg)	1.86	6.46	14.13	N.E.	N.E.
TP (g/kg)	0.2	7.23	10.58	N.E.	N.E.
NH ₄ ⁺ (mg/L)	86	176	342	N.E.	N.E.
Cu (mg/kg)	<1.0	31.65	148.26	1750	1,500
Cd (mg/kg)	<1.0	0.11	0.22	40	39
Cr (mg/kg)	<1.0	11.19	52.75	1,500	1,200
Zn (mg/kg)	6.5	202.25	1,176.52	2,800	2,800
Hg (mg/kg)	<0.01	<0.01	<0.01	20	17
Mo (mg/kg)	<2.30	<2.30	2.30	75	75
Ni (mg/kg)	4.5	7.76	32.84	420	420
Pb (mg/kg)	<0.01	3.12	23.01	400	N.E.
Se (mg/kg)	<0.01	<0.01	<0.01	100	36
Mg (g/kg)	9.61	5.11	7.20	N.E.	N.E.
Microbiological and parasitological characterization					
FC (CFU/100 mL)	N.D.	0	0	<2E + 6	<1,000
<i>Samonella spp.</i> (CFU/25 g)	N.D.	Absence	Absence	<1 E + 3	<3 NMP/4 g
HE (Egg Units/g)	N.D.	16	0	<10	1

^aClass B Classification; N.E.: Not established; N.D.: Not determined.

promotes PSP. Furthermore, the high phosphorus concentration in C2 may be associated with the formation of precipitates with the different metals observed in this digestate.

In the case of Mg, FW is often composed of magnesium-rich banana peels and herbs; Mg constitutes the main chelate that produces the chlorophyll commonly found in FW. The Mg level observed in the substrate exceeded 9 g/kg. In the C2 digestate, the Mg concentration was 7.2 g/kg, which is higher than the Mg concentration reported for C1 (5.1 g/kg). Again, these values are consistent with the results reported by *Tuszynska et al.* (2021).

Figure 4 shows the PSP for each configuration based on Equation (13), as well as the possible revenue from struvite. The PSP value obtained in the case of C2 (75.60 g of struvite per kg of FW) was much higher than the PSP value reported for C1 (11.64 g of struvite per kg of FW), representing an 84.5% increase and confirming the potential of the two-phase configuration in the

**Figure 4** | (a) Potential struvite precipitation, (b) potential revenue from struvite for each digestate.

production of this fertilizer. These results are consistent with those presented by Wid & Ayut (2019), who report a maximum production of 136 g of struvite per kg of FW, depending on the substrate type and characteristics and the configuration used. This provides further evidence that FW can be used as an efficient source of this fertilizer through anaerobic FW digestion.

According to some authors, such as Ma *et al.* (2018), PSP also fosters digestate sanitation as struvite precipitation facilitates the reduction of pathogens present in the digestates. On the contrary, PSP can have a reducing effect on COD as pointed out by authors such as Zeng *et al.* (2021); this shows that the production of struvite is important from an agricultural perspective and has relevance in the degradation of organic matter through anaerobic processes.

Another aspect to highlight regarding the PSP in the single-phase reactor is the relationship of alkalinity and the formation of struvite; Barampouti *et al.* (2020) point out that during the generation of struvite in the digestates a high consumption of alkalinity is required. Therefore, this phenomenon can be related to what is observed in Figure 2(c), for the one-phase reactor, where an alteration in the buffer capacity can be observed. This can be associated as a possible cause of the low PSP for the one-phase configuration.

Regarding other environmental benefits, PSP obtained through the two-phase configuration is a potential alternative for the traditional ammonia production methods, such as ammonia stripping (Sheets *et al.* 2015) and the use of magnesium hydroxides (Castro *et al.* 2017), and presents two important aspects associated with energy and economic consumption due to the need for external processes and inputs (Lorick *et al.* 2020). In addition, it can also generate an annual revenue of ~US\$ 26,505 for a population of <15,000 people, which is in line with the concepts of circular economy and biorefineries associated with comprehensive and sustainable FW management (Margallo *et al.* 2019).

Overall, in addition to a better performance in terms of methane production, the two-phase AD-FW configuration generates a digestate with better physicochemical, microbiological, and parasitological characteristics in accordance with the Colombian (Executive Order 1287-2014) and the US (EPA 503-1994) standards. Based on its metal content, low FC count, and the absence of *Salmonella spp.* and HE, the C2 digestate is classified as a Type-B material, which means that it can be used as a soil conditioner or biofertilizer for crops that require further processing (e.g., sugar cane, oil palm, and corn) (USEPA 1995; MVCT 2014).

Similarly, C2 exhibits potential for struvite precipitation without requiring external agents, which would also guarantee economic returns. This would further contribute to the application of AD of FW using the principles of circular and ecological economies in developing countries, where final disposal has usually been the main FW management option (Rojas & Flórez 2019; Cesaro 2021).

4. CONCLUSIONS

To conclude, it was found that the two-phase AD configuration, or separate phases in semicontinuous reactors, favor the hydrolysis of complex waste such as FW. This supports an efficient transformation of complex organic matter to simpler compounds assimilable by both acetogens and methanogenic *archaea*, which guarantees an 18% increase in the OLR from the one-phase configuration. In addition, a greater buffer capacity stability is achieved, as well as an increase in biogas production and quality in terms of a higher methane content.

This study also concluded that through a two-phase AD, a larger amount of organic matter is converted in each AD stage, reporting an increase of up to 45% in the hydrolysis phase, 28% in the acidogenesis phase, 29.4% in the acetogenesis phase, and 34.1% in the methanogenesis phase from the one-phase reactor. This behavior is also reflected in the process reaction rates, as well as in the biomass growth observed in each stage.

The two-phase configuration also provides the possibility of obtaining a digestate of high agricultural value and with better quality in terms of essential macronutrient content, such as N and P, as well as an 80% higher PSP than the one-phase configuration. The digestate obtained satisfies the criteria for Class-B materials.

It is necessary to continue analyzing the quality of biogas and the digestate obtained from the two-phase configuration, mainly to determine its hydrogen content and its effect on different soils according to the crop where it is intended to be applied.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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