ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.11, e280349, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n11e280349

ORIGINAL ARTICLE

Anaerobic mono-and co-digestion of fruit and vegetable residues: Effects on biogas yield and biofertilizer[1]

Mono e codigestão anaeróbia de resíduos de frutas e vegetais: Efeitos no rendimento de biogás e no biofertilizante

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HIGHLIGHTS:
Anaerobic mono-digestion of fruit and vegetable residues is viable using biofertilizer as a diluent.
Anaerobic co-digestion of fruit and vegetable residues and dairy cattle wastewater improves biogas and methane yields.
Anaerobic co-digestion of fruit and vegetable residues and dairy cattle wastewater improves biofertilizer quality.

ABSTRACT: The proper disposal of fruit and vegetable waste is essential to promote environmental sustainability, reduce the carbon footprint, improve soil quality, and contribute to the transition to a circular economy. This study examined the impact of incorporating dairy cattle wastewater (DCWW) into anaerobic co-digestion with fruit and vegetable residues and utilization of the resulting biofertilizer as a diluent in the anaerobic mono-digestion of fruit and vegetable residues (recycle). The specific biogas and methane production and the agronomic quality of the biofertilizer were evaluated in a semi-continuous trial. Two startup strategies were employed: initially, the reactors were entirely fed with inoculum (biofertilizer derived from DCWW), and fruit and vegetable residue feedstock was gradually introduced. Anaerobic co-digestion of fruit and vegetable residues with DCWW yielded the highest specific production of biogas and methane at 720 and 436 L kg^{-1} of volatile solids (VS), respectively. The addition of DCWW increases fruit and vegetable residue alkalinity by 249% and reduces the volatile acidity by 83.4%. Anaerobic mono-digestion of fruit and vegetable residues enhances macronutrient recovery in the biofertilizer through recycle. Logistically, directing fruit and vegetable residues to rural areas for anaerobic co-digestion with DCWW promotes agricultural biofertilizer use.

Key words: specific biogas and methane production, process stability, nutrient recovery, recycle

RESUMO: A destinação adequada dos resíduos de frutas e vegetais é fundamental para promover a sustentabilidade ambiental, reduzir a pegada de carbono, melhorar a qualidade do solo e contribuir para a transição para uma economia circular. Neste estudo, foram avaliados os efeitos da adição de água residuária da bovinocultura de leite em codigestão anaeróbia com resíduos de frutas e vegetais e o uso do biofertilizante como diluente na monodigestão anaeróbia dos resíduos de frutas e vegetais (reciclo). A produção específica de biogás e metano, bem como a qualidade agronômica do biofertilizante em um estudo semicontínuo, foram avaliados. Foram utilizadas duas estratégias para partida dos reatores: o abastecimento inicial dos reatores totalmente com inóculo (biofertilizante proveniente da digestão anaeróbia da água residuária da bovinocultura de leite) e a progressão de carga para os resíduos de frutas e vegetais. A maior produção específica de biogás e metano foi atingida pela codigestão anaeróbia de resíduos de frutas e vegetais com água residuária da bovinocultura de leite, 720 e 436 L kg^{-1} de sólidos voláteis (SV), respectivamente. A adição da água residuária da bovinocultura de leite aumentou em 249% a alcalinidade dos resíduos de frutas e vegetais e diminuiu em 83,4% sua acidez volátil. A recuperação de macronutrientes no biofertilizante é favorecida pela monodigestão anaeróbia dos resíduos de frutas e vegetais em função do uso do reciclo. Entretanto, visando a destinação destes ao meio rural, a codigestão anaeróbia com água residuária da bovinocultura de leite favorece o uso agrícola do biofertilizante.

Palavras-chave: produção específica de biogás e metano, estabilidade do processo, recuperação de nutrientes, reciclo

• Ref. 280349 – Received 10 Nov, 2023
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• Accepted 04 Jun, 2024 • Published 01 Jul, 2024
Editors: Toshik Iarley da Silva & Walter Esfrain Pereira

Introduction

Fruit and vegetable residues (FVR) in landfills are rapidly degraded through microbial action, producing harmful leachate and greenhouse gases (Zafar et al., 2023). However, FVR can be directed toward biological stabilization processes such as anaerobic digestion (AD). Nevertheless, it also faces challenges including FVR acidification due to rapid hydrolysis and the issue of biofertilizer disposal (Tsigkou et al., 2023) when AD occurs in supply centers (CEASAs). Anaerobic co-digestion (ACoD) of FVR with animal manure and recycle (reuse of biofertilizer in daily feedstock composition) can increase alkalinity in the system (Tsigkou et al., 2023) and address the biofertilizer disposal issue (Bortoloti et al., 2023).

Both strategies share a common mechanism to reduce acidification resulting from the rapid hydrolysis of carbohydrates in FVR (Tsigkou et al., 2023). Nitrogen compounds from protein degradation provide buffering capacity, supplying alkalinity and restoring balance to the acetogenic and methanogenic phases (Sitorus et al., 2013; Bres et al., 2018). ACoD enhances biogas production compared to anaerobic mono-digestion (AMoD) of residues separately, while the recycle benefits the AMoD process by increasing nutrient concentration and reducing effluent production, crucial in scenarios in which logistics for agricultural biofertilizer use are unfavorable. The choice between these scenarios offers different disposal options for the same residue. Environmental sanitation and energy generation are favored in CEASAs, while all three advantages (environmental sanitation, agronomic recycling, and energy recovery) can be achieved from FVR in rural areas. Effective decision-making requires comprehensive information on these scenarios, considering local factors such as edaphoclimatic conditions, social dynamics, cultural aspects, and economic realities. Gathering such information is critical for making informed decisions that align with local contexts. Therefore, this study aimed to provide insights into energy and nutrient recovery in three scenarios involving FVR AD: anaerobic mono-digestions of FVR and dairy cattle wastewater (DCWW) and the combination of both, anaerobic co-digestion of FVR with DCWW.

Material and Methods

The research was conducted at the annex of the Laboratório de Análise de Resíduos Agroindustriais (LARA), located in the Universidade Estadual do Oeste do Paraná (UNIOESTE), campus Cascavel, Paraná, Brazil. Cascavel is located at 24° 57' 21" S, 53° 27' 9" W and 780 m of altitude. According to the Köppen-Geiger classification, the city predominantly experiences a Cfa climate, corresponding to a Mesothermal Subtropical Climate. This climate is characterized by hot summers, infrequent frosts, higher rainfall in the summer, and the absence of a defined dry season. The annual average temperature is 20 °C, with an average annual atmospheric pressure of 936.34 hPa (IAPAR, 2019).

Biofertilizer from a full-scale horizontal tubular anaerobic biodigester served as inoculum (Figure 1B). This biodigester operates in a semi-continuous system, receiving dairy cow manure (Figure 1A). The manure undergoes intermittent mechanical stirring and fraction separation (solid/liquid) before its introduction into the biodigester. The dairy cow manure originates from a dairy production agroindustry located in Céu Azul, Paraná State (50.3 km away from the experimental site).

Fruit and vegetable residues (FVR) were sourced from the Cascavel Food Bank in Cascavel, PR, and comprised five types of fruits and five types of vegetables: banana, potato, beetroot, onion, carrot, chayote, papaya, mango, watermelon, and tomato. They were shredded using a TRAPP brand TR-200 model shredder before being introduced to the FVR into the reactor.

Dairy cattle wastewater (DCWW) was obtained from the same dairy production unit where the inoculum was collected. DCWW consists of urine, feces, milk, hair, wash water, rainwater, and water from drinking troughs. It was collected from the collection box preceding the entrance to the anaerobic biodigester. Table 1 shows the physicochemical

A.

B.

Figure 1. Anaerobic biodigester (A) and outlet pipe for inoculum biofertilizer (B)

Table 1. Physicochemical characterization of FVRs and DCWW and anaerobic co-digestion (AcoD)

Variables	Unity	FVR	DCWW	ACoD
pH		4.06±0.06	6.55±0.17	5.54±0.03
Electrical conductivity	mS cm^{-1}	5.22±0.06	7.75±0.49	6.58±0.07
Humidity	%(NM)	87.57±0.22	97.39±0.50	94.63±0.07
Total solids	%(NM)	12.42±0.22	2.60±0.50	5.36±0.07
Volatile solids	%(TS)	91.70±1.05	77.68±1.19	88.84±0.23
Fixed solids	%(TS)	8.29±1.05	22.31±1.19	11.15±0.23
Total organic carbon	%(TS)	50.94±0.1	43.15±0.2	49.35±0.1

NM - Natural matter; FVR - Fruit and vegetable residues; DCWW - Dairy cattle wastewater; ACoD - Anaerobic co-digestion. Mean ± standard deviation characterization of the substrates used in the study, including the anaerobic co-digestion of FVRs + DCWW.

The experiment used three anaerobic reactors operating semi-continuously (Figure 2), following established models at the Laboratory of Anaerobic Biodigestion of the Universidade Estadual Paulista - Faculdade de Ciências Agrárias e Veterinárias de Jaboticabal (UNESP - FCAVJ). Each reactor had a working volume of 60 L and represented a specific treatment (Table 2).

The experiment spanned 109 days, with 52 days devoted to gas production measurement (repetitions). A hydraulic retention time (HRT) of 30 days was assumed for all treatments once daily volumetric biogas production stabilized, achieving a coefficient of variation below 5%. Temperature control maintained the mesophilic phase (between 30 and 40 °C) using a heating plate equipped with nickel-chromium resistors.

Gasometers were constructed with two concentric PVC tubes: the outer tube, 300 mm in diameter, was filled with water, while the inner tube, 230 mm in diameter, was submerged in a sealing solution to measure displacements caused by biogas production in the digestion chamber. A graduated ruler on the outer surface facilitated the displacement determination. After measuring, biogas was fully discharged and emptied from the gasometers.

Table 2. Composition of treatments in semi-continuous reactors

Treatment	Composition
T_1	FVR AMoD
T_2	FVR + DCWW anaerobic co-digestion
T_3	DCWW AMoD

T_1: Anaerobic mono-digestion of fruit and vegetable residues (AMoD of FVR); T_2: Anaerobic co-digestion of fruit and vegetable residues + dairy cattle wastewater (ACoD of FVR + DCWW); T_3: Anaerobic mono-digestion of dairy cattle wastewater (AMoD of DCWW)

During the initial seven days of the experiment, all three reactors were filled with 60 liters of inoculum only to acclimate anaerobic microorganisms. Subsequently, treatments T_1 and T_2 were fed with incremental total solids loads of FVR (1, 1.5, 2, 2.5, 3, and 3.5%) for a daily feeding of two liters. For T_1, the load included FVRs, water, and a 40% recycle from the process, totaling a daily load of 2 L.

After biogas production stabilized, gas samples were collected (instantaneous chromatographic analysis - one sample per week), and biofertilizer samples were collected (subsequent physicochemical analysis - three samples per week) over 30 days (HRT). The volume of biogas produced during the experiment was standardized to standard temperature and pressure conditions (STP).

The following variables were analyzed for reactor effluent (biofertilizer) monitoring and control, including pH, electrical

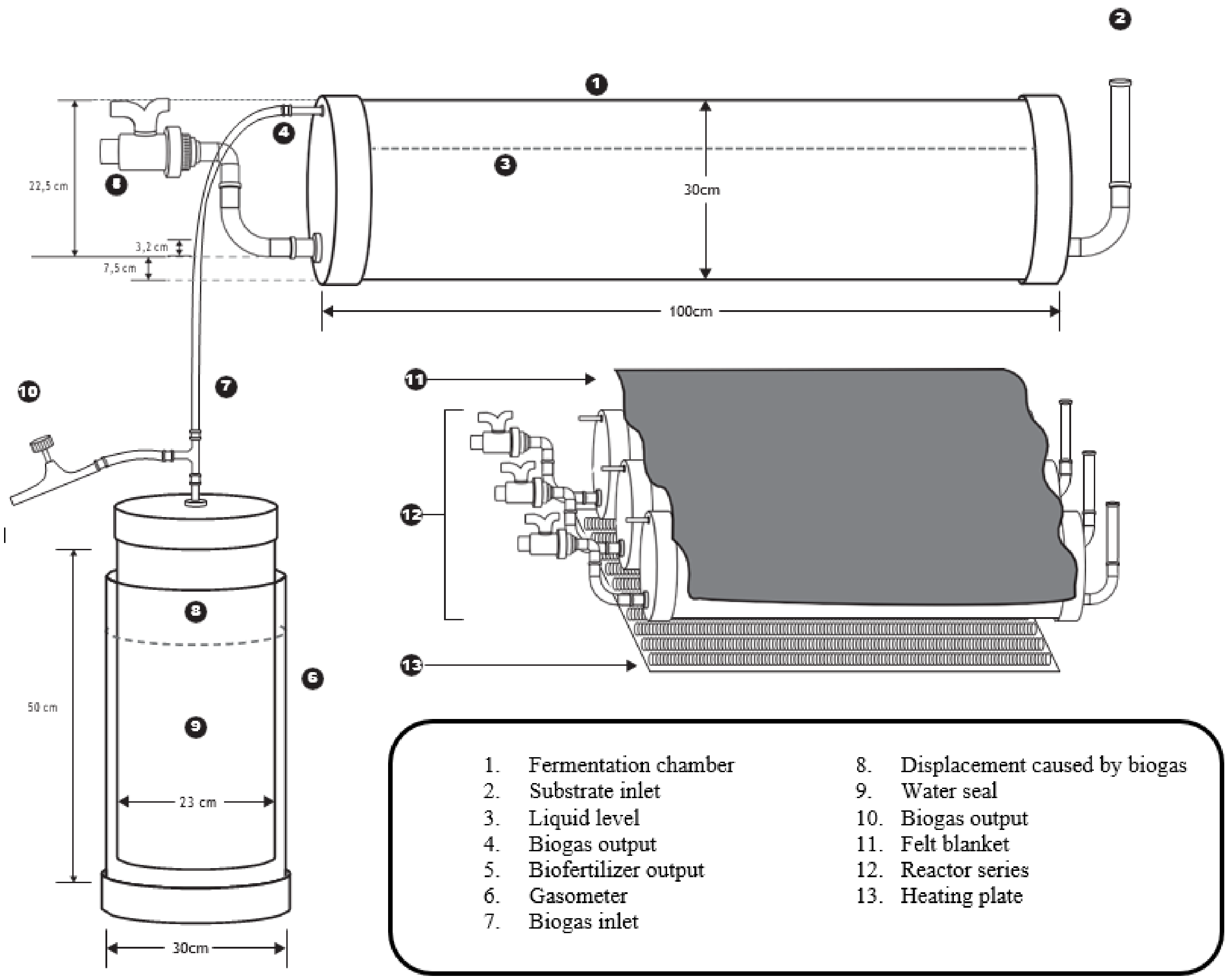


Figure 2. Schematic diagram of the semi-continuous model reactor

conductivity (EC), alkalinity (IA/PA and AV/AT), humidity, solids series, total organic carbon (TOC), total Kjeldahl nitrogen (TKN), phosphorus (P), potassium (K), secondary macronutrients (Ca and Mg), and micronutrients (Fe, Zn, Cu, Mn, and Na).

Biogas composition was determined using a gas chromatograph (model CG-2010, Shimadzu Scientific Instruments, Columbia, MD, USA) equipped with a thermal conductivity detector (GC/TCD). Argon served as the carrier gas in a Carboxen® 1010 Plot column (30 m, 0.53 mm). Injector and detector temperatures were maintained at 220 and 230 °C, respectively, with an initial column temperature of 130 °C, gradually heated to 135 °C at a rate of 46 °C min^{-1} (Perna et al., 2013). The chromatograph was calibrated using standard biogas gas containing specific percentages of oxygen, nitrogen, methane, and carbon dioxide, as well as standard hydrogen gas.

Readings of pH and electrical conductivity (EC) were obtained using a benchtop pH meter (TECNAL®, model TEC-3MP) and a benchtop conductivity meter (MS Tecnopon®, model mCA 150), respectively. Gravimetric methods based on standardized procedures (APHA, 2012) were used to determine total solids (TS), volatile solids (VS), fixed solids (FS), and total Kjeldahl nitrogen (TKN) (APHA, 2012). Total organic carbon (TOC) was calculated by dividing the percentage of volatile solids (VS) by 1.8, following the method by Carmo & Silva (2012).

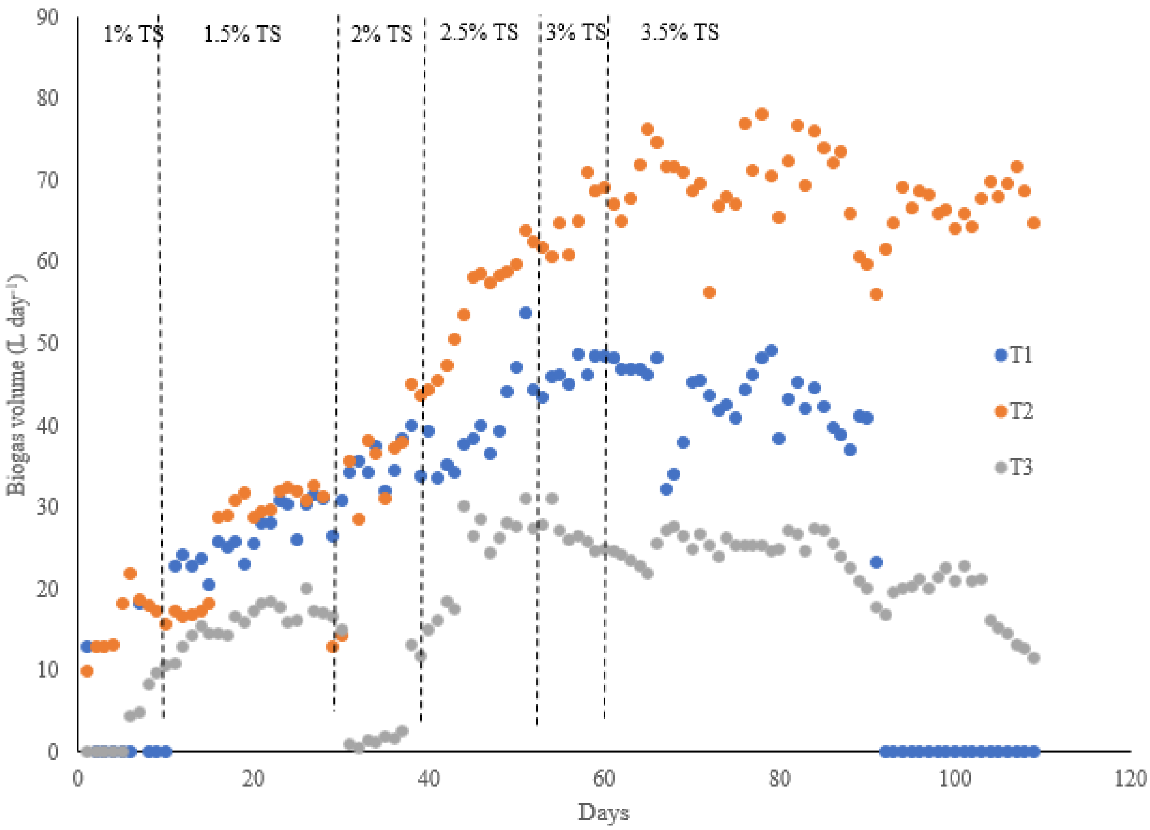
Partial alkalinity (PA), intermediate alkalinity (IA), and volatile acidity (VA) were determined through titration according to the method recommended by Ripley et al. (1986). The AV/AT ratio was calculated by dividing AV by the sum of PA and IA, resulting in the total alkalinity (TA).

Total phosphorus (P) and total potassium (K) were measured by digesting samples in nitric-perchloric acid solution (3:1), with P detected via absorbance using a UV-VIS spectrophotometer (Hach®) and K quantified using a flame photometer, following the procedure outlined in Malavolta et al. (1997). Secondary macronutrients (Ca and Mg) and micronutrients (Fe, Zn, Cu, Mn, and Na) were determined using an atomic absorption spectrometer (Shimadzu®, model AA-6300) based on an extract from nitric-perchloric digestion.

The assay was conducted in a strip-plot experimental design containing 3 treatments (anaerobic mono-digestion of RFV, anaerobic mono-digestion of DCWW, and anaerobic co-digestion of RFV+DCWW), with 52 repetitions characterized as daily biogas measurements. The daily measurements were considered repetitions based on the premise of reactor stability, that is, when the coefficient of variation between one biogas measure and the next was not greater than 10%. Five replicates (composite samples) of each treatment were used in the statistical analysis of the chemical composition of the biofertilizer. The composite samples were made with sub-samples collected during one week of reactor supply. The results underwent analysis of variance, and the means were compared by Tukey's test at $p \leq 0.05$ using the SISVAR program.

Results and Discussion

Two strategies were employed to initiate the reactors in this experiment: initial filling with inoculum (biofertilizer from anaerobic digestion of DCWW) and loading progression in T_1 and T_2 (Figure 3). These strategies are particularly useful



T_1- AMoD of FVR; T_2- ACoD of FVR + DCWW; T_3- AMoD of DCWW

Figure 3. Biogas production volume as a function of the loading progression of total solids (TS - %)

when dealing with waste rich in labile carbohydrates such as FVRs. The natural alkalinity of DCWW biofertilizer mitigates the effects of rapid hydrolysis of FVRs and serves as an effective inoculum (Damaceno et al., 2019). Loading progression prevents overloading the system beyond its capacity during the adaptation phase (Li et al., 2022).

The system responded positively to loading progressions up to 3.5% of total solids (TS), increasing biogas production (Figure 3). The incremental loading strategy allowed for monitoring parameters such as biogas volume production, pH, alkalinity, volatile acidity, and the IA/PA ratio. It enabled the tracking of reactor behavior and estimation of safe loading limits, ranging from 1 to 3.5% of TS, without compromising anaerobic digestion (AD).

The microbial community adapted to the new conditions with each loading progression, going through lag, log, and stationary growth phases. Weaker microorganisms died off, and more resistant ones survived, gradually increasing TS and microbial adaptation (Zhan et al., 2022).

Additionally, T_1 was operated with recycle, meaning that a portion of the biofertilizer was reused to compose daily loads. This recycle enhanced the effects of the start-up strategies, acting as an inoculant and alkalizing agent. The efficiency of recycle use was also confirmed by previous studies (Damaceno et al., 2019; Restrepo et al., 2022).

Both AMoD of FVRs and ACoD of FVRs with DCWW demonstrated the feasibility of the AD process for environmentally safe disposal of FVRs while generating renewable energy (biogas) and nutrient-rich biofertilizer. These conditions suit on-site processing at CEASA markets or on rural properties with co-digestion capabilities (ACoD).

Table 3 shows the energy recovery results from FVRs in AMoD and ACoD with DCWW. Considering the specific production per kg of VS added, ACoD of FVRs with DCWW showed an increase of 11.3 in biogas quantity and 28.2% in methane compared to AMoD of FVRs. Similarly, ACoD of FVRs with DCWW exhibited higher energy recovery compared to AMoD of DCWW, with a 30.2% increase in biogas and a 16.3% increase in methane.

The higher energy recovery observed in ACoD scenarios can be attributed to the synergy between waste materials. DCWW acts as a universal inoculum due to the presence of methanogenic archaea in the intestinal tract of ruminants, which promotes methanogenesis (Magaço & Duarte, 2019). Additionally, the nitrogen content in DCWW helps to increase alkalinity, facilitating pH balance in the reaction medium (Bres et al., 2018). However, the solid fraction of DCWW primarily consists of recalcitrant fibers from the animals' diet, which are less susceptible to anaerobic degradation.

In contrast, FVRs contain labile carbohydrates in their solid fraction, which are easily degradable. This characteristic promotes the hydrolysis phase and yields high concentrations of sugars in the initial phase of AD. However, the release of hydrogen ions (H^+) during hydrolysis can lead to a pH reduction (Sitorus et al., 2013).

The addition of DCWW to FVRs helps by diluting the wastes to obtain a solids content compatible with the horizontal tubular flow reactor technology. This dilution also mitigates the effects of toxic compounds and acts as a buffering agent (Chatterjee & Mazunder, 2020). Nitrogen compounds, such as amines and ammonium ions (NH_4^+), originating from protein degradation, play a key role in buffering the system by reacting with CO_2 and H_2O to capture excess hydrogen ions, resulting in alkalinity through the formation of ammonium carbonate [$(NH_4)_2CO_3$] (Meng et al., 2018). This restoration of pH balance benefits both the acetogenic and methanogenic phases of anaerobic digestion (AD).

Table 4 shows the efficiency of organic material removal, including total solids, volatile solids, and total organic carbon. T_1 exhibited the highest removal efficiency for total solids, volatile solids, and total organic carbon.

The efficiency of organic material removal is usually related to the potential for biogas/methane production since organic carbon constitutes a significant portion of the waste. However, the results of biogas and methane production (Table 3) seem not to be directly correlated to the efficiency of organic material removal. Energy production did not follow the order of removal efficiency ($T_2 > T_1 > T_3$).

Table 4. Characterization of effluents and influents, and organic material contents removed by treatments

Variables	Material	T_1	T_2	T_3
TS (%)	Affluent	3.83±0.25	5.38±0.07	2.61±0.51
	Effluent	0.63±0.05	1.08±0.12	0.96±0.11
	Reduction (%)	83.6±1.2 a	79.9±2.1 b	63.7±5.6 c
CV (%)			4.69	
VS (%)	Affluent	89.54±2.47	88.71±0.41	77.69±1.20
	Effluent	52.81±6.36	45.22±3.10	45.4±4.15
	Reduction (%)	91.3±1.2 a	87.6±1.5 b	74.4±4.5 c
CV (%)			3.36	
TOC (%)	Affluent	49.75±1.37	49.28±0.23	43.16±0.67
	Effluent	29.34±3.54	25.12±1.72	25.22±2.31
	Reduction (%)	95.0±0.5 a	93.7±0.7 a	62.1±5.7 b
CV (%)			3.97	

Means followed by the same letter among treatments do not differ from each other by Tukey's test at p ≤ 0.05. T_1 - Anaerobic mono-digestion of fruit and vegetable residues (AMoD of FVR); T_2 - Anaerobic co-digestion of fruit and vegetable residues + dairy cattle wastewater (ACoD of FVR + DCWW); T_3 - Anaerobic mono-digestion of dairy cattle wastewater (AMoD of DCWW); CV (%) - Coefficient of variation

Table 3. Specific biogas production in anaerobic mono (AMoD) and co-digestion (ACoD) of fruit and vegetable residues (FVR) of dairy cattle wastewater (DCWW)

Treatments	Biogas production (L kg TS^{-1})	Biogas production (L kg VS^{-1})	Methane production (L kg TS^{-1})	Methane production (L kg VS^{-1})	Methane (%)
AMoD of FVR	579±49 b	647±55 b	305±26 b	340±29 b	52.6±1.09 c
ACoD of FVR + DCWW	639±45 a	720±51 a	387±27 a	436±31 a	60.5±0.55 b
AMoD of DCWW	429±61 c	553±80 c	291±42 c	375±54 c	67.8±1.13 a
CV (%)	9.53	9.89	9.88	10.34	1.59

AMoD of FVR - Anaerobic mono-digestion of fruit and vegetable residues; ACoD of FVR + DCWW - Anaerobic co-digestion of fruit and vegetable residues + dairy cattle wastewater; AMoD of DCWW - Anaerobic mono-digestion of dairy cattle wastewater; CV (%) - Coefficient of variation. Means followed by the same letter among treatments do not differ from each other by Tukey's test at p ≤ 0.05

One hypothesis for the higher efficiency of organic material removal in T_1 but not in T_2, despite the higher biogas production in T_2, is related to the characteristics of the solid fractions in the two treatments. The solid fraction of T_1 comprises peels, seeds, and pulp, while T_2 includes peels, seeds, pulp, and contributions from the solid fraction of DCWW, which contains fibers. The behavior of different solid fractions in the horizontal tubular reactor may have favored the settling of peels, seeds, and pulp in T_1, resulting in higher efficiency in reducing organic materials but not necessarily converting them into biogas.

Importantly, the solid fraction segregation inside the reactor could introduce imprecision in sampling, particularly at the effluent outlet, where there is no opportunity for homogenization within the reactor. This potential issue might overestimate reduction values, as noted by Costa et al. (2016).

Table 5 provides data indicating the stability of the AD process. T_1 showed lower total alkalinity (TA) and higher volatile acidity (VA) compared to T_2 and T_3, leading to a statistically higher VA/TA ratio in T_1 than in T_2 and T_3. A VA/TA ratio > 0.3 - 0.4 typically indicates process instability (Fan et al., 2021).

The accumulation of volatile acids during AD can reduce the pH of the reaction medium (Li et al., 2022), as observed in T_1, which had lower pH than T_2 and T_3. The primary pH control mechanism in anaerobic reactors is the bicarbonate buffer system, reliant on alkalinity in the medium. Microorganisms present in cattle waste from their intestinal tract contribute to this buffering effect, ensuring process stability (Toumi et al., 2015).

The IA/PA ratio reflects the relationship between acid production and buffering in the AD process. Treatment T_1 exhibited a statistically higher IA/PA ratio than T_2 and T_3. An IA/PA ratio > 0.4 indicates overloading, while a ratio < 0.3 indicates underloading (Martín-González et al., 2013). These results suggest that the AMoD of FVRs might overload the reactor, potentially causing instability. The addition of DCWW to FVRs shifts the reactor toward an underloaded state, allowing for higher FVR concentrations until the IA/PA ratio reaches the ideal range of 0.3 - 0.4, as recommended by Martín-González et al. (2013). It indicates that the FVR concentration could have been higher than 3.5% of TS without causing instability.

Brazil is the fourth-largest global grain producer and the world's top beef exporter, following China, the United States, and India (EMBRAPA, 2021). However, Brazil heavily relies on imported fertilizers, with 85% coming from Russia, including 23% of its nitrogen (urea and ammonium nitrate), 28% of potassium chloride, and 31% of phosphorus (monoammonium phosphate - MAP). The Russia-Ukraine conflict has exacerbated this dependency issue. In this sense, Brazil introduced the National Fertilizer Plan (Plano Nacional de Fertilizantes, PNF) in March 2022 to reduce this reliance and promote sustainability.

This plan emphasizes the use of organic and organomineral fertilizers, aligning with principles of sustainable agriculture and the circular economy (MAPA, 2022). The PNF focuses on harnessing byproducts as viable agricultural fertilizers. It places a strong emphasis on environmental sustainability, circular economy principles, and the promotion of low-carbon agriculture. Additionally, the plan underscores the necessity for public policies that encourage the utilization of organic waste in agricultural practices (MAPA, 2022).

As per the National Association for Fertilizer Dissemination (ANDA, 2019), the most commonly used nutrients in agriculture are potassium (K) at 38%, followed by phosphorus (P) at 29%, and nitrogen (N) at 29%. The effectiveness of a biofertilizer is closely tied to its chemical composition. In essence, higher concentrations of primary and secondary macronutrients, such as N, P, K, Ca, and Mg, enhance its performance in the soil. Table 6 shows the nutrient levels in biofertilizers derived from either AmoD or AcoD of FVR and DCWW.

In terms of macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), AMoD of FVRs showed higher concentrations compared to ACoD of FVRs with DCWW and

Table 5. Concentrations of alkalinity

Treatment	TA (mg $CaCO_3$ L^{-1})	VA (mg L^{-1})	VA/TA ratio	IA/PA ratio	pH
T_1	2619±510 b	1187±327 a	0.47±0.2 a	1.06±0.5 a	8.1±0.2 b
T_2	9149±2078 a	197±48 b	0.02±0 b	0.05±0 b	8.7±0.3 a
T_3	9762±2099 b	178±24 b	0.02±0 b	0.05±0 b	8.7±0.2 a
CV (%)	26.96	41.13	61.35	88.26	2.92

Means followed by the same letter in the column do not differ from each other by Tukey's test at p ≤ 0.05
T_1 - Anaerobic mono-digestion of fruit and vegetable residues (AMoD of FVR); T_2 - Anaerobic co-digestion of fruit and vegetable residues + dairy cattle wastewater (ACoD of FVR + DCWW); T_3 - Anaerobic mono-digestion of dairy cattle wastewater (AMoD of DCWW); CV (%) - Coefficient of variation; TA - Total alkalinity; VA - Volatile acidity; PA - Partial alkalinity; IA - Intermediate alkalinity

Table 6. Concentrations of primary (N, P, K) and secondary macronutrients (Ca and Mg) found in the biofertilizers obtained by AmoD or AcoD of FVRs and DCWW

Treatments	N	P	K	Ca	Mg
			(g kg TS^{-1})		
T_1	48.92±2.14 a	7.24±1.98 a	91.62±9.93 a	18.11±6.58 c	11.10±1.32 a
T_2	38.81±0.88 b	4.67±0.96 b	68.11±12.15 b	54.53±4.28 b	11.94±0.74 a
T_3	31.08±0.72 c	4.19±0.50 c	55.66±11.34 c	77.13±4.70 a	12.55±1.12a
CV (%)	8.54	24.20	15.57	10.58	9.18

Means followed by the same letter in the column do not differ from each other by Tukey's test at p ≤ 0.05. T_1 - Anaerobic mono-digestion of fruit and vegetable residues (AMoD of FVR); T_2 - Anaerobic co-digestion of fruit and vegetable residues + dairy cattle wastewater (ACoD of FVR + DCWW); T_3 - Anaerobic mono-digestion of dairy cattle wastewater (AMoD of DCWW); CV (%) - Coefficient of variation

AMoD of DCWW. The recycling of biofertilizer in T_1 enhanced both FVR AD and the agronomic value of the biofertilizer.

However, when considering the use of AD technology on-site, such as at CEASA markets, the effluent from the biodigester may need to be discharged into the sewage system if suitable locations for agricultural use are unavailable within a compatible distance. In such cases, the increased nutrient levels could be a drawback, requiring post-treatment to remove excess nutrients to meet sanitation company regulations.

ACoD conditions appear to be the most favorable from an agricultural perspective. Treatment T_2 exhibits statistically higher values compared to AMoD of DCWW (Table 6). This benefits rural producers by providing higher nutrient content in the biofertilizer. For example, there is an increase of approximately 25% in nitrogen (N), 11% in phosphorus (P), and 22% in potassium (K) compared to AMoD of DCWW.

Limited literature exists on the effectiveness of biofertilizers, comparing AMoD and ACoD. Most studies tend to concentrate on evaluating the environmental quality of biofertilizers, with a focus on concentrations of soluble ions such as N, P, and K. These assessments are often conducted within the context of post-treatment measures for environmentally responsible disposal (Akhiar et al., 2017).

The agronomic valorization of biofertilizers obtained through ACoD, as compared to AMoD, due to increased nutrient content is evident in previous studies (Montoro et al., 2019). For instance, adding sweet potatoes to DCWW increased nitrogen (N) by 13.5 to 22.9% and potassium (K) by 5.8 to 8.3%.

Regarding the concentration of micronutrients in the biofertilizer, the results are influenced by the specific conditions established in each treatment, except for copper (Cu) levels (Table 7). Other micronutrients show variations depending on the treatment, with AmoD of DCWW presenting the highest concentrations of such elements.

Biofertilizer chemical compositions are strongly influenced by the diet of animals, as demonstrated in the case of T_3. FVRs introduced into this residue result in a dilution of micronutrient concentrations. Interestingly, this dilution, in certain instances, can be a beneficial strategy, particularly concerning sodium (Na).

Excessive sodium concentrations can have detrimental effects on both soil and plant health, impacting their physical and chemical properties. The adverse consequences of excess salts primarily stem from the electrochemical interaction between salts and clay particles. Excess sodium accumulation in the soil can lead to the formation of a dense layer that hinders vital plant functions such as growth, respiration, root expansion, water absorption, and the ability to fix CO_2 (Zhao et al., 2020). As a precaution, conducting periodic chemical characterization analyses of the biofertilizer and applying it at appropriate intervals to mitigate the risk of soil salinization are advisable.

Copper and zinc are categorized as heavy metals and have the potential to accumulate in the soil, water, and living organisms. It justifies their inclusion in the characterization of produced biofertilizers. These elements can be found in various sources, including fungicides, biofertilizers, animal manure, sewage sludge, and urban waste. Elevated concentrations of copper and zinc in the soil can lead to soil toxicity (Marsola et al., 2005).

Nutrients in biofertilizers are present in their ionic form, allowing for rapid absorption by plants through leaf or soil application. This results in immediate benefits for plant growth and development. Sigurnjak et al. (2017) evaluated the liquid fraction (LF) from biofertilizer during a 3-year field trial and concluded that the LF as a source of N and K in animal manure or biofertilizer treatments had similar effects on biomass yields and soil properties as the classical fertilization regime using animal manure and synthetic N and K fertilizers.

Table 8 provides a breakdown of the amounts of primary and secondary macronutrients recovered per 1000 kg of total solids (TS) for each treatment aiming to assess the agronomic value of the biofertilizers obtained under the studied conditions.

Table 8 also underscores the potential of biofertilizers derived solely from AD of FVR only. This finding holds value not only for livestock farmers but also for those interested in harnessing the energy and nutrient recovery potential of FVR. T_3, in which only DCWW undergoes AD, generates a biofertilizer that excels in soil acidity correction due to its higher recovered concentrations of calcium (Ca) and magnesium (Mg).

Table 7. Concentrations of micronutrients found in the biofertilizers obtained by AmoD or AcoD of FVRs and DCWW

Treatments	Fe	Zn	Cu	Mn	Na
	(g kg ST^{-1})				
T_1	0.49±0.17 c	0.45±0.05 c	0.03±0.03 a	0.08±0.03 c	12.97±2.30 b
T_2	0.79±0.17 b	0.59±0.11 b	0.03±0.01 a	0.13±0.01 b	44.56±7.03 b
T_3	1.08±0.16 a	0.69±0.20 a	0.06±0.01 a	0.23±0.02 a	122.02±40.76 a
CV (%)	20.82	23.28	56.89	13.37	39.97

Means followed by the same letter in the column do not differ from each other by Tukey's test at p ≤ 0.05. T_1 - Anaerobic mono-digestion of fruit and vegetable residues (AMoD of FVR); T_2 - Anaerobic co-digestion of fruit and vegetable residues + dairy cattle wastewater (ACoD of FVR + DCWW); T_3 - Anaerobic mono-digestion of dairy cattle wastewater (AMoD of DCWW); CV (%) - Coefficient of variation

Table 8. Quantity (in kg) of primary and secondary macronutrients recovered from biofertilizers for each ton of total solids

Treatments	Ammonium sulfate	Triple superphosphate	Potassium chloride	Calcium hydroxide	Magnesium hydroxide
T_1	245	39.5	184.0	25.3	18.3
T_2	194	25.5	136.8	76.3	19.8
T_3	155	22.8	111.8	107.9	20.8

T_1 - Anaerobic mono-digestion of fruit and vegetable residues (AMoD of FVR); T_2 - Anaerobic co-digestion of fruit and vegetable residues + dairy cattle wastewater (ACoD of FVR + DCWW); T_3 - Anaerobic mono-digestion of dairy cattle wastewater (AMoD of DCWW)

Considering nitrogen (N) as the basis for fertilizer recommendations in corn cultivation (180 kg N ha^{-1}), the following areas would be possible to be cultivated for each 1,000 kg of TS subjected to ACoD in T_2 or AMoD in T_1: T_1 = 0.27 ha; T_2 = 0.22 ha, and T_3 = 0.17 ha. Additionally, the corresponding amounts of biofertilizer required to obtain 1,000 kg of TS would be as follows: T_1: 158,730 liters; T_2: 92,592 liters; and T_3: 104,167 liters. Hence, the significance of valorizing biofertilizers as agricultural inputs becomes evident, particularly for a nation heavily reliant on imported fertilizers.

Conclusions

1. Anaerobic co-digestion of FVR and DCWW resulted in a substantial increase in biogas production compared to the anaerobic mono-digestion of either FVR or DCWW alone.

2. The addition of FVR significantly enhances the agronomic value of the biofertilizer produced through anaerobic digestion when compared to the mono-digestion of DCWW.

Contribution of authors: Bruna Hinterholz: Investigation, Methodology, Data curation; Mônica S. S. de M. Costa: Conceptualization, Methodology, Writing – review and editing, Supervision, Resources; Jorge de Lucas Junior: Writing-Review & Editing; Edilene da S. Pereira, Eduardo L. Buligon, Jessica C. de Lima and Ritieli Marostica: Data curation, Writing - original draft preparation.

Supplementary documents: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest: The authors declare no conflict of interest.

Financing statement: This research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

Acknowledgement: The authors are grateful to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

Literature Cited

Akhiar, A.; Battimelli, A.; Torrijos, M.; Carrere, H. Comprehensive characterization of the liquid fraction of digestates from full-scale anaerobic co-digestion. Waste Management, v.59, p.118-128, 2017. https://doi.org/10.1016/j.wasman.2016.11.005

ANDA - Associação Nacional para Difusão de Adubos. Dados 2019 - Principais indicadores do setor de fertilizantes, 2019. Available on: https://anda.org.br/wp-content/uploads/2020/05/Principais_Indicadores_2019-1.pdf. Accessed on: Jun. 2020.

APHA - American Public Health Association. Standard methods for the examination of water and wastewater. 21.ed. Washington: American Water Works Association, 2012. 1368p.

Bortoloti, M. A.; Challiol, A. Z.; Navarro, B. L.; Sicchieri, I. M.; Kuroda, E. K.; Fernandes, F. Challenges of load variation on anaerobic digestion of organic waste on a full scale: an applied study. Waste Biomass Valorization, v.14, p.4141-4154, 2023. https://doi.org/10.1007/s12649-023-02120-9

Bres, P.; Beily, M.E.; Young B. J.; Gasulla, J.; Butti, M.; Crespo, D.; Candal, R.; Komilis, D. Performance of semi-continuous anaerobic co-digestion of poultry manure with fruit and vegetable waste and analysis of digestate quality: A bench scale study. Waste Management, v.82, p.276-284, 2018.

Carmo, D. L.; Silva, C. A. Métodos de quantificação de carbono e matéria orgânica em resíduos orgânicos. Revista Brasileira de Ciência do Solo, v.36, p.1211-1220, 2012. https://doi.org/10.1590/S0100-06832012000400015

Chatterjee, B.; Mazumder, D. New approach of characterizing fruit and vegetable waste (FVW) to ascertain its biological stabilization via two-stage anaerobic digestion (AD). Biomass and Bioenergy, v.139, e105594, 2020. https://doi.org/10.1016/j.biombioe.2020.105594

Costa, M. S. S. M.; Lucas Junior, J. De.; Mendonça Costa, L. A.; Orrico, A. C. A. A highly concentrated diet increases biogas production and the agronomic value of young bull's manure. Waste Management, v.48, p.521-527, 2016. https://doi.org/10.1016/j.wasman.2015.09.038

Damaceno, F. M.; Buligon, E. L.; Restrepo, J. C. P. S.; Chiarelotto, M.; Niedzialkoski, R. S.; Costa, L. A. M.; Lucas Junior, J. de.; Costa, M. S. S. M. Semi-continuous anaerobic co-digestion of flotation sludge from broiler chicken slaughter and sweet potato: Nutrients and energy recovery. Science of The Total Environment, v.683, p. 773-781, 2019. https://doi.org/10.1016/j.scitotenv.2019.05.314

EMBRAPA - Empresa Brasileira de Pesquisa Agropecuária. Estudos socioeconômicos e ambientais, 2021. Available on: <https://www.embrapa.br/busca-de-noticias/-/noticia/62619259/brasil-e-o-quarto-maior-produtor-de-graos-e-o-maior-exportador-de-carne-bovina-do-mundo-diz-estudo>. Acessed on: Dec. 2021.

Fan, Y.; Yang, X.; Lei, Z.; Adachi, Y.; Kobayashi, M.; Zhang, Z.; Shimizu, K. Novel insight into enhanced recoverability of acidic inhibition to anaerobic digestion with nano-bubble water supplementation. Bioresource Technology, v. 326, e124782, 2021. https://doi.org/10.1016/j.biortech.2021.124782.

IAPAR- Instituto Agronômico do Paraná. Cartas climáticas do Paraná: Classificação climática, 2019. Available on: https://www.idrparana.pr.gov.br/Pagina/Atlas-Climatico. Acessed on: Jul. 2022.

Li, B.; Xia, Z.; Gou, M.; Sun, Z.; Huang, Y.; Jiao, S.; Dai, W.; Tang, Y. Production of volatile fatty acid from fruit waste by anaerobic digestion at high organic loading rates: Performance and microbial community characteristics. Bioresource Technology, v.346, e126648, 2022. https://doi.org/10.1016/j.biortech.2021.126648

Magaço, F. dos S.; Duarte, E. R. Interação microbiana e metanogênese em ruminantes - uma revisão. Medicina Veterinária, v.13, p.88-95, 2019. https://doi.org/10.26605/medvet-v13n1-2615

Malavolta, E.; Vitti, G. C.; Oliveira, S.A. Avaliação do estado nutricional das plantas: princípios e aplicações. 2.ed. Piracicaba: POTAFOS, 1997. 319p.

MAPA. Ministério da Agricultura, Pecuária e Abastecimento. Brasília: MAPA, 2022. Available on: < https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/plano-nacional-de-fertilizantes/o-plano-nacional-de-fertilizantes >. Accessed on: Dec. 2023.

Marsola, T.; Miyazawa, M.; Pavan, M. A Acumulação de cobre e zinco em tecidos do feijoeiro em relação com o extraído do solo. Revista Brasileira de Engenharia Agrícola e Ambiental, v.9, p.92-98, 2005. https://doi.org/10.1590/S1415-43662005000100014

Martín-González, L.; Font, X.; Vicent, T. Alkalinity ratios to identify process imbalances in anaerobic digesters treating source-sorted organic fraction of municipal wastes. Biochemical Engineering Journal, v.76, p.1-5, 2013. https://doi.org/10.1016/j.bej.2013.03.016.

Meng, X.; Yu, D.; Wei, Y.; Zhang, Y; Zhang, Q.; Wang, Z.; Liu, J.; Wang. Y.; Endogenous ternary pH buffer system with ammonia-carbonates-VFAs in high solid anaerobic digestion of swine manure: An alternative for alleviating ammonia inhibition? Process Biochemistry, v.69, p.144-152, 2018. https://doi.org/10.1016/j.procbio.2018.03.015

Montoro, S. B.; Lucas Júnior, J. de; Santos, D. F. L.; Costa, M. S. S. M. Anaerobic co-digestion of sweet potato and dairy cattle manure: a technical and economic evaluation for energy and biofertilizer production. Journal of Cleaner Production, v.226, p.1082-1091, 2019. https://doi.org/10.1016/j.jclepro.2019.04.148

Perna, V.; Castelló, E.; Wenzel, J.; Zampol, C.; Lima, D. M. F.; Borzacconi, L.; Varesche, M.B.; Zaiat, M.; Etchebehere, C. Hydrogen production in an upflow anaerobic packed bed reactor used to treat cheese whey. International Journal of Hydrogen Energy, v.38, p.54-62, 2013. https://doi.org/10.1016/j.ijhydene.2012.10.022

Restrepo, J. C. P. S.; Damaceno, F. M.; Chiarelotto, M.; Bofinger, J.; Niedzialkoski, R. K.; Costa, L. A. M.; Lucas Junior, J.; Costa, M. S. S. M. Sugarcane juice improves energy production in the anaerobic co-digestion with flotation sludge from broiler slaughter. Fuel, v.330. e125577, 2022. https://doi.org/10.1016/j.fuel.2022.125577

Ripley, L. E.; Boyle, W. C.; Converse, J. C. Improved alkalimetric monitoring for anaerobic digestor of high-strength waste. Journal Water Pollution Control Federation, v.58, p.406-411, 1986. https://www.jstor.org/stable/25042933

Sigurnjak, I.; Vaneeckhaute, C.; Michels, E.; Ryckaert, B.; Ghekiere, G.; Tack, F. M. G.; Meers, E. Fertilizer performance of liquid fraction of digestate as synthetic nitrogen substitute in silage maize cultivation for three consecutive years. Science of the Total Environment, v.599-600, p.1885-1894, 2017. http://dx.doi.org/10.1016/j.scitotenv.2017.05.120

Sitorus, B.; Sukandar; Panjaitan, S. D. Biogas Recovery from Anaerobic Digestion Process of Mixed Fruit -Vegetable Wastes. Energy Procedia, v.32, p.176-182, 2013.

Tsigkou, K.; Sventzouri, E.; Zafiri, C.; Kornaros, M. Digestate recirculation rate optimization for the enhancement of hydrogen production: The case of disposable nappies and fruit/vegetable waste valorization in a mesophilic two-stage anaerobic digestion system. Renewable Energy, v.215, e119010, 2023. https://doi.org/10.1016/j.renene.2023.119010.

Toumi, J.; Miladi, B.; Farhat, A.; Nouira, S.; Hamdi, M.; Gtari, M.; Bouallagui, H. Microbial ecology overview during anaerobic co-digestion of dairy wastewater and cattle manure and use in agriculture of obtained bio-fertilisers. Bioresource Technology, v.198, p.141-149, 2015. https://doi.org/10.1016/j.biortech.2015.09.004

Zafar, H.; Peleato, N.; Roberts, D. A comparison of reactor configuration using a fruit waste fed two-stage anaerobic up-flow leachate reactor microbial fuel cell and a single-stage microbial fuel cell. Bioresource Technology, v.374, e128778, 2023. https://doi.org/10.1016/j.biortech.2023.128778.

Zhan, Y.; Cao, X.; Xiao, Y.; Wei, X.; Wu, S.; Zhu, J. Start-up of co-digestion of poultry litter and wheat straw in anaerobic sequencing batch reactor by gradually increasing organic loading rate: Methane production and microbial community analysis. Bioresource Technology, v.354, e127232, 2022. https://doi.org/10.1016/j.biortech.2022.127232

Zhao, C.; Zhang, H.; Song, C.; Zhu, J.K.; Shabala, S. Mechanisms of Plant Responses and Adaptation to Soil Salinity. The Innovation, v.1, e100017, 2020. https://doi.org/10.1016/j.xinn.2020.100017