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REGULAR ARTICLE

Treatment and bioenergy recovery from livestock wastewater in UASB reactor: novel approaches for engineering projects

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Abstract

This study presents an innovative approach for energy recovery and treatment of cattle wastewater, exploring the performance of a UASB reactor operated at 40°C, a condition that has received scant attention in the extant literature. The experiment was conducted using a semi-continuous feeding regime, with hydraulic retention times of 6, 5, 3, and 2 days, and organic loading rates of 4, 5, 7, and 11 kg COD m^{-3} d^{-1}. The range of organic matter removal for total COD was 60% to 80%, and for soluble COD, it was 50% to 75%. These values resulted in methane yields ranging from 0.20 to 0.34 m³ CH_4 per kilogram of total COD removed and from 0.4 to 0.5 m³ CH_4 per kilogram of soluble COD removed. The findings underscore the efficacy of operating the reactor under these conditions, not only in achieving substantial biogas production but also in ensuring the efficient removal of organic matter. This reinforces the potential of the processes as a sustainable and effective alternative for treating effluents with high pollutant loads, thereby combining environmental mitigation and clean energy generation.

Keywords

Anaerobic digestion; Biogas; Methane; Pollution control; Bioenergy.

Introduction

In recent years, with the growth of livestock activity in Brazil, there has been a need to promote intensive cattle farming in confined areas, leading to an intensification of wastewater generation (Lomeu et al., 2023).

Cattle production has been found to generate approximately 130 liters of wastewater per animal per day, which is largely composed of waste resulting from the mixture of excrement with the water used for cleaning stables. This effluent exhibit high concentrations of nitrogen and phosphorus, as well as high levels of organic matter, usually expressed as biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD). The removal of these nutrients is imperative for their proper disposal in aquatic ecosystems, as improper management can cause significant environmental impacts, such as eutrophication and the release of unpleasant odors. In this context, the appropriate disposal of such waste represents a significant challenge in the agricultural and environmental spheres due to its complexity, which encompasses technical, sanitary, and economic aspects (Y. El et al., 2024; Mello et al., 2024).

Given the need to manage these waste streams to reduce their environmental impact, the application of anaerobic digestion for the treatment of such effluents emerges as a suitable option, with the additional advantages of energy and agricultural valorization through biogas/biomethane production and digested effluent (Mendonça, 2022). Anaerobic digestion has been identified as a significant technological advancement in the field, demonstrating notable efficacy in reducing waste volume while concurrently generating energy and valuable by-products. The process is facilitated by the concerted action of four distinct groups of microorganisms, which are indispensable for the substrate into biogas is contingent upon the symbiotic interaction between fermentative bacteria, syntrophic acetogens, homoacetogens, hydrogenotrophic methanogens and acetoclastic methanogens. The metabolic activities of these microorganisms are interdependent and essential for the stability and efficiency of the anaerobic system (Musa et al., 2020).

Various types of reactors have been used in the anaerobic digestion of agro-industrial effluents, including the horizontal plug flow reactor (HPFR) and the anaerobic sequencing batch reactor (ASBR) (de Mendonça et al., 2021; Nasir, 2012). In recent years, new reactor models have been studied and adapted to improve the digestion process efficiency, making it possible to use smaller units to treat the same volume of effluent (Nasir, 2012), such as the anaerobic filter (AF), up-flow anaerobic sludge blanket (UASB), anaerobic fluidized bed reactor (AFBR), and oscillatory flow reactor (OFR).

AF, UASB, and AFBR reactors accumulate a high biomass concentration, allowing for extended solids retention time even at low hydraulic retention times (HRT) (Nasir, 2012). The utilization of UASB reactors confers numerous advantages, including but not limited to reduced capital expenditures, diminished excess sludge generation, minimal

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energy requirements, and decreased operational and maintenance expenses in comparison to chemical processes. These reactors are characterized by ease of operation, economic viability, efficiency, and flexibility, accompanied by a relatively low environmental impact. Furthermore, these reactors are capable of producing effluents of satisfactory quality, which contributes to their widespread acceptance as an effective alternative for wastewater treatment (de Mendonça et al., 2021; A. El et al., 2024; Miah et al., 2025).

The UASB reactor has not yet been explored in terms of its biogas production capacity and treatment of cattle wastewater, which is the main objective of this study. Therefore, this article presents a new reliable approach for designing UASB reactors for agro-industrial effluents with a high organic load. This work also aims to characterize the performance of the reactor along its vertical column and identify the function of various sections in the overall treatment process. Finally, the goal of the work is to provide data for engineers and designers to develop engineering projects focused on the treatment of high-organic-load pollutant wastewater, such as those from cattle farming.

Materials and methods

Experimental setup

The experiment was conducted in an Upflow Anaerobic Sludge Blanket reactor – UASB (Figure 1), constructed from polymethyl methacrylate and with a working volume of 2 L. The reactor had a water recirculation jacket to maintain the operating temperature in the central cylinder at 40 ± 1 °C. The reactor feed was performed in semi-continuous mode and controlled by a peristaltic pump (8 rpm and flow rate of 1.1 ml/min). The biogas production was measured using a wet mechanical meter, and the corresponding volume was converted to standard temperature and pressure conditions (273.15 K, 1 atm). The hybrid reactor had four sampling points along its vertical column, allowing for sample collection from different reaction zones. The sampling points (P1 to P4), measuring ½”, were distributed along the reactor and used simultaneously with the influent (in) and effluent (out) points to trace the COD removal behavior along the reactor column. The spacing measurements, reactor details, and sampling points are presented in detail in Figure 1.

Substrate/Effluent

The substrate was collected from a confined cattle farm (Free Stall). The effluent underwent a preliminary solid separation process using a decanter with a hydraulic retention time (HRT) of 3 hours. The characterization of the bovine livestock wastewater (BLW) is presented in Table 1.

Analytical and chromatographic methods

The total and soluble chemical oxygen demand (CODt and CODs), total solids (TS), volatile solids (VS), fixed solids (FS), total suspended solids (TSS), volatile suspended solids (VSS), and fixed suspended solids (FSS), ammoniacal nitrogen (NH^{4+}), total Kjeldahl nitrogen (TKN), alkalinity, pH, phosphate (PO4-3), and nitrate (NO^{-3}) were determined in duplicate according to the methodologies described in the Standard Methods (APHA et al., 2017). The volatile fatty acids (VFAs) were analyzed by High-performance liquid chromatography (HPLC) using an Agilent 1100 model. The gases CH_4 and CO_2 in the biogas were measured by gas chromatography using a Varian 430-GC instrument equipped with a thermal conductivity detector and a Varian Capillary Column SelectTM Permanent Gases/CO_2 HR - Malsieve 5 A Parabond Q Tandem #CP7430 column. The column, injector, and detector temperatures were set at 50, 80, and 120 °C, respectively. Helium was used as carrier gas (52 mL.min^{-1}). The injection volume used in the chromatograph was 0.25 mL of biogas collected from the upper portion of the reactor.

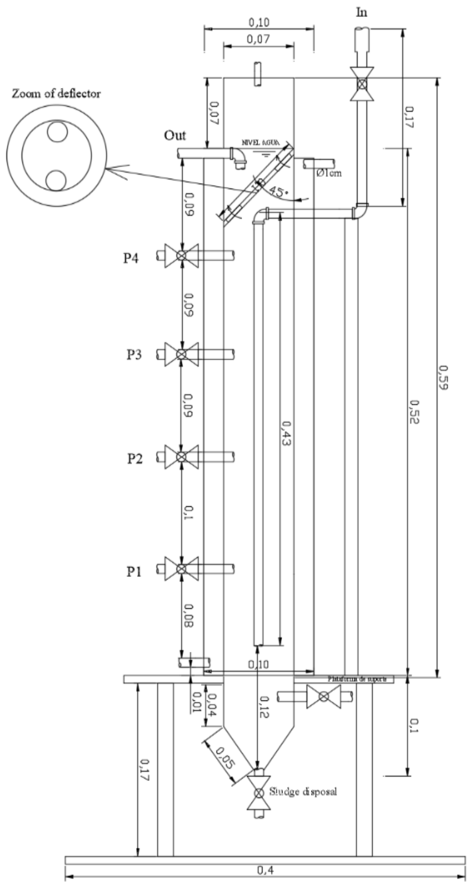

Figure 1. UASB reactor prototype tested.

Table 1. Characterization of cattle wastewater.

Parameter	Value
pH	$7.5_{(0.1)}$
Alkalinity	$4234_{(0.08)}$
COD_t (mg.L^{-1})	$21000_{(4.1)}$
COD_s (mg.L^{-1})	$9698_{(2.7)}$
TKN (mg.L^{-1})	$1200_{(0.05)}$
NH_4 (mg.L^{-1})	$422_{(0.3)}$
NOrg (mg.L^{-1})	$778_{(1.1)}$
PO_4^{-3} (mg.L^{-1})	$41_{(4)}$
ST (mg.L^{-1})	$15267_{(18)}$
SF (mg.L^{-1})	$3793_{(61.2)}$
SV (mg.L^{-1})	$11475_{(31)}$
VFA (mg.L^{-1})	$3.035_{(8)}$

CODt - Total Chemical Oxygen Demand; CODs - Soluble Chemical Oxygen Demand; (%) CODs - percentage of soluble COD; NTK - Total Kjeldahl Nitrogen; N org - Organic Nitrogen; TS - Total Solids; VS - Volatile Solids; FS - Fixed Solids; TSS - Total Suspended Solids; VSS - Volatile Suspended Solids; FSS - Fixed Suspended Solids, VFA - Volatile Fatty Acids. Values in parentheses indicate standard deviation.

Operational Mode

The reactor operation was carried out in six phases, with the first two phases related to system startup and the remaining four phases related to unit operation under different hydraulic retention times (HRTs). After 30 days of inoculation, a chromatographic analysis was performed, which recorded a methane concentration of 60% (± 0.9). With the confirmed methane production and the progressive increase in biogas production, reactor operation was initiated. The main operational characteristics of the reactor during the different phases are presented in Table 2.

Table 2. Operation of the hybrid anaerobic reactor.

Regime-phases	HRT (days)	OLV ($kg.COD_t.m^{-3}.d^{-1}$)	OLSV ($kg.VS.m^{-3}.d^{-1}$)	Time (days)
I - *Start-up*	---	---	---	0-30
II - semi continuous	6	4	4.3	31-61
III- semi continuous	5	5	5.2	62-85
IV - semi continuous	3	7	8	86-120
V - semi continuous	2	11	12	121-140

HRT - Hydraulic Retention Time; OLR - Organic Loading Rate in terms of COD_t; OLR' - Organic Loading Rate in terms of VS.

Results and discussion

Biogas Production

The range of biogas production was from 0.65 to 1.5 $m^3\ m^{-3}\ d^{-1}$, with methane concentrations ranging from 69% to 75% over the 140-day experimental period (Figure 2). A gradual increase in biogas production was observed with an increase in organic load, especially with an increase in the concentration of volatile organic compounds (VOCs), as illustrated in Figure 2. This behaviour was particularly evident in phases IV and V, when daily volumes exceeded 1 m^{-3}, indicating a positive correlation between the input of organic matter and biogas generation. These results reinforce the efficiency of the system in converting organics substrates into biogas, highlighting the importance of controlling the organic load to optimise production. Table 3 presents the average values of gas production, COD removal, and methane production yield (CH_4 yield) recorded for each experimental period.

Similar values obtained in this study were found by Rico et al., (2011) and Dareioti et al., (2010), both operating with a mesophilic CSTR reactor. They reported biogas production rates of around 1.3 $m^3.m^{-3}.d^{-1}$, using HRT_s of 10 and 19 days, respectively. The UASB reactor in this study operated with significantly shorter HRTs, indicating cost savings in terms of reactor volume requirements and the absence of mechanical substrate agitation systems. On the other hand, Demirer & Chen, (2005b), when treating cattle manure in a hybrid anaerobic reactor with HRTs of 10 and 20 days, recorded biogas production values of 0.21 and 0.83 $m^3.m^{-3}.d^{-1}$ (63.5% CH_4), respectively. Uggetti & Ferrer-martı, (2011) in Peru and Resende et al., (2016) in Brazil operated horizontal tubular digesters (HTD) at ambient temperature.

Uggetti & Ferrer-martı, (2011) reported productivities of 0.07 and 0.47 $m^3.m^{-3}.d^{-1}$ with HRTs of 60 and 90 days, while Resende et al., (2016) achieved productivities of 0.27 and 0.31 $m^3.m^{-3}.d^{-1}$ with a 60-day HRT. The highest biogas production values reported by these authors were below the lowest average value achieved by the UASB reactor (0.65 $m^3.m^{-3}.d^{-1}$), operating with HRTs 10 to 15 times shorter. Even in tropical countries, low temperatures during winter can adversely affect anaerobic digestion performance. Resende et al., (2016) observed temperature fluctuations between 14 and 25 °C in winter and 24 to 35 °C in summer. One of the factors that enhanced gas production was maintaining a constant reactor temperature of 40°C. As described by Gerardi, (2003) and (Witarsa & Lansing, 2015), the most suitable temperatures for anaerobic digestion of BLW are in the mesophilic range (30-35 °C), although the value of 40°C had a significant influence on gas production. Therefore, this temperature should also be considered for UASB reactor operation.

These statements, combined with the results of the current research, prompt a reflection on the advantages of initiating the adoption of reactors operating in the mesophilic range in countries with a tropical climate, such as Brazil, where currently plants operating at ambient/psychrophilic temperatures (10-25°C) are employed. According to Noorollahi et al., (2015), the average methane concentration in biogas falls within the range of 55 to 65%. Other authors, Comino et al., (2009), Dareioti et al., (2010), Dias et al., (2014), Rico et al., (2011), using CSTR reactors, and Demirer & Chen, (2005b), using a hybrid reactor, report methane concentrations with minimum values of 51% and 64% and maximum values of 67% and 69%. Comparatively, the lowest value obtained in the present study (69% CH_4) corresponds to the highest percentage reported in the literature, indicating that the process occurring in the current reactor allowed to produce biogas with a higher methane concentration.

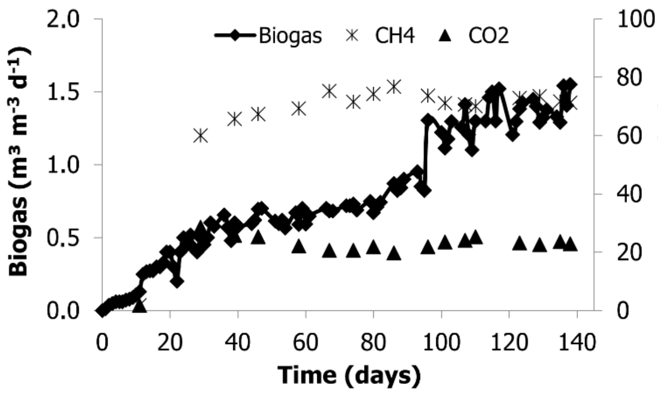

Figure 2. Evolution of biogas for each experimental phase and concentrations of CH_4 and CO_2.

Removal of total and soluble COD

An increase in the applied organic load and a decrease in the HRT were observed, resulting in a decrease in the unit's removal capacity, as illustrated in Table 3. The highest total COD removal efficiencies (CODt) were attained during operations with longer HRTs (5 and 6 days), yielding average efficiencies of 76% and 80%, respectively. When benchmarked against the studies by Marañón et al., (2012) and Marañón & Vázquez, (2001), which utilized HRTs of 14 an 22.5 days, respectively, COD removal efficiencies of 85% and

75.5% were obtained. It is noteworthy that the HRTs employed in the present study are 2.3 and 3.8 times higher than those used in the aforementioned studies.

The removal efficiencies of 55% and 61% obtained by Marañón & Vázquez, (2001) when altering the HRT from 8.9 to 10.6 days and applying loads close to those tested in the hybrid reactor, 4.91 and 4.32 versus 4.6 $kg.COD.m^{-3}.d^{-1}$ (Phase III), continue to indicate a clear advantage in performance by the present reactor.

COD removal values of 79.7%, comparable to those recorded in the UASB reactor, were obtained in a system operated under thermophilic conditions (55°C) with a HRT of 22.5 days L. Castrillón et al., (2002). This result is particularly significant when compared to those obtained in other types of reactors. In a separate study, Comino et al., (2009) utilized a CSTR batch reactor to digest a mixture of cattle manure and whey, achieving a COD removal of 74% after a residence time of 56 days.

The decrease in HRT to 3 and 2 days (Phases IV and V) did not favor the removal capacity of the UASB, compared to the results obtained in the previous two phases, resulting in a decrease to values of 64% and 60%, respectively. However, compared to other studies, it was found that the use of higher HRT_s, around 10 days, did not benefit the performance of either the hybrid reactor (Demirer & Chen, 2005b) or the UASB (Marañón & Vázquez, 2001), which achieved removals of 64% and 61%, respectively, when operating with loads of approximately 7 and 4 $kg.COD.m^{-3}.d^{-1}$.

Additionally, the use of higher temperatures (53°C) and HRTs of 10 days in a horizontal tubular reactor (Abubakar & Nasir, 2012) and 17 days in a Biostat B batch reactor in Germany (Omar et al., 2008) resulted in COD removals of 49% and 51%, respectively, which were lower than those achieved in the reactor of this study operated under mesophilic temperature conditions. The lower removals (61% and 55% COD) recorded in the study by (L. Castrillón et al., (2002) are comparable to the lower values obtained in the UASB reactor (Phase V), but with the disadvantages of applying higher digestion temperatures and longer HRTs than those used in this study: thermophilic range, HRT of 8.9 and 7.3 days versus mesophilic range, HRT of 2 to 6 days.

The UASB reactor examined in this study exhibited an enhanced capacity for organic matter removal under mesophilic conditions, accompanied by reduced hydraulic retention times (HRTs). This observation is distinctly illustrated in Figure 3, which presents a correlation between COD values at the reactor outlet and hydraulic retention times. The fitted equation serves as a valuable instrument for the design and prediction of reactor performance under diverse operating conditions, facilitating the optimization of pollutant removal.

As demonstrated in Figure 4, up to point P3, the soluble COD removal behavior was similar for all hydraulic retention times (HRTs) that were tested. However, from point P4 onwards, a sharp drop in COD concentration was observed in the HRTs of 5 and 6 days. This behavior can be attributed to a change in reactor condition, when the generated sludge is no longer in suspension or forming a blanket. Therefore, lower concentrations of organic matter are found in the effluent.

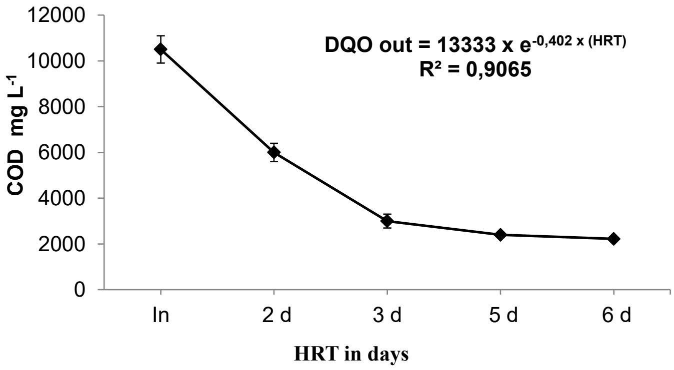

Figure 3. COD removal kinetics curve as a function of TRH containing the adjusted equation to obtain COD from the output of the reactor.

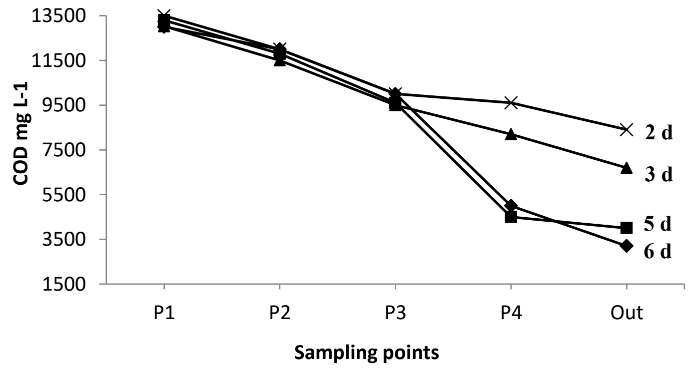

Figure 4. COD removal curves along the column of the reactor.

Biogas and methane yield as a function of removed COD

As shown in Table 3, an increase in methane (CH_4) production was observed with rising COD loads applied and falling HRTs during the initial three phases of the experiment. However, in Phase V, the methane yield remained comparable to the values recorded in Phases II and III. The findings suggest that Phase IV, with an HRT of 3 days, yielded the highest methane yield, reaching 0.183 and 0.513 m^3 of CH_4 per kg of total and soluble COD removed, respectively.

The CH_4 yield values, in relation to total COD (DQO_t), were lower than those obtained based on soluble COD (Table 3). This indicates that the HRTs adopted in the research were sufficient for the degradation of soluble material, while a portion of the particulate organic matter, which is more difficult to biodegrade, remained retained inside the reactor. The retention of this material inside the reactor explains the higher values of DQO_t removal compared to soluble COD (DQO_s) in all experimental phases. Over time, this particulate fraction will be degraded or may be removed along with the sludge discharge at the bottom of the reactor.

Solid removal

As demonstrated in Tabe 4, the data on the removal of Total Solids (TS) and Volatile (VS) indicates a decline in removals as the HRTs decrease. This phenomenon can be attributed to an increase in microbial biomass within the reactor, leading to the release of biological material (anaerobic sludge) along with the treated effluent. Furthermore, a reduction in the HRT has been shown to decrease the time available for substrate degradation, thereby promoting material accumulation within the system. A parallel trend was observed for Suspended Solids (SS) and Sedimentable Solids (SSV), as indicated in Table 4, which also presents the values of solids applied to the hybrid system, their respective removals and the methane yield as a function of the Volatile Solids removed (VS_r).The removal of Volatile Solids (VS) reached a maximum of 70% in Phase II and gradually decreased to a minimum of 35% in Phase V, for the initial HRT of 6 days and final HRT of 2 days, respectively. Similar values were achieved by several authors: (Demirer & Chen, 2005a and 2005b), using a CSAD (Conventional Slurry Anaerobic Digestion) process; Resende et al., (2016), operating a DTH (Horizontal Tubular Digestor) reactor at predominantly mesophilic temperatures; and Jensen et al., (2016), using the TPAD (Temperature Phased Anaerobic Digestion) process.

The methane yield obtained with an HRT of 3 days is similar to the one found by Uggetti & Ferrer-martı (2011) in their study, where they operated a DTH (Horizontal Tubular Digestor) reactor at ambient temperature with HRTs ranging from 60 to 90 days. Demirer & Chen, (2005b) tested cattle manure mixed with water in a 2:1 (v/v) ratio (Wen et al., 2004) in a hybrid anaerobic reactor. The authors achieved methane production yields of 0.299 and 0.255 m³ per kg of removed Volatile Solids (SV_r) with HRTs of 20 and 10 days, respectively, resulting in reductions of 44% and 69% of VS. In this research, the SV removal values were similar to those of the previously mentioned study, but with lower HRTs.

pH, Alkalinity, and Volatile Fatty Acids (VFAs)

The pH values inside the reactor remained close to neutral (between 6.9 and 7.4), indicating favorable conditions for organic matter degradation and microbial growth (Kothari et al., 2014) in all experimental phases. The recorded alkalinity values in the reactor ranged from 2,500 to 5,000 mg.L^{-1}, within the range recommended by Grandy & Lim (1980). This indicates that the buffering effect was sufficient to maintain the anaerobic process in good operational conditions.

The successful operation of the UASB reactor is finally confirmed by the removal of volatile organic acids (VFA_s), which ranged from 92% to 100% in all experimental phases. The VFAs did not accumulate in the system at any stage of the treatment; instead, they were consumed and transformed primarily into CH_4 and CO_2, as described by Demirer & Chen (2005a). The VFA values at the reactor outlet remained between 50 and 500 mg.L^{-1}, a range considered safe for the stability of an anaerobic process, as stated by Gerardi (2003). According to Sung & Santha (2001), the alkalinity of well-functioning anaerobic sludge is capable of neutralizing excess VFAs and maintaining the pH within an ideal range of 6.5 to 7.5.

Conclusions

The UASB reactor with heating can be used for efficient treatment of cattle wastewater, with HRT ranging from 2 to 6 days. To maximize biogas production for energy recovery, an HRT of 2 days is recommended. The shorter HRTs observed in this study resulted in smaller reactor volumes, which contributed to significant COD removal efficiency. The reactor demonstrated good methane production capacity, indicating stable microbiology throughout all experimental phases. There was no accumulation of VFA within the reactor, indicating no acidification issues in all tested phases. The UASB reactor with heating shows promising potential for bioenergy recovery and cattle wastewater treatment in a real application.

Table 3. COD removal and biogas production.

Phase	COD_t		COD_s		*Biogas	*CH_4	[1]CH_4 yield	[2]CH_4 yield
	In (mg.L^{-1})	Rem (%)	In (mg.L^{-1})	Rem (%)	(m³.m^{-3}.d^{-1})	(%)	m³.kg^{-1}.COD_t	m³.kg^{-1}.COD_s
II	22963(7.3)	80	9445(4.1)	75	0.50(0.3)	69(5.5)	0.20	0.401
III	23096(9.4)	76	9865(6.3)	71	0.74(0.9)	75(0.19)	0.22	0.408
IV	20986(4.2)	64	8758(2.1)	58	1.25(0.12)	71(0.3)	0.30	0.513
V	21512(3.2)	60	9314(1.6)	51	1.50(0.6)	75(0.11)	0.34	0.423

In - Influent; Rem - Removal; *averages per phase. CH_4 yield - Methane yield.

Table 4. Solids removal by UASB and methane yield (CH_4 yield).

Phase	TS		VS		Ashes (SF)		[1]CH_4 yield
	In (mg.L^{-1})	Rem (%)	In (mg.L^{-1})	Rem (%)	In (mg.L^{-1})	Rem (%)	m³.kg^{-1}.VS_r
II	17200(65)	66	13076(24)	70	2000(9)	37	0.30
III	16600(41)	65	12401(59)	65	2100(79)	31	0.30
IV	15983(28)	52	14898(42)	50	1702(13)	21	0.35
V	17423(10)	45	11025(36)	35	1000(5)	18	0.40

Ent - Influent; Rem - Removal; [1]CH_4 yield - Methane yield based on VSS.

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