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Anaerobic–Aerobic Treatment of Fruit and Vegetable Wastes and Municipal Wastewater

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Abstract: Waste management in large urban centers is one of the main challenges for public administration. Two of the most abundant wastes in cities are waste solid and municipal wastewater (MWW). Their management can be optimized if they are treated together. This work analyzed an anaerobic–aerobic system for the treatment of fruit and vegetable wastes (FVWs) and MWW. Firstly, FVWs were collected and characterized; once in the laboratory, they were placed in a tank with the MWW, aiming at transferring to the water those solids with a particle size below 105 µm; then, they were separated by sieving. The mixture of MWW and FVWs with a particle size below 105 µm was fed into an up-flow anaerobic sludge reactor (UASB); in the latter, dissolved and suspended organic matter was transformed into methane and carbon dioxide. The water that left the UASB was sent to be post-treated in an activated sludge reactor (ASR). The chemical oxygen demand (COD) was used as an evaluation parameter of the anaerobic–aerobic system; a removal efficiency higher than 80% was achieved, whereas it was 60% in the ASR. Another evaluation parameter was methane (CH_4) productivity, with an average of 3.0 L_{CH4} L^{-1} d^{-1}. VWF leaching achieved an average COD extraction of 7.68 $kg{\cdot}m^{-3}$. The UASB efficiency was on average 70% for the assayed loads (2–8 kg $COD{\cdot}L^{-1}{\cdot}d^{-1}$). The energy potential calculated for the anaerobic–aerobic system was 510.2 $kW{\cdot}h{\cdot}d^{-1}$

Keywords: UASB; activated sludge; anaerobic digestion; leachates

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1. Introduction

One of the biogenic wastes of great abundance in large cities is fruit and vegetable residues (FVWs), which can represent up to 32% of organic solid waste [1]. Landfills and incineration are the most widely used methods for the management and treatment of FVWs despite their negative environmental impact. It has been determined that processes that include anaerobic digestion have less environmental impact during FVW treatment. For example, Trujillo-Reyes et al. [2] determined through a comparative life cycle study that the use of integrated processes for the treatment of FVWs, which include anaerobic digestion, generates significant reductions in global warming and terrestrial ecotoxicity impacts when compared with the current treatment scenario. Furthermore, the higher production of electrical energy (413%), as well as the production of co-products, would avoid the production of 100 $kg{\cdot}d^{-1}$ of inorganic fertilizers.

The energy revaluation of these can occur if they are treated by anaerobic digestion since biogas with a high methane content and solid and liquid digestates with characteristics of fertilizers, soil recuperators, and agricultural tea are generated. However, one of the problems associated with FVW anaerobic digestion is the high amount of suspended solids, which prevents the use of high-rate anaerobic reactors, such as the UASB and EGSB. This implication reduces the use of anaerobic digestion for the treatment of FVWs in low-rate anaerobic reactors [3–5], limiting in turn the energy produced.

Different pretreatments have been developed for solid organic waste in general (FVWs, stubble, pruning, and agro-industrial waste) with the intention of conditioning them for treatment in high-rate anaerobic reactors [6–9], but most of these pretreatments increase operating costs. A low-cost pretreatment consists of the extraction of solids from the FVW matrix by means of water.

This water–FVW contact allows for increasing the chemical oxygen demand (COD) in the water up to concentrations of 60 $g \cdot L^{-1}$, with a low concentration of solids suspended and particle sizes of the solids suspended less than 105 μm [10,11]. This stage makes it possible to generate an effluent with adequate conditions to be fed to a high-rate reactor. Efficient methane productivity for power generation is obtained when anaerobic reactors are operated at high organic loads, greater than 4 $g\ COD \cdot L^{-1} \cdot d^{-1}$. Due to the fact that the efficiency of high-rate anaerobic reactors is around 80%, the load of the anaerobic reactor outlet effluent is still high (greater than 1000 $mg\ COD \cdot L^{-1} \cdot d^{-1}$), which requires post-treatment of the effluent.

The standard configuration of wastewater treatment plants consists of the following six main stages: a wastewater conditioning system, an activated sludge reactor, a secondary settler, an anaerobic reactor to stabilize the sludge wastes, a post-treatment system of treated water, and a drying and condition stage of biosolids. In 2020, 72.7% of the wastewater treatment infrastructure in Mexico corresponded to activated sludge reactor systems [12]. Performing an energy balance of a treatment system with these characteristics yields 19 $kW \cdot h$ produced for every 100 kg of processed carbon [13]; this implies that the treatment systems are self-sustaining in energy terms. However, in Mexico, a large proportion of this type of treatment plants lacks an anaerobic reactor, which prompts an energy deficit on the order of 44 $kW \cdot h$ for each 100 kg of fed carbon; the latter makes the treatment process unviable and causes deterioration of treatment plants, leading to their abandonment.

A configuration that gives better energy balances is an anaerobic reactor followed by an aerobic one. First, it transforms the fed carbon into energy (biogas) and then cleans the effluent with a lower energy expense in the aerobic reactor. In this way, a positive energy balance of 122 $kW \cdot h$ is obtained for each 100 kg of fed carbon [13]. To maintain profitable energy efficiency, it is necessary to have at least 3 $kg\ COD \cdot m^{-3} \cdot d^{-1}$ of organic load at the input of the anaerobic reactor during the whole year; this condition limits municipal wastewater (MWW) treatment systems because they have maximal organic loads of 1.0 $kg\ COD \cdot m^{-3} \cdot d^{-1}$. The organic load at the input can be maintained above 3 $kg\ COD \cdot m^{-3} \cdot d^{-1}$ using other substrates; a viable alternative is the fruit and vegetable waste (FVW) that after conditioning can fulfill the mentioned purpose.

The objective of this work was to evaluate the efficiency of an anaerobic–aerobic system for the joint treatment of FVWs and MWW based on methane productivity and COD removal assessments.

2. Materials and Methods

2.1. Characterization of Fruit and Vegetable Wastes

Fruit and vegetable wastes (FVWs) were obtained from a juice- and cocktail-expending shack in the municipality of Ecatepec de Morelos, Estado de México, Mexico. Wastes were transported to the laboratory in 20 L containers and conditioned as follows:

1. Classification of the FVW according to the type of waste.
2. Reduction of the particle size to approximately 1 cm (Figure 1).
3. Weighing each type of waste to calculate its fraction in the original mixture using Equation (1).

$$\text{Fraction} = \frac{\text{kg of one type of waste}}{\text{kg total wastes}} \quad (1)$$

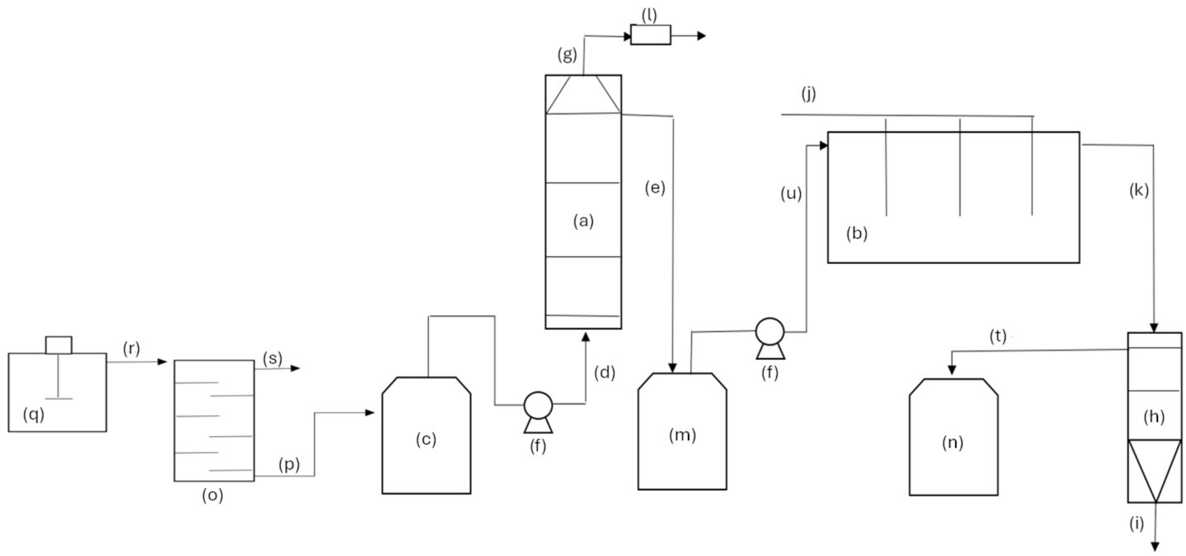

Figure 1. Anaerobic–aerobic system. (a) UASB, (b) ASR, (c) pH homogenization tank, (d) input flow to UASB, (e) output flow from UASB, (f) peristaltic pump, (g) biogas output, (h) settler, (i) sludge purge, (j) air input, (k) output flow from the ASR, (l) biogas counter, (m) UASB effluent storage tank, (n) storage system, (o) sieve, (p) liquid FVW-MWW fraction with a Dp < 105 µm, (q) leaching tank, (r) output of solids and liquid fraction, and (s) FVW with Dp > 105 µm, (t) treated water, (u) input flow to ASR. Dp = diameter of the particle.

Once the fractions had been calculated, a mixture was formed with the same proportion of wastes as the original. The mixture was characterized physiochemically in terms of COD, phosphorus, and nitrogen concentrations, as well as pH, conductivity, packing density, and the mass of total solids/mass of wastes relation.

2.2. Characterization of the Wastewater

The wastewater was sampled from the pretreatment channel of the wastewater treatment plant of the Higher Studies Technological Institute of Ecatepec campus. To characterize the wastewater, simple and compound samples were taken. Each sample was conserved and analyzed according to the Norms listed in Table 1.

Table 1. Wastewater analysis techniques.

Parameter	Reference Norm
Chemical oxygen demand	ISO 15705:2002 [14]
Total solids	ISO 11923:1997 [15]
pH	ISO 10523:2008 [16]
Conductivity	ISO/DIS 7888-1985 [17]
Escherichia coli	ISO 9308-2:2012 [18]
Nitrogen	ISO 5663:1984 [19]
Phosphorus	4500-P D Standard Methods [20]
Fats	5520 D Standard Methods
Temperature	2550 Standard Methods

2.3. Lixiviation of FVWs in MWW

To determine the amount of water needed to transfer the highest amount of solids smaller than 105 µm of the mixture of FVWs in MWW, the latter was poured into a 2 L working volume tank for the lixiviation and maintained in contact for a determined time, according to Table 2.

Table 2. Factorial design with two variables including contact time and the FVW:MWW relation.

Experiment	Time (d)	FVW:MWW
1	1.0	1.0
2	1.0	4.0
3	15.0	1.0
4	15.0	4.0
5	8.0	2.5
6	8.0	2.5
7	8.0	2.5
8	8.0	2.5
9	8.0	2.5

Column 3 (FVW: MWW) specifies the relation mass: volume of FVWs and MWW.

Once the contact time had elapsed, the FVW:MWW mixture of each experiment was passed through a 1 mm sieve and then through a 105 μm sieve. The solid wastes with a particle size greater than 105 μm were sent for composting, and the total volume of the leachate was measured in a graduated cylinder, determining its concentration of total solids (TS) and subtracting the total solids of the MWW to obtain the total solids of the leachate ($TS_{leachate}$); this and the concentration of solids in the FVW mixture (TS_{FVW}) were used to determine the efficiency of the extraction during leaching (Ef_leaching).

$$Ef_{leaching} = 1 - \frac{TS_{FVW} - TS_{leachate}}{TS_{FVW}} \quad (2)$$

To determine the effect of contact time and the FVW:MWW ratio, a 22-factorial design with 5 centers was used, as shown in Table 2. Once the extraction efficiency of solids less than 105 μm during leaching was determined, a regression analysis was performed using Minitab® (Minitab Inc., State College, PA, USA) to determine the effect of the two variables tested.

2.4. Anaerobic–Aerobic System for the Joint Treatment of FVWs and MWW

The anaerobic–aerobic system consists of a leaching tank, an up-flow anaerobic reactor (UASB), and an activated sludge aerobic reactor (ASR), as shown in Figure 1. First, the FVWs and the MWW were placed in a tank without agitation, as shown in Figure 1 q, with a retention time of 24 h; the FVW solids with a particle size smaller than 105 μm that were lixiviated by the MWW were separated by sieving those with a particle size greater than 105 μm, as shown in Figure 1 o. Afterward, the pH of the MWW was adjusted to 7 and the COD concentration was adjusted in a homogenization tank, as shown in Figure 1 c, using HCl/NaOH and FVW with a particle size smaller than 105 μm, respectively. Once the COD concentration was adjusted to the MWW (to feed organic loads of 2, 3, 4, 5, 6, 7, and 8 kg COD·m^{-3}·d^{-1}), this was fed into the UASB with a constant hydraulic retention time (HRT) of 12 h.

The UASB is made of acrylic with a surface area of 400 cm^2 and a height of 80 cm, as shown in Figure 1 a. The UASB operated at 35 °C within a controlled temperature chamber. The reactor was equipped with a feeding pump that controlled the input flow, three sampling points of the liquid, one effluent output, and a gas line connected to the biogas collector that contained a sampling port and a magnetic counter to quantify the flow of the biogas. In the UASB, the volume of the produced gas was measured, and the COD removal efficiency was determined as well as the alkalinities.

The effluent that left the UASB fed the activated sludge aerobic reactor, ASR, as shown in Figure 1 b, for which a hydraulic retention time of 24 h was established. The relation COD/SS in the ASR was 0.3 kg COD·kg^{-1} SSML (suspended solids in the mixed liquid) and the aeration was 20 L·min^{-1}, using sintered glass dispersers to diminish the air bubble.

Separation of the treated water–SSML was performed in an acrylic settler, as shown in Figure 1 h, with a 200 cm^2 area and a 100 cm height with an SSML delivery at 60 cm from the water output at the bottom of the tank. A portion of the concentrated sludge was recycled to the ASR to impose a cellular retention time of 10 d. The COD removal efficiency was determined in the ASR.

Assessment of the anaerobic–aerobic system was performed in terms of methane productivity, COD removal efficiency, and energy potential.

2.5. Calculations and Energetic Potential Perspective

The estimation of methane was carried out based on the model of Metzner and Lemmer [21] (Equation (3)) as follows:

$$C_{250}H_{611}O_{77}N_{55}S + 347.5O_2 \rightarrow 250CO_2 + 55NH_3 + H_2S + 272H_2O \quad (3)$$

where $C_{250}H_{611}O_{77}N_{55}S$ is the condensed formula for the *VS* [21]. It is considered that 82 kg C generates 128 kW·h during anaerobic digestion [13]. Equation (4) is used to determine the energy potential of the substrate.

$$\text{Energy} = \text{Population} * \text{VGP} * f_{\frac{OSW}{USW}} * f_{\frac{FVW}{OSW}} * f_{VS/FVW} * f_{C/VS} * \aleph_{E/C} \quad (4)$$

where VGP is the waste generation per capita, $f_{OSW/USW}$ is fraction of organic solid waste in urban waste, $f_{FVW/OSW}$ is the fraction of fruit and vegetable waste in organic solid waste, $f_{VS/FVW}$ is the fraction of VS in FVW, $f_{C/VS}$ is the fraction of C in the VS, and $f_{VS/FVW}$ is the energy yield per C processed

3. Results

3.1. Characterization of the Mixture of Fruit and Vegetable Wastes (FVWs)

The composition of the organic fraction of municipal solid waste (MSW) in rural zones is different from urban zones due to a higher fraction of garden waste. Composition is also affected by season, geographic changes, and different lifestyles and cultures in terms of recycling practices and the type of generated waste as a function of eating habits [22]. Hence, it is recommended to always report the composition of the studied wastes disregarding their nature. Table 3 presents the composition of the FVW mixture used in these experiments. In this mixture, 77.4% correspond to melon, papaya, watermelon, pineapple, and grapefruit.

Table 3. Composition of the collected FVW mixture.

Waste	Mass (g)	Fraction Mass/Mass
Melon	1632	0.177
Papaya	1618	0.175
Orange	372	0.040
Watermelon	1664	0.180
Mango	427	0.046
Pineapple	1127	0.122
Grapefruit	1663	0.180
Carrot	164	0.018
Cucumber	559	0.061
Total	9229	1.00

Knowledge of the physical and chemical characteristics of solid organic waste allows for choosing the type of treatment and the best operational conditions to achieve good treatment efficiencies.

The FVW mixture depicts acid values characteristic of this type of waste, as shown in Table 4. Several authors have reported similar pH values between 3 and 5 for similar solid organic wastes; dos Santos et al. [3] reported pH values of 3.7, 4.0, and 4.2 for maracuja peel, orange bagasse, and cashew bagasse, respectively. Whereas Mateus et al. [23] reported pH values of 3.96 for peaches, 3.45 for raspberries, and 4.18 for white guava.

Table 4. Physicochemical characteristics of the FVW mixture.

Parameter		Parameter	
pH	5.05	g COD/g TS	1.56
Conductivity µS/cm	257	g COD/g VS	1.57
g fat/g waste	0.024	g carbohydrates/g TS	0.887
g TS/g waste	0.10	g protein/g TS	0.200
g VS/g waste	0.089	mg phosphorus/g TS	2.38
Packing density (g/mL)	0.836	mg nitrogen/g TS	14.3

The total FVW solids showed an average moisture of around 90%. This value is close to that reported by Swamy et al. [24] and Gomes et al. [25], who obtained a 90.23% moisture for mixtures of fruit and vegetable wastes.

For anaerobic digestion (AD), a series of nutrients are needed to convert carbon into gas. Among all the needed ones (macro and micronutrients), nitrogen and phosphorus are considered the most important. Nutrient balance is generally estimated by the relation C:N:P, expressing C as the chemical oxygen demand (COD) in the practice; for the AD, the most adequate relation of COD:N:P is 350:5:1 when the wastes have a high carbohydrates content [22]. The relation COD:N:P (350:1.3:0.2) was around the value proposed for wastes with a high carbohydrate content; however, the mixture was deficient in phosphorus and nitrogen, but the feeding medium was balanced with the MWW used to obtain a 350:5:1 relation of COD:N:P.

3.2. Characteristics of the Wastewater

Table 5 presents the characteristics of the used wastewater. The values are averages of the compound and simple samples.

Table 5. Characterization of the sample.

Parameter	Units	Result
COD, soluble	$mg \cdot L^{-1}$	445 ± 126
Total solids	$mg \cdot L^{-1}$	690 ± 42
pH	dimensionless	9.6–8.5
Conductivity	$\mu S \cdot cm^{-1}$	533 ± 174
Escherichia coli	MPN in 100 mL	>24,000
Nitrogen	$mg \cdot L^{-1}$	77 ± 18
Phosphorus	$mg \cdot L^{-1}$	26 ± 14
Fats	$mg \cdot L^{-1}$	44 ± 5
Temperature	°C	18.4–22.4

Most probable number (MPN).

In terms of COD, this effluent can be classified as municipal with a mean concentration of 500 $mg \cdot L^{-1}$. For the wastewater, chlorides had an average value of 150 $mg \cdot L^{-1}$; therefore, it is acceptable to use the COD as a decision parameter. The electrical conductivity (Table 5) was below 2500 $\mu S \cdot cm^{-1}$; hence, it is acceptable to report *E. coli*. In turn, total solids amounted to 690 $mg \cdot L^{-1}$ on average, supporting the proposal of classifying this effluent as household wastewater with a high concentration according to Valdez and Vázquez [26], who classified them as such when the TS was higher than 350 $mg \cdot L^{-1}$.

3.3. Leaching of FVWs

Table 6 presents the leaching efficiency values for each of the assayed conditions. The maximal extraction efficiency during leaching (38.1%) occurred when the FVW:MWW relation was of 1:4.

Table 6. Factor 2^2 design for leaching the FVWs in MWW.

MWW Proportion	Time (d)	Efficiency (%)
1	1	29.8
4	1	35.2
1	15	27.9
4	15	38.1
2.5	8	32.9
2.5	8	35.8
2.5	8	32.5
2.5	8	32.5
2.5	8	31.6

A regression analysis performed with the data presented in Table 7 revealed that the FVW:MWW contact time did not have a significant effect on the extraction process in the extraction tank (p = 0.544); rather, it was the water proportion that ruled the process (p = 000). It also revealed that the interaction of the variables of interest had no significant effect on the process (p = 0.702). Hence, to determine the best FVW:MWW relation, the FVW was subjected to different MWW proportions with a constant contact time of 1 day (d). The results are shown in Table 8.

Table 7. Efficiency of TS extraction in the leaching tank at different FVW:MWW relations with 1 day of contact time.

Proportion FVW:MWW	Solids Extraction Efficiency (%)	
1:1	36.2	36.0
1:2.5	46.4	46.3
1:4	48.1	48.0
1:5	50.0	50.1
1:7	53.8	53.7
1:9	46.1	46.0

Table 8. Variance analysis of the means of the treatments.

Source	G. L	Sum of Quadratic Sequence	Mean Squares	F Value	*p*-Value
MWW	5	0.035135	0.007027	9634.22	0.000
Error	6	0.000004	0.000001		
Total	11	0.035140			

A variance analysis among the means of the extraction efficiency depicted in Table 8 revealed that there is a significant difference between at least two means of the treatments. Table 9 shows that this difference exists among treatments, except for the 1:2.5 and 1:9 relations.

Table 9. Grouping information using the Tukey test (95% confidence).

FVW:MWW	Means	Groups
1:7	53.75	A
1:5	50.05	B
1:4	48.05	C
1:2.5	46.35	D
1:9	46.05	D
1:1	36.10	E

The means with different letters are significantly different.

Once the best FVW:MWW relation for the extraction of solids smaller than 105 µm was determined to be 1:7 with a 1 d contact time, these conditions were used to operate the lixiviation tank. The COD soluble in the FVW:MWW liquid fraction at the 1:7 relation after 1 contact day was 7.68 g·L^{-1}.

3.4. Evaluation of the UASB Efficiency

Once the operational conditions of the lixiviation tank were established, a 40 L lixiviation tank was installed that produced the needed effluent to feed the UASB. Figure 2 depicts the COD concentration fed into the UASB (•), the maximal COD concentration was 4 kg·m^{-3}; the COD concentration was a control parameter to increase the organic load in the interval from 2 to 8 kg COD·m^{-3}·d^{-1}; and the change in the COD concentration was performed every 25 days, keeping the hydraulic retention time (HRT) constant.

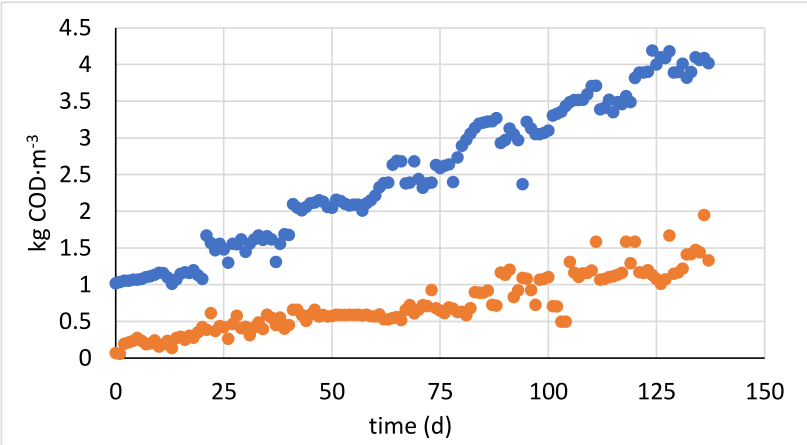

Figure 2. Input entrance (•) to the UASB of the solids extracted from the FVWs in the solubilizing tank. Output concentration (•) from the UASB.

To assess the stability of the UASB, the average COD removal efficiency was set at 80%. Figure 3 shows that at all the assayed loads of 2 to 8 kg COD.m^{-3}.d^{-1}, the COD removal efficiency was on average 70% with a 10% standard deviation. Hence, it was considered a stable process under these operational conditions.

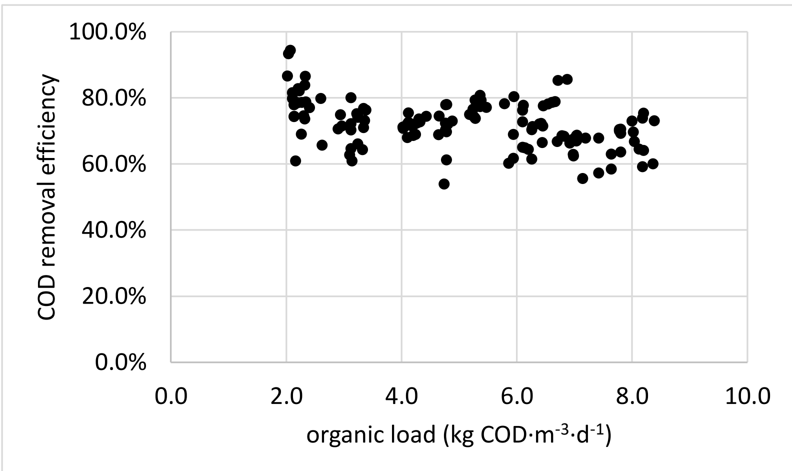

Figure 3. COD removal efficiency in the UASB vs. organic load.

The methane production for the FVW:MWW relation increased when increasing the organic load, reaching an average value of 3.0 m$^3_{CH4}$·m^{-3}·d^{-1} for loads of 8 kg COD·m^{-3}·d^{-1} (Figure 4). This productivity is within the range reported for similar systems. The maximal methane productivity values reported by Montes et al. [10], Mateus et al. [23], and Browne and Murphy [27] for two-stage systems were 1.83, 1.5, and 2.1 $m^3{}_{CH4}\cdot m^{-3}\cdot d^{-1}$, respectively. The produced methane could be used to generate up to 79.5 MJ $m^{-3}{}_{reactor}$ d^{-1} [23].

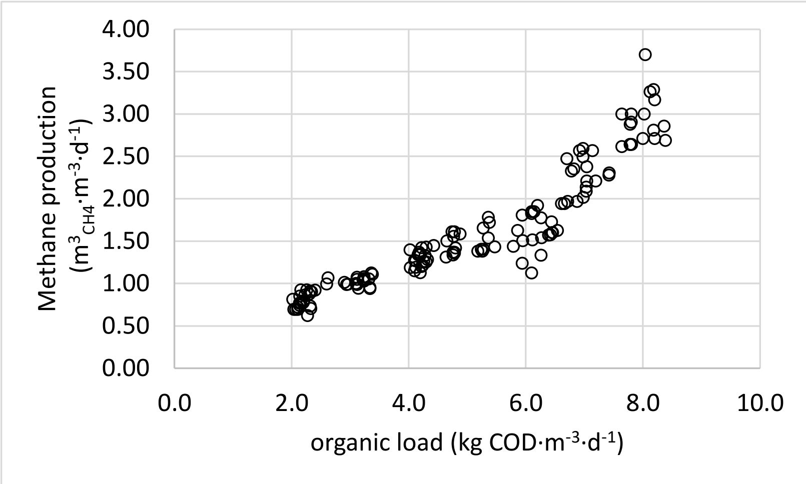

Figure 4. Methane production at different organic loads.

The highest volumetric production of methane of 3.0 $m^3{}_{CH4}\cdot m^{-3}\cdot d^{-1}$ was achieved with an organic load of 8 kg COD$\cdot m^{-3}\cdot d^{-1}$, which is similar to that obtained by Saidi et al. [28], at 2.92 $m^3{}_{CH4}\cdot m^{-3}\cdot d^{-1}$, when treating fruit wastes by anaerobic digestion with an organic load of approximately 8.41 kg COD$\cdot m^{-3}\cdot d^{-1}$ (4.25 kg VS$\cdot m^{-3}\cdot d^{-1}$) and a hydraulic retention time of 8 d; however, the HRT was higher than that used in this study (1.6 d, including the water contact time).

3.5. Assessment of the Activated Sludge Reactor (ASR) Efficiency

The UASB output was fed into the ASR to improve the quality of the effluent. The COD concentration that entered the ASR ranged from 0.5 to 2 kg COD$\cdot m^{-3}$. This increase was generated by the increment in the load to the anaerobic–aerobic system, while the COD output was between 0.066 and 0.237 kg$\cdot m^{-3}$. The COD removal efficiency of the ASR was around 80%, presenting a minimal efficiency (66%) when the global load was 2 kg COD$\cdot m^{-3}\cdot d^{-1}$ and maximal (89%) when the global load was 4 kg COD$\cdot m^{-3}\cdot d^{-1}$ (Figure 5).

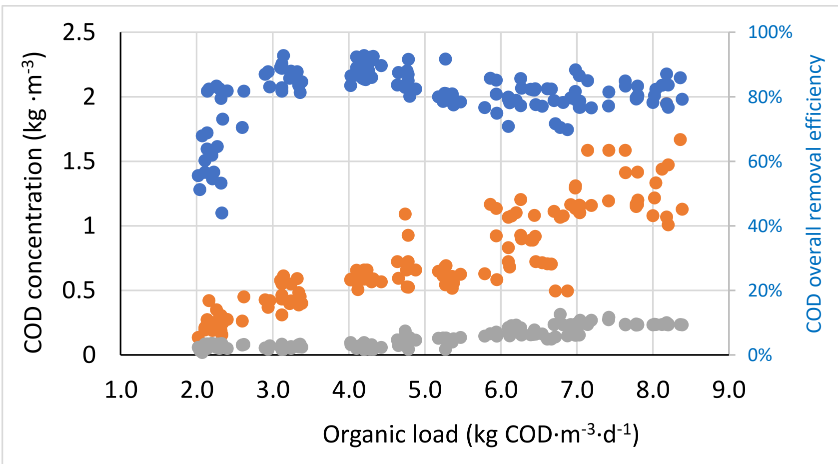

Figure 5. COD concentration at the output (•) of the aerobic reactor as a function of the loads fed into the UASB (•). Output concentration (•) from the UASB.

For treated water to be reused in Mexico, it must comply with the Mexican norm, that is, it must have a concentration lower than 20 mg·L^{-1} to be used in karstic soils (minimal required value) and up to 210 mg·L^{-1} for their disposal in rivers and streams (maximal required value). To homogenize the treated water, the ASR effluent was fed to an activated charcoal filter. On average, the filter was able to remove up to 31% more of the COD in the effluent, and the maximal COD concentration at the output was 163.5 ± 17 mg·L^{-1}.

3.6. Energy Potential and Yield of the Anaerobic–Aerobic System

The energy potential of the system was determined based on the stoichiometry of Equation (3).

Considering a population of 100,000 inhabitants and that the per capita production of household waste is 0.653 kg·hab^{-1}·d^{-1} [29], in Mexico, a population of that size generates 65,300 kg·d^{-1} of household waste, of which 33.07% is of food origin and of this, 35% is FVWs. So, the amount of FVWs generated for this population is 7558 kg·d^{-1}. From the above, and because this study revealed that the FVWs used contain 0.089 kg VS/kg FVWs, it was determined that the amount of VS generated by this population is 672 kg d^{-1}. If it is considered that 82 kg C generates 128 kW·h during anaerobic digestion [13], the energy generated for a population of 100,000 inhabitants would be about 55 7.2 kW·h·d^{-1}.

In turn, the energy yield was 1914 kW·h·d^{-1}. This value was obtained from the maximal methane production in the anaerobic–aerobic system used herein (3 $m^3{}_{CH4}$·$m^{-3}{}_{reactor}$·d^{-1}), which corresponds to values reported in other studies [30]. The calorific capacity of methane of 5.137 kW·h·m^{-3}, as well as the organic load at which the system operated (8 kg COD·m^{-3}·d^{-1}), and the relation kg COD·kg^{-1} VS were determined in this study (1.52 kg COD·kg^{-1} VS). Thus, the energy yield was obtained from the generated energy (15.95 kW·h·$m^{-3}{}_{reactor}$·d^{-1}) multiplied by the volume required by the reactor to treat the FVWs generated by the population of 100,000 inhabitants (120 m^3).

4. Conclusions

During the operation of the anaerobic–aerobic system, it was observed that one of the critical stages is leaching since the organic load fed to the ascending flow anaerobic reactor (ARFA) depends on leaching. The maximum extraction of solids smaller than 105 µm during conditioning was obtained at a retention time of 1 d with a 1:7 FVW:MWW ratio without stirring, reaching an average COD concentration of 7.68 g·L^{-1}. Obtaining a high concentration of COD in the leachate with a low concentration of large suspended solids guarantees the good operation of reactors with a sludge bed, so the conditioning of the FVW used here (leaching of the fresh FVWs) generates a tributary with the appropriate characteristics for the operation of the UASB. The concentration reached in the leaching also implies that the RAFA could be operated even at loads greater than 10 g COD·L^{-1}·d^{-1}, further favoring the efficiency of the reactor since this type of system operates better at loads between 10 and 40 g COD·L^{-1}·d^{-1}.

The UASB efficiency was on average 70% for the assayed loads (2–8 g COD·L^{-1}·d^{-1}). Meanwhile, that of the anaerobic–aerobic system was greater than 90% for all the assayed loads; thus, the system has the potential to be used for the treatment of organic solid waste and wastewater on a large scale. The use of the aerobic-activated sludge reactor allows for improving the overall removal of COD by up to an additional 20% compared with treatment in a UASB.

The energy potential calculated for the anaerobic–aerobic system was 510.2 kW·h·d^{-1}, and the estimated energy yield for an organic load of 8 g COD·L^{-1}·d^{-1} and 100,000 inhabitants was 1914 kW·h·d^{-1}.

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