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Kinetic Study of Anaerobic Digestion of Compost Leachate from Organic Fraction of Municipal Solid Waste

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Abstract: The anaerobic digestion (AD) of compost leachate has been scarcely investigated and, to the best of our knowledge, no previous work has analyzed the kinetics of the process in completely stirred tank reactors (CSTR). To overcome this lack of knowledge, the present work aimed to deepen the study of the AD of compost leachate in CSTR and to identify the kinetics that can represent the process evolution under different operating conditions. In this regard, an experimental investigation was carried out on a laboratory anaerobic pilot plant that worked in semi-continuous mode under mesophilic conditions. After the start-up phase, the digester was fed with organic loading rates (OLR) between 4 and 30 g_{COD}/Ld. The chemical oxygen demand (COD) removal ranged between 80 and 85% for OLR values up to 20 g_{COD}/Ld and, then, it was observed as 54% at 30 g_{COD}/Ld. The deterioration of process performance was caused by an excessive generation of volatile fatty acids leading to a decrease of methane production yield from 0.32–0.36 $L_{CH4}/g_{CODremoved}$ at 20 g_{COD}/Ld, to 0.23–0.26 $L_{CH4}/g_{CODremoved}$ at 30 g_{COD}/Ld. Using kinetic analysis, the Monod model was shown to be quite accurate in modelling the trends of COD degradation rates for OLR values up to 20 g_{COD}/Ld. On the other hand, a better fit was achieved with the Haldane model at 30 g_{COD}/Ld. The conducted modelling allowed to identify the kinetic parameters for each model. The detected results could help in the management and design of the digesters for the treatment of compost leachate.

Keywords: anaerobic digestion; biogas; compost leachate; kinetic; methane; modeling

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1. Introduction

Composting is the most widely used technology for the treatment and valorization of the organic fraction of municipal solid waste (OFMSW) [1–3]. This process transforms the OFMSW into a stabilized product free of pathogens [4–6]. The produced compost can be used as an organic soil conditioner as it is rich in N, K, and P, all beneficial nutrients for plant growth [7,8]. However, large volumes of leachate are generated during the biochemical stabilization process of organic matter [9–11]. Leachate is generated from the water contained in the composted matrix, the water produced during the stabilization process, the water added during the process to regulate the moisture content of the heaps, and finally, where the composting process takes place outdoors, from rainwater [12,13].

The leachate quantities generated depend on the type of treatment plant and the composition of the composted organic matrix [14,15]. For example, recent studies indicated that the production of leachate from OFMSW varies between 75 and 100 L/ton [16], whereas from composting matrices composed essentially of urban green waste and garden clippings, the quantities generated fall between 5 and 50 L/ton [17]. Furthermore, the chemical–physical composition of compost leachate shows an extreme variability depending on the type of organic matrix and composting process, which makes it difficult to choose an appropriate treatment capable of effectively removing the contaminants. In this regard, both physicochemical and biological processes have been investigated in the past years. Among the available physicochemical technologies, advanced oxidation processes (AOPs) are often investigated in the treatment of highly concentrated wastewater [18–20], such as compost leachate [21–24]. However, the main limitations of these technologies are the high consumption of reagents and/or energy, and the generation of large quantities of residual sludge that require further treatment before their disposal [25,26]. Moreover, the combination of more than one physicochemical treatment is usually necessary to meet the discharge requirements [21].

Biological treatments effectively reduce the organic load of wastewaters and can be a suitable option for the treatment of compost leachate. Aerobic biological treatment is faster and easier to operate than the anaerobic process. However, aerobic processes are more energy-intensive and thus costly due to the aeration of the reactors. On the contrary, anaerobic digestion (AD) allows a better stabilization of waste, with energy and economic advantages [27–29]. In fact, AD does not require oxygen or air insufflation and, moreover, does not involve the emission of greenhouse gases into the atmosphere [30]. AD consists of a complex biological process through which organic matter is transformed into a gaseous mixture consisting of methane (50–70%) and carbon dioxide (35–45%) with trace amounts of H_2S, ammonia and steam [28–30]. Biogas generated from waste digestion is characterized by a lower heating value (LHV) of about 21.5 MJ/m^3 that can be easily exploited for energy production [30–32]. The process takes place in closed reactors and, together with the biogas, gives rise to a liquid effluent known as digestate. The digestate can be used as an organic soil conditioner in agronomic practices [13,33]. AD can be categorized based on the number of stages (usually 1 or 2), the operational temperature (mesophilic, thermophilic), and the total solids (TS) content (wet TS < 10%, semi-dry 15% < TS < 20%, dry TS > 20%) [34]. Several studies have been conducted in recent years on the anaerobic treatments of compost leachate [35–37]. Many works have focused on the use of particularly complex types of reactors, obtaining extremely variable efficiencies of the conversion of chemical oxygen demand (COD) to methane [36,37]. In particular, Liu et al. [16] investigated the AD of fresh compost leachate in an expanded granular sludge bed (EGSB) and reported that 80% of total COD and 83% of soluble COD were converted to methane at an organic loading rate (OLR) of 22.5 kg_{COD}/m^3d. Moktarani et al. [36] analyzed the performance of a hybrid organic anaerobic reactor and reported that the COD removal efficiency decreased to less than 70% for OLR values higher than 10 kg_{COD}/m^3d.

The studies on the anaerobic digestion of compost leachate in simple treatment units such as completely mixed reactors (CSTR) are quite limited [13,31,37]. This type of reactor has several advantages, such as simpler operation and management. Some studies on the treatment of compost leachate in CSTR reactors indicated good performance in methane production and COD reduction. For example, Siciliano et al. [13] reported COD removal efficiencies above 90% for OLR up to 14.5 kg_{COD}/m^3d with high CH_4 percentage (70–78%). Other authors, however, reported lower values of the maximum tolerable OLR. Indeed, Lim et al. [37] suggested that the maximum OLR that can be applied is less than 10 kg_{COD}/m^3d.

The variability of the results obtained by the different authors underlines the necessity to investigate the AD of compost leachate in CSTR in more depth to clarify the process evolution and to identify the optimal conditions to maximize the production yields. In this regard, the analysis of process kinetics plays an important role. In fact, the knowledge of kinetics can help to understand the factors affecting the biogas production and the COD removal and to define a suitable procedure for the design and management of anaerobic bioreactors [38–40].

In this regard, the objective of this study was to evaluate the performance and to assess the kinetics of the anaerobic digestion of compost leachate in CSTR. This is a new contribution in the development of AD as, until now, there is a lack of information on the kinetics of compost leachate degradation in anaerobic CSTR. The study was carried out in a laboratory pilot plant that worked at a semi-continuous mode under different operating conditions. The process was monitored in terms of biogas production and digestate characteristics. A specific procedure was defined to conduct the kinetic analysis, and mathematical modelling was performed.

2. Materials and Methods

2.1. Materials

The AD tests were performed using leachate from the tunnel composting plant of Calabra Maceri e Servizi SpA located in Rende (CS, Calabria Region, Italy) that treats source-sorted organic household wastes and residues from gardens and parks. The leachate was stored in 30 L tanks at 4 °C to avoid sample deterioration.

An activated sludge withdrawn from the recirculation line of the urban wastewater treatment plant of Lamezia Terme (CZ, Calabria Region, Italy) was used as inoculum. Before starting the AD tests, the activated sludge was kept in the digester for 15 days under anaerobic mesophilic conditions without substrate addition.

Analytical grade reagents were used for the chemical determinations of the AD process parameters.

2.2. Pilot Plant

Semi-continuous AD tests were performed in a laboratory scale reactor built at the Sanitary and Environmental Engineering laboratory of the University of Calabria (Italy) (Figure 1a,b) [13,31]. The reactor is composed of a cylindrical tank in 316 stainless steel with a volume of 3 L wrapped in an insulated heating jacket (Figure 1c). The unit is hermetically sealed by a top flange fitted with a pipe suitable for the inlet of the compost leachate and for the withdrawal of the digestate (Figure 1c). The reactor was equipped with a vertical axis steel stirrer moved by an external gear motor of 0.33 kW (Figure 1c). The stirrer was run for 15 min every two hours.

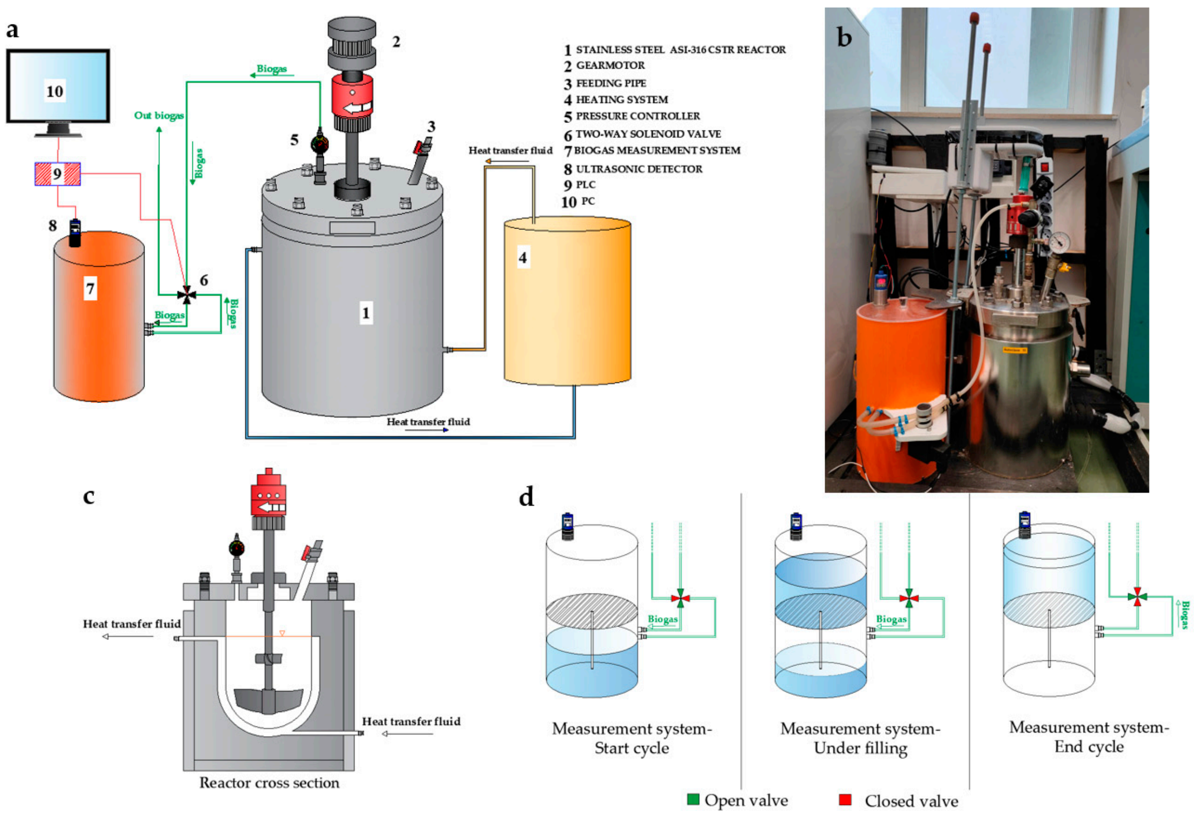

Figure 1. (**a**) Lab-scale pilot plant; (**b**) picture of Lab-scale pilot plant; (**c**) reactor cross section; and (**d**) biogas measurement system.

The heating system consists of a stainless-steel thermostatic bath connected to the reactor heating jacket by multilayer pipes and equipped with a volumetric pump for the recirculation of heat transfer fluid. The external heating system made it possible to conduct the tests in mesophilic conditions (37 °C).

The produced biogas flowed freely through the Rilsan® pipeline into the biogas measuring system provided with an ultrasonic distance sensor (Microsonic® mic + 25/DIU/TC; Microsonic GmbH, Dortmund, Germany) and a programmable logic controller (Arduino® Mega 250; Arduino, Turin, Italy) (Figure 1a,d). The operation of the biogas measurement system is schematized in Figure 1d. The pilot plant and the measurement system used in this study were described in more detail in previous works [13,31].

2.3. Experimental Setup

After this time, a start-up phase of about 3 weeks was applied to allow the good acclimatization of the biomass to the compost leachate. During this phase, the reactor was fed with low amounts of compost leachate by gradually increasing the OLR from 0.5 to 2 g_{COD}/Ld. Since the leachate had low buffering capacity and acidic pH, $KHCO_3$ in grains was added to the leachate to promote the effective start-up of the AD process [13,31]. Indeed, the high solubility of $KHCO_3$ increased the leachate alkalinity up to values suitable for the AD process.

At the end of the process start-up, the actual operational phase began. During this phase, raw leachate was fed (without addition of $KHCO_3$) and the OLR was increased from 4 to 30 g_{COD}/Ld. The working volume of the reactor (V_R) was kept constant at 1.5 L throughout the experiments. Feeding of compost leachate and sampling of digestate were carried out manually. The digestate samples withdrawn from the reactor were characterized daily with respect to the main chemical–physical parameters (Table 1). The acquisition system continuously recorded the biogas production. The amount of methane was evaluated daily after the neutralization of acid gases contained in the biogas through NaOH beads. Specifically, 50 mL of biogas extracted from the biogas measurement system using a graduated syringe were slowly flowed through a small plexiglass box containing 8 g of NaOH beads and, subsequently, in a next one graduated syringe [13,31]. The volume measured in the last syringe, after that the biogas passed through the NaOH beads, was the methane content.

Table 1. Compost leachate and activated sludge chemical–physical characteristics.

Parameters	U.M.	Compost Leachate	Activated Sludge Inoculum
pH	-	5.3 ± 0.2	6.9 ± 0.1
Conductivity	[mS/cm]	5.6 ± 0.1	1.2 ± 0.1
TS	[g/L]	61.9 ± 2.01	10.8 ± 0.08
VS	[g/L]	38.2 ± 2.11	8.9 ± 0.09
COD	[g/L]	66.5 ± 3.5	12.8 ± 0.33
COD_{sol}	g/L	54.3 ± 0.24	1.7 ± 0.11
Alkalinity	[g_{CaCO3}/L]	12.6 ± 0.77	0.5 ± 0.04
VFA	[$g_{CH3COOH}$/L]	15.2 ± 0.78	0.08 ± 0.003
TKN	[g/L]	1.52 ± 0.14	0.78 ± 0.008
$N\text{-}NH_4^+$	[g/L]	0.7 ± 0.05	1.4 ± 0.11
$P\text{-}PO_4^{3-}$	[g/L]	0.6 ± 0.03	39.3 ± 3.6
SO_4^{2-}	[g/L]	0.5 ± 0.028	88.7 ± 2.3
Ca	[g/L]	3.6 ± 0.021	0.01 ± 0.02
Mg	[g/L]	0.8 ± 0.04	0.04 ± 0.001
K	[g/L]	0.6 ± 0.017	-
Fe	[mg/L]	113.8 ± 4.1	0.3 ± 0.01
Pb	[mg/L]	34.4 ± 1.1	-
Mn	[mg/L]	10.6 ± 0.21	0.1 ± 0.005
Zn	[mg/L]	20.0 ± 0.4	-
Ni	[mg/L]	0.2 ± 0.01	-

2.4. Kinetic Analysis Procedure

The kinetic analysis of the AD process was performed by determining the COD removal rates for each applied OLR. These rates were assessed from the curves of COD degradation which in turn were elaborated from continuous biogas measurements and daily digestate characterization. The practical methods for constructing the COD removal curves and removal rates are provided below.

2.4.1. Daily COD Degradation Curves

For each OLR, the COD removal curves were constructed by considering the central day of the period during which the OLR was applied (reference day). In this day the anaerobic process was not affected by the variation of the working conditions.

First of all, the mass of COD removed (ΔC; g_{COD}) was calculated by means of the following expression:

$$\Delta C = (C_{in} - C_{out}) \cdot V_R \quad (1)$$

where C_{in} (g_{COD}/L) is the COD concentration of raw leachate fed in the reactor, C_{out} (g_{COD}/L) is the organic matter concentration of digestate withdrawn from the reactor, and V_R (L) is the working volume of the reactor.

On the basis of the biogas measurements recorded over time through the acquisition system and the percentage of methane determined, the cumulative volumetric productions of methane ($V_{CH4}(t)$; L_{CH4}) were obtained. From these values, the total daily methane volume ($V_{CH4,d}$; L_{CH4}) was determined. By dividing this volume by the overall COD removed, the methane production yield ($V_{CH4,d}/\Delta C$; L_{CH4}/g_{COD}) was calculated. From these parameters, it was possible to calculate the values of COD over the time (COD(t)) using the following equation:

$$C(t) = \frac{\left(C_{in} \cdot V_R - \frac{V_{CH4}(t)}{\frac{V_{CH_4,d}}{\Delta C}}\right)}{V_R} \quad (2)$$

The values of C(t), expressed as a function of time, represent the COD degradation curves.

2.4.2. Substrate Removal Rate Curves

Once the trend of COD concentration was obtained, the reaction rate ($\bar{r}(t)$) over time was determined using Equation (3):

$$\bar{r}(t) = \frac{C(t)_i - C(t)_{i+1}}{\Delta t} \quad (3)$$

where $C(t)_i$ and $C(t)_{i+1}$ are the COD concentrations at instant i-th and i + 1-th respectively, and Δt it is the time interval that was fixed at 1 h.

The calculated reaction rate was expressed as a function of the average COD concentration ($\overline{C}(t)$) in the time interval Δt:

$$\overline{C}(t) = \frac{C(t)_i + C(t)_{i+1}}{2} \quad (4)$$

The experimental curves ($\bar{r}(t)$ vs. $\overline{C}(t)$) were mathematically interpolated using the MatLab (R2016a) software according to the Monod and Haldane models [34,41,42]. As previously stated, the kinetic analysis was conducted with the data obtained on the reference day for each OLR.

By referring to our data, the Monod kinetic can be written as follows:

$$\bar{r}(t) = \frac{d\overline{C}(t)}{dt} = -\frac{\mu_{max}}{Y} \frac{\overline{C}(t)}{K_c + \overline{C}(t)} X = -\mu_m \frac{\overline{C}(t)}{K_c + \overline{C}(t)} \quad (5)$$

where X (g_{VSS}/L) is the active biomass concentration inside the reactor, μ_{max} (h^{-1}) the maximum specific growth rate, Y (g_{VSS}/g_{COD}) the growth yield coefficient, and K_C (g_{COD}/L) the semi-saturation constant that corresponds to the substrate concentration at which the reaction rate is half of the maximum value [38]. In the above expression, the ratio μ_{max}/Y (g_{COD}/g_{SSV} h) represents the maximum specific substrate utilization rate, and $\mu_m = (\mu_{max}/Y)\cdot X$ (g_{COD}/Lh) is the maximum substrate degradation rate.

As known, according to Monod's kinetic, the maximum value of the substrate removal rate is reached at high concentration values. At the same time, the reaction rate decreases approximately linearly for C << K_C.

If the substrate concentration is higher than the degradation capacity of the biomass, the process is inhibited. This effect is not taken into consideration by Monod's equation, but it is included in the model proposed by Haldane [38,42]:

$$\bar{r}(t) = \frac{d\overline{C}(t)}{dt} = -\frac{\mu_{max}}{Y}\frac{\overline{C}(t)}{K_c + \overline{C}(t) + \frac{\overline{C}(t)^2}{K_I}}X \quad (6)$$

in which K_I (g_{COD}/L) represents the inhibition constant.

2.5. Analytical Methods

The pH and conductivity were detected by benchtop analyzers (Crison BASIC 20 pH, Crison BASIC 30 E.C.). COD was determined after digestion at 150 °C for two hours with $K_2Cr_2O_7$ and titration with Mohr's salt solution [43]. Total solids (TS) and volatile solids (VS) were determined by gravimetric analysis after drying the sample at 105 °C for 24 h and at 550 °C for 30 min, respectively [43]. Volatile fatty acids (VFA) were determined by distillation and, subsequently, titration with NaOH [43]. Total Kjeldahl Nitrogen (TKN) was determined by mineralization, distillation, and titration of the distillate with HCl [43]. Alkalinity (ALK) was detected by the potentiometric procedure [43]. Ammoniacal nitrogen (N-NH_4^+), phosphates (P-PO_4^{3-}), and sulphate (SO_4^{2-}) were determined by spectrophotometric analysis (Thermo Spectronic Genesys 10 uv) [43]. Metals were determined through atomic absorption spectrophotometry (GBC-933-plus) after acid mineralization [43]. Each analysis was carried out in triplicate, and the mean value was assumed.

3. Results and Discussion

3.1. Compost Leachate and Activated Sludge Characteristics

Table 1 depicts the chemical–physical composition of the compost leachate and activated sludge inoculum used during the experiments.

The leachate was characterized by a total COD value of approximately 66.5 g_{COD}/L, whose soluble fraction was more than 80%. These values are representative of a large amount of rapidly available organic matter. The leachate was also characterized by significant levels of nutrient compounds (nitrogen and phosphorus). The high conductivity value is a consequence of great quantities of dissolved ionic compounds. The acidic pH is congruent with the remarkable VFA concentrations and suggests that the leachate was generated in a process with low oxygen content in which acetogenesis reactions probably occurred. The results detected in this paper align with those reported by other authors [16,44].

The low content of alkaline compounds compared to VFA raised the VFA/ALK ratio to values above 1 $g_{CH3COOH}/g_{CaCO3}$. According to Khanal [34], the activity of methanogenic bacteria is significantly reduced for VFA/ALK values greater than 0.8. Therefore, as described in the Materials and Methods, to reduce the VFA/ALK ratio to around 0.3 $g_{CH3COOH}/g_{CaCO3}$, proper amounts of $KHCO_3$ were added to the compost leachate fed into the reactor during the start-up phase. The acidic pH justifies the notable amounts of metal ions detected. The activated sludge had typical characteristics of sludges from an urban wastewater treatment plant. In particular, it was characterized by a TS content of 10.8 g/L with a volatile fraction of 82%. Furthermore, it had a COD concentration of 12.8 g/L, a pH close to neutral value, and a conductivity of about 1.2 mS/cm.

3.2. Anaerobic Digestion Performance

The semi-continuous AD process was conducted in two different phases. The start-up phase promoted the biomass acclimatization and the process parameters stabilization. During this phase, the addition of $KHCO_3$ to the leachate fed into the reactor allowed the AD initiation by balancing the leachate acidity [13].

After the start-up phase, the reactor was fed with raw compost leachate without $KHCO_3$, as the system had reached a suitable buffer capacity, with a VFA/ALK ratio of around 0.2 $g_{CH3COOH}/g_{CaCO3}$.

The AD performance was assessed both in the start-up and operational monitoring phase. Figure 2 provides the COD removal efficiency (η_{COD}) as a function of OLR. COD reductions greater than 85% were observed for OLR below 4 g_{COD}/Ld, whereas the efficiency ranged between 80 and 85% for OLR values up to 20 g_{COD}/Ld. These yields agree with the results obtained in previous AD studies in CSTR reactors fed with compost leachate as substrate [13,31].

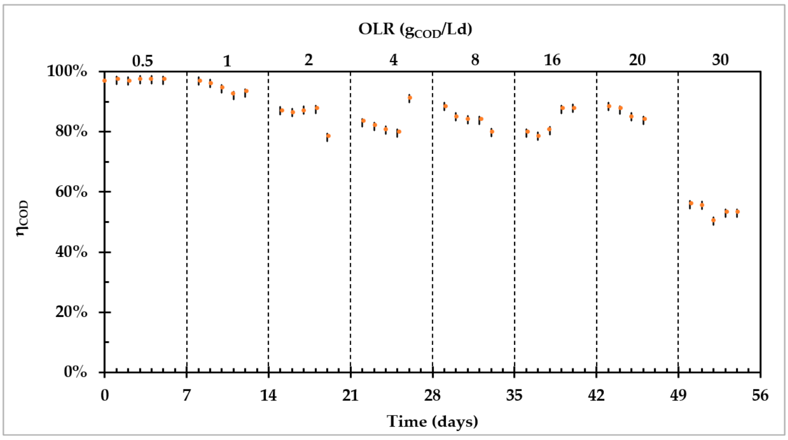

Figure 2. COD removal efficiency (η_{COD}) vs. time and OLR values.

However, a reduction in COD removal efficiency of approximately 50% was observed at an OLR of 30 g_{COD}/Ld. The decrease in performance occurred despite the VS in the reactor growing from values close to 4 g_{VS}/L to over 45 g_{VS}/L in response to increasing the OLR to 30 g_{COD}/Ld (Figure 3). This indicated that an inhibitory effect occurred, and the biomass reduced its activity in the degradation of COD. This statement is in agreement with Rao et al. [45], who reported that after a sudden increase of OLR to high values, the biomass activity decreases. The inhibitory effect, as reported below, is probably related to an excessive VFA production during the acetogenic phase, which is a well-known consequence of overload conditions.

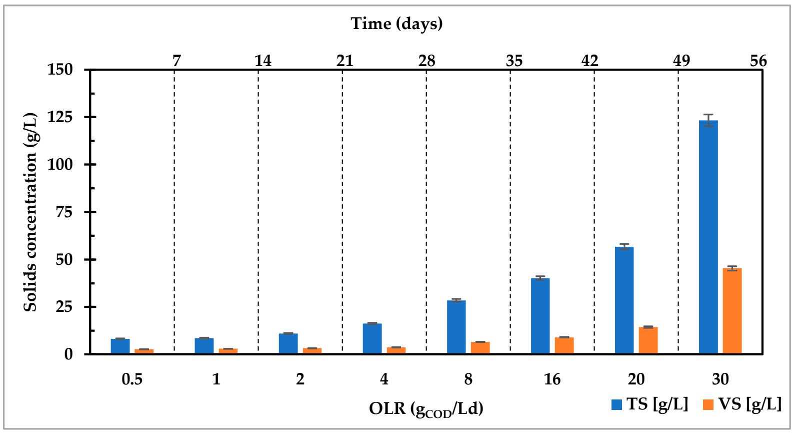

Figure 3. Solids concentration vs. time and OLR values.

The decline in COD removal efficiency was also reported in other works on the anaerobic digestion of compost leachate. Mokhatarani et al. [36], using hybrid biological anaerobic reactors, found a significant reduction in COD degradation efficiency already at OLR above 6 g_{COD}/Ld [36]. These worse results with respect to those observed in our work are probably imputable to a lower performance of the hybrid system (with biomass attached on a fixed bed) compared to the CSTR. Eslami et al. [46] observed an organic load shock that caused a decrease in COD removal when the OLR was increased up to 18.52 g_{COD}/Ld in an anaerobic migrating blanket reactor (AMBR), and up to 23.33 g_{COD}/Ld in an advanced sequencing batch reactor. Ebrahimi et al. [35] monitored a progressively decreasing trend of COD removal with increasing OLR to 19.65 g/Ld in AMBR. Nayono et al. [47] investigated the process performance of anaerobic digestion of pressed OFMSW leachate and observed a COD reduction between 55 and 70% with OLR from 14.9 to 27.7 g_{COD}/Ld, respectively. Similar results to that observed in our investigations were found by Liu et al. [16]. The authors reported that it is necessary to keep the OLR below 30 g_{COD}/Ld to achieve the maximum COD removal in an expanded granular sludge bed bioreactor [16].

Based on these observations, our results demonstrated that CSTR have a capacity in the degradation of organic matter at least comparable to that of other more complex anaerobic systems. The ability to operate with high OLR values is presumably a consequence of the mixing conditions that, by homogenizing the mixture throughout the entire reactor volume, allow to mitigate the inhibitory effect of any adverse compounds, such as VFA.

As previously described, biogas production was monitored continuously. Figure 4 depicts the overall biogas and methane weakly produced for each OLR level. The productions were consistent with the COD removal efficiencies (Figure 2). Indeed, increasing volumes of biogas were observed for OLR up to 20 g_{COD}/Ld, whereas a reduction in production was highlighted at the OLR of 30 g_{COD}/Ld. At this OLR, the biomass in the reactor fails to effectively degrade the organic matter due to an overload condition and a very low corresponding hydraulic retention time of about 1.7 days. Thus, the organic compounds produced during the acetogenic phase (VFA) were not properly consumed, causing an inhibition effect, which resulted in a reduction in the production of biogas and CH_4.

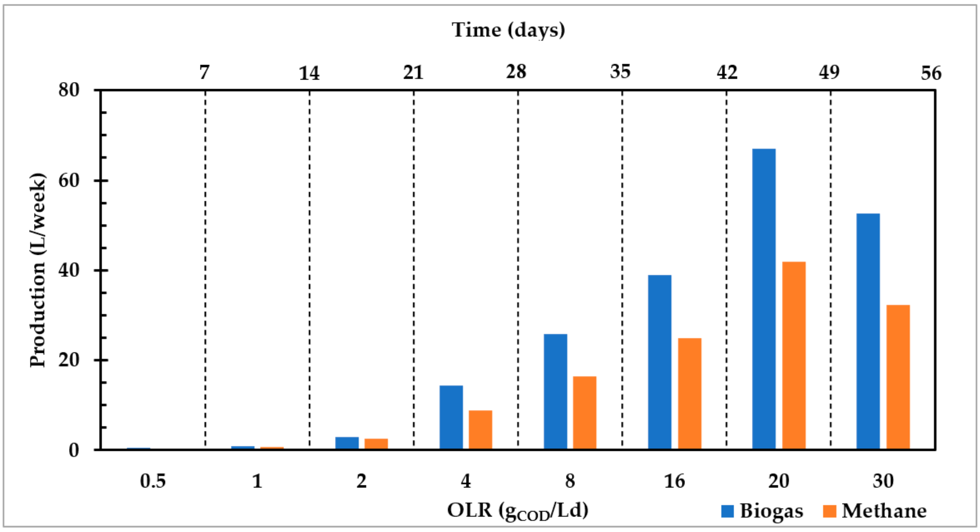

Figure 4. Biogas and methane production vs time and OLR values.

In any case, the performance of investigated CSTR can be considered quite satisfactory compared to those monitored in previous works using other types of reactors.

Indeed, consistent with what has already been discussed on COD degradation, other authors found significant reductions in biogas production by applying OLR lower than those tested in the present work [25,46–48]. For example, Hashemi et al. [25], when studying the AD of compost leachate in advanced sequencing batch reactors (ASBR), observed a significant decrease of the biogas production at OLR of 19.65 g_{COD}/Ld, with a daily production value of about 6.65 L/d. Eslami et al. [46] detected a production peak with an OLR of 10.08 g_{COD}/Ld by studying the treatment of compost leachate in a laboratory-scale anaerobic migrating blanket-advanced sequencing batch reactor (AMBR-ASBR).

The methane content was between 64 and 67% of the total biogas and confirmed a good production performance. The CH_4 percentages detected in this study were perfectly in line with those reported by Nayono et al. (64.6–67.9%) [47] and slightly higher than those monitored by Hashemi et al. (55–65%) [25]. At the OLR of 20 g_{COD}/Ld, the CH_4 production reached a value of 42 L_{CH4}/week with a yield of about 18 L_{CH4} per litre of added leachate (Figure 4).

Other important information on the AD process evolution is given by the methane production yields (MPY) expressed as litres of CH_4 per gram of COD removed. As shown in Figure 5, the MPY grew linearly for OLR values up to 16 $L_{CH4}/g_{CODremoved}$ and then ranged between 0.32–0.36 $L_{CH4}/g_{CODremoved}$ by increasing the organic loading rate to 20 g_{COD}/Ld. These yields are not much lower than the stoichiometric value which at the process temperature of 37 °C is equal to about 0.4 $L_{CH4}/g_{CODremoved}$. The MPY we found are higher than the yields reported by Liu et al. (0.28–0.29 $L_{CH4}/g_{CODremoved}$) [16] using an expanded granular sludge bed bioreactor, and by Pirsaheb et al. [49] (0.23 $L_{CH4}/g_{CODremoved}$) when treating the compost leachate in a zeolite/anaerobic baffled reactor at an OLR of 10.3 g_{COD}/Ld. The high yield detected in our study confirmed the process effectiveness, as approximately 80–85% of the removed COD was converted to CH_4. A significant MPY reduction was monitored at an OLR of 30 g_{COD}/Ld, indicating a reduced fraction of organic matter transformed into CH_4 compared to that observed at 20 g_{COD}/Ld.

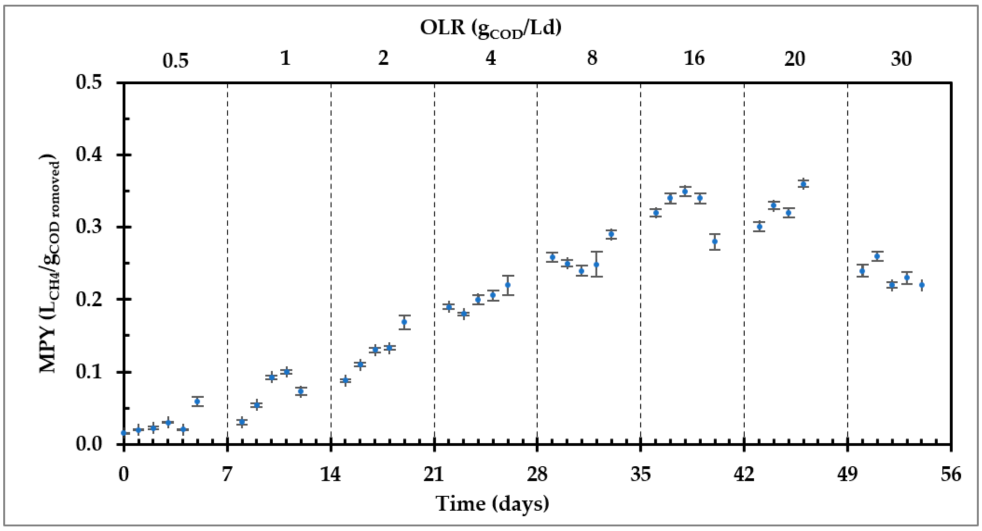

Figure 5. Methane production yield (MPY) vs time and OLR values.

As already stated, the performance reduction can be caused by unfavourable values of some fundamental parameters such as pH and VFA/ALK ratio [29,34,41]. Figure 6 provides the trends of pH and VFA/ALK throughout the study. pH values close to 8 were observed when applying OLR up to 20 g_{COD}/Ld. On the other hand, at OLR of 30 g_{COD}/Ld, a moderate decrease in pH to values slightly below 7.2 was observed.

With regard to the VFA/ALK ratio, values between 0.2 and 0.4 were observed for OLR values from 4 to 20 g_{COD}/Ld. By increasing the OLR to 30 g_{COD}/Ld, the ratio was raised above 0.5 $g_{CH3COOH}/g_{CaCO3}$. These values, as reported in previous works [13,31], are representative of a reactor overloading able to significantly reduce the biogas production. In effect, the increase of VFA/ALK ratio that occurred at 30 g_{COD}/Ld corresponds to the reduction in process performance (Figure 6). Moreover, the data detected during our experiments suggest that a deterioration of anaerobic digestion caused by overloading conditions can occur, despite the pH values not falling below the neutral value. Therefore, the adverse effect on the AD is probably caused by an accumulation of organic compounds able to inhibit the biomass activity [29]. However, this condition occurred only when very high OLR values were applied to the digester, which proved the effectiveness of the investigated system.

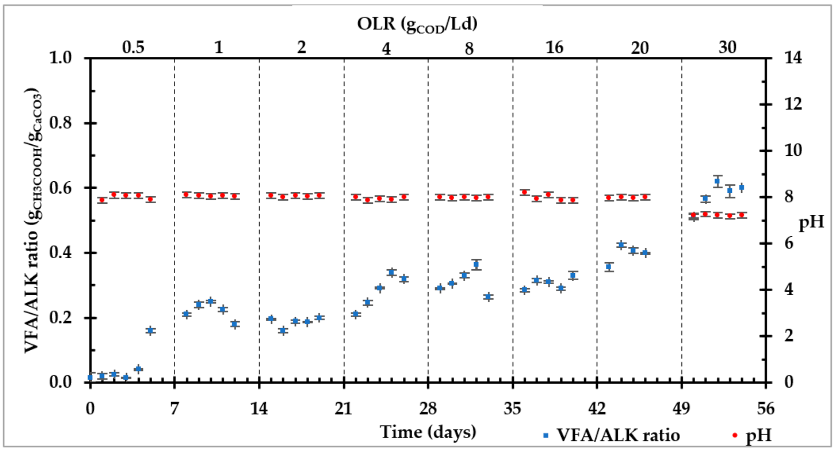

Figure 6. VFA/ALK ratio and pH vs time and OLR values.

3.3. Kinetic Analysis

3.3.1. Daily COD Degradation Curves

As described in Section 2.4, the kinetic analysis required the construction of COD degradation curves, which were obtained on the basis of continuous daily measurements of biogas and methane. In this regard, the productions monitored on the reference day were considered for each OLR between 4 and 30 g_{COD}/Ld. These trends are plotted in Figure 7. As it can be easily seen, a considerable increase in production was monitored as the OLR increased up to 20 g_{COD}/Ld. At this OLR, a cumulative daily biogas production close to 14 L was reached with an overall CH_4 volume of about 8.5 L. Working at 30 g_{COD}/Ld, the total daily volume reduced notably, confirming the deterioration of the anaerobic process.

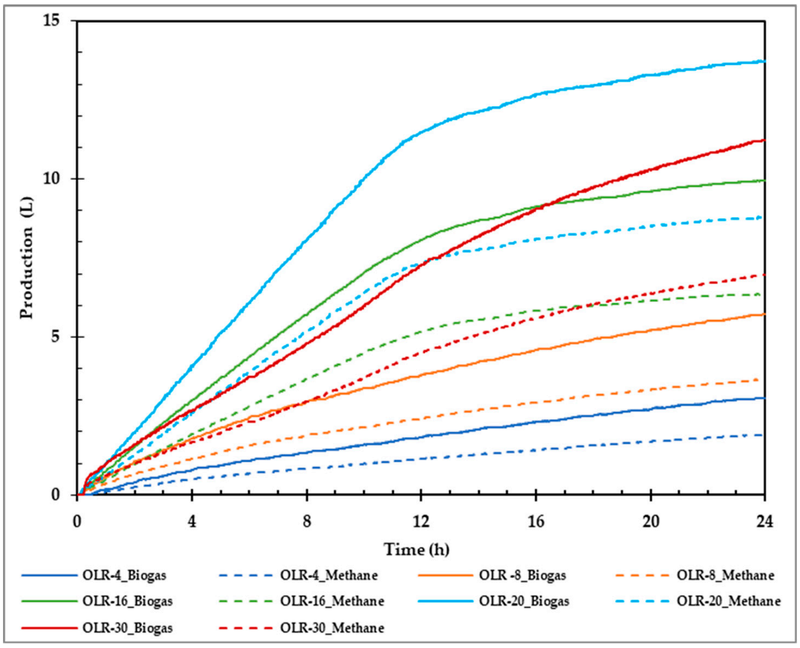

Figure 7. Biogas and methane productions at OLR values between 4 and 30 g_{COD}/Ld.

From the methane and biogas production trends, it was possible to obtain information on the production rate. For the OLR of 20 g_{COD}/Ld, a linear trend was observed during the first 12 h with a rate of approximately 0.45 L_{biogas}/h. Subsequently, a reduction to a value below 0.2 L_{biogas}/h was detected. At an OLR of 30 g_{COD}/Ld, compared to 16 and 20 g_{COD}/Ld, slower biogas production was observed in the first 12 h. This is a clear consequence of the overload conditions that reduced not only the overall biogas production but also the production rate.

Figure 8 provides the COD removal curves derived from the methane production data using Equation (2). Clearly, the curves obtained correspond to the production trends reported in Figure 7. In effect, an increase in COD removal was observed as the OLR increased up to 20 g_{COD}/Ld. In particular, a gradual and slow degradation occurred for OLR values of 4 and 8 g_{COD}/Ld, whereas rapid reductions took place at 16 and 20 g_{COD}/Ld, which were completed in about 12 h. The residual COD concentration probably consists mainly of the non-biodegradable organic matter that has accumulated in the reactor.

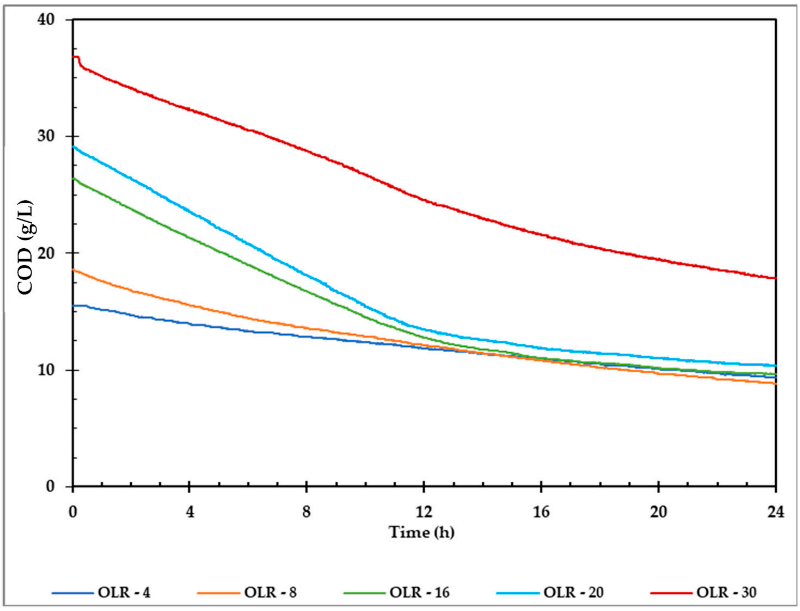

Figure 8. COD degradation curves at OLR values between 4 and 30 g_{COD}/Ld.

At an OLR of 30 g_{COD}/Ld, the reduction of COD was slower than that observed at 16 and 20 g_{COD}/Ld. This indicates that the system had less ability to degrade the organic matter fed into the reactor.

3.3.2. Substrate Removal Rates and Mathematical Modelling

The COD removal rates ($\bar{r}(t)$) were obtained by means of Equation (3) using the data of COD degradation plotted in Figure 8. Therefore, the values of $\bar{r}(t)$ were expressed as a function of the COD concentration $\overline{C}(t)$ calculated with Equation (4) considering a time interval of one hour and not taking into account the residual non-biodegradable amount of organic matter. These curves express the dependence of the reaction rate on the concentration in the system and, consequently, are indicative of the kinetic that characterizes the process. For OLR values between 4 and 20 g_{COD}/Ld, typical trends of saturation kinetics were observed. Indeed, a first pseudo-linear increase in the reaction rate with concentration was observed, followed by an asymptotic behaviour towards the maximum value of $\bar{r}(t)$. As it can be observed, the reaction rate increased in response to the OLR growth. In particular, both the slope of the initial linear trend and the threshold $\bar{r}(t)$ value grew with the OLR. The increase in these parameters is attributable to the growth of anaerobic biomass in the reactor, which allowed a quicker rise of the reaction rate and the achievement of higher asymptotic values.

The trend obtained for an OLR of 30 g_{COD}/Ld (Figure 9e) was significantly different from those detected with the lower OLR values. Indeed, a distinct increase up to 1.15 g_{COD}/Lh was achieved for a substrate concentration of about 7 g_{COD}/L. Above this concentration, however, the removal rate dropped to around 0.9 g_{COD}/Lh. This trend is typical of an overload condition that inhibits the anaerobic process. In particular, as above mentioned, the inhibitory effect and the decrease in the removal rate started for a COD concentration of about 7 g_{COD}/L. This concentration did not lead to any reduction in the COD removal rate at OLR values between 4 and 20 g_{COD}/Ld. This indicates that with OLR 30 g_{COD}/Ld a concentration of 7 g_{COD}/L corresponds to an accumulation of compounds capable of hindering the conversion of organic matter to methane. As described in Section 3.2, the excessive production of VFA that occurred at OLR 30 g_{COD}/Ld probably caused the deterioration of the AD process, despite the high biomass amount reached.

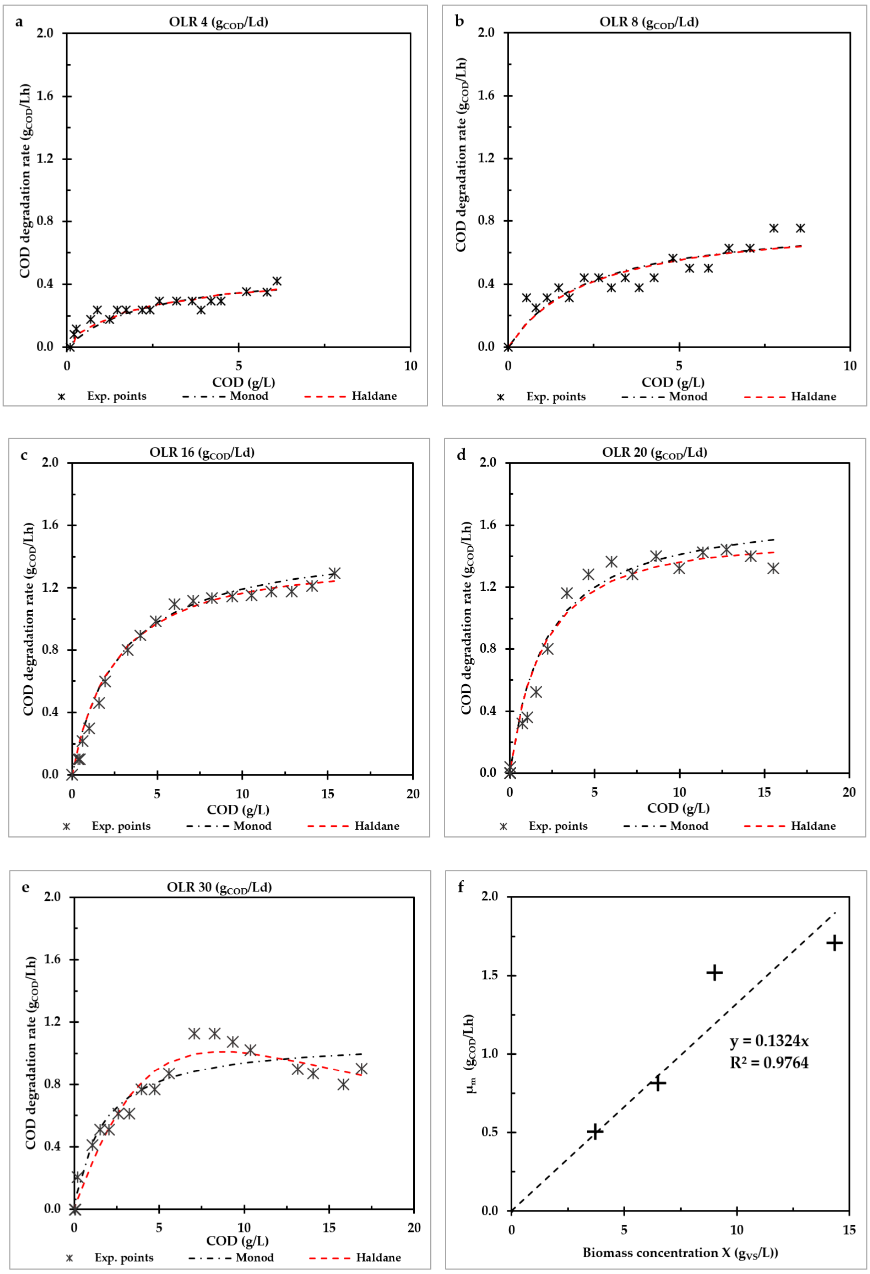

Figure 9. (**a**–**e**) COD removal rate modelled according to Monod and Haldane models for OLR from 4 g_{COD}/Ld to 30 g_{COD}/Ld; and (**f**) linear relationship between μ_m and X.

The curves of COD removal rate were modelled based on the Monod and Haldane models. As expected, the Monod equation interpolated the obtained saturation curves quite well for OLR values up to 20 g_{COD}/Ld (Figure 9a–d), with very high values of R^2 for organic loads of 16 and 20 g_{COD}/Ld (Table 2). The Monod model was developed for pure cultures and simple substrates [38,41,42], however, the results of our simulations proved that the model could represent even complex processes. As expected, the model was inadequate in modelling the curve at 30 g_{COD}/Ld (Figure 9e). In this case, as proved the R^2 values (Tables 2 and 3), a better fit was reached with the Haldane model, which accounts for the inhibitory effects that could occur under certain operating conditions. The identification of the most suitable model in relation to the operating conditions represents a valuable result in the analysis of the compost leachate anaerobic digestion. Indeed, different kinetic models were considered for the modelling of the process [35], but no previous work analysed the inhibitory effects.

Table 2. Kinetic parameters for substrate removal rates with Monod model.

OLR	g_{COD}/Ld	4	8	16	20	30
$\mu_m = (\mu_{max}/Y)$ X	g_{COD}/Lh	0.5079	0.8165	1.5211	1.7096	1.0971
X	g_{SV}/L	3.71	6.50	9.02	14.34	45.35
K_C	g_{COD}/L	2.3596	2.3367	2.7503	2.1042	1.702
R^2	-	0.86	0.82	0.99	0.98	0.89

Table 3. Kinetic parameters for substrate removal rates with Haldane model.

OLR	g_{COD}/Ld	4	8	16	20	30
$\mu_m = (\mu_{max}/Y)$ X	g_{COD}/Lh	0.5042	0.8171	1.5146	1.7039	4.513
X	g_{SV}/L	3.71	6.50	9.02	14.34	45.35
K_C	g_{COD}/L	2.3513	2.3987	2.7005	2.1139	14.93
K_I	g_{COD}/L	21860	11580	367.1	253.6	4.99
R^2	-	0.89	0.82	0.99	0.98	0.95

The interpolation of the removal rate curves allowed for the identification of the kinetic constants characteristic of the process (Table 2). The parameters of the Monod model obtained for OLR up to 20 g_{COD}/Ld indicated similar values of the semi-saturation constant K_C. This finding is a confirmation of the goodness of the kinetic analysis conducted. In fact, Kc is related to the characteristic of substrate fed into the reactor, and its value should not change significantly if the substrate is the same during the overall working period of the system, as it was in our experiments. The stability in the K_C values was also corroborated by the fact that the conditions in the digester (eg. pH, VFA/ALK ratio, temperature, etc.), on which the process evolution depends, did not substantially vary for OLR between 4 and 20 g_{COD}/Ld. Comparing our results with those of other works, the values of K_C were in agreement with the values found by Borja et al. [39].

As regards the other kinetic parameters obtained from the modelling conducted, an increase in μ_m was observed with OLR values up to 20 g_{COD}/Ld. This enhancement is justified by the growth of the active biomass in the reactor that was promoted by the organic load increase. In fact, a linear relationship can be identified between μ_m and X (Figure 9f). The proportional increase of μ_m with the amount of active biomass is a further confirmation that the conditions affecting the process did not vary for OLR up to 20 g_{COD}/Ld.

The ratio μ_{max}/Y was obtained from the slope of the straight line and resulted in being equal to 0.1324 $g_{COD}/g_{SV}h$. This value is very close to the values found by Hu et al. [40] by treating synthetic ice-cream wastewater in a CSTR.

Table 3 shows the kinetic parameters obtained with the Haldane model. As it can be observed, the inhibition constant K_I decreased as OLR increased. In particular, for OLR of 4 and 8 g_{COD}/Ld, the K_I value is very high. Therefore, the C^2/K_I ratio tends to zero and the model can be approximated to that of Monod. Indeed, the values of μ_m and K_C obtained with the two models were almost identical.

With higher OLR values, the K_I term decreased by two orders of magnitude and, consequently, the C^2/K_I ratio progressively increased. Despite this, the model showed slight differences compared to that of Monod for OLR of 16 and 20 g_{COD}/Ld. On the other hand, the lowest K_I value was recorded for an OLR of 30 g_{COD}/Ld, and the inhibitory effect on COD removal rates was clearly visible.

4. Conclusions

In this work, the anaerobic digestion of compost leachate in a CSTR was investigated. The obtained results allowed to identify the evolution of the main process parameters in response to the OLR variation, to define the operating conditions capable of ensuring the maximum methane productions, and to recognize the process kinetics.

The treatment was able to reach very satisfactory COD removal efficiencies at high OLR values (up to 20 g_{COD}/Ld) with methane production yields between 0.32 and 0.36 $L_{CH4}/g_{CODremoved}$. The increase of OLR to 30 g_{COD}/Ld caused a significant deterioration in process performance, which was attributed to an overload condition leading to the accumulation of VFA and, consequently, to the inhibition of biomass activity.

A kinetic analysis demonstrated that when the anaerobic process is not overloaded, it follows the saturation kinetic described by the Monod model. Under overload conditions, instead, the Haldane model allowed for a better representation of the removal rate trend, as it considers the inhibition effects on the process.

In conclusion, the suitable models in relation to the applied operating conditions were identified, and the detected kinetic parameters could allow a correct use of the models both in the management and in the design of the digesters.

Clearly, further studies aimed at investigating other aspects of the process would be useful in the technology development. In particular, the performance under different temperature regimes should be evaluated. In effect, a higher process temperature could allow the increase of the maximum applicable OLR value. To achieve this aim, the AD conducted in sequential stages can be another valuable option and deserves additional study. Further investigation on the pressurized AD could provide significant information on the potential improvement of the biogas quality. Finally, the analysis of the process in larger scale reactors should be conducted to facilitate industrial applications of the technology.

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References

1. Miller, F.C. Composting of Municipal Solid Waste and Its Components. In *Microbiology of Solid Waste*; CRC Press: London, UK, 2020; Chapter 4. [CrossRef]
2. Khan, S.; Anjum, R.; Raza, S.T.; Ahmed Bazai, N.; Ihtisham, M. Technologies for Municipal Solid Waste Management: Current Status, Challenges, and Future Perspectives. *Chemosphere* **2022**, *288*, 132403. [CrossRef]

3. Vyas, S.; Prajapati, P.; Shah, A.V.; Varjani, S. Municipal Solid Waste Management: Dynamics, Risk Assessment, Ecological Influence, Advancements, Constraints and Perspectives. *Sci. Total Environ.* **2022**, *814*, 152802. [CrossRef]
4. Sayara, T.; Basheer-Salimia, R.; Hawamde, F.; Sánchez, A. Recycling of Organic Wastes through Composting: Process Performance and Compost Application in Agriculture. *Agronomy* **2020**, *10*, 1838. [CrossRef]
5. Chen, P.; Xie, Q.; Addy, M.; Zhou, W.; Liu, Y.; Wang, Y.; Cheng, Y.; Li, K.; Ruan, R. Utilization of Municipal Solid and Liquid Wastes for Bioenergy and Bioproducts Production. *Bioresour. Technol.* **2016**, *215*, 163–172. [CrossRef]
6. Oliveira, L.S.B.L.; Oliveira, D.S.B.L.; Bezerra, B.S.; Silva Pereira, B.; Battistelle, R.A.G. Environmental Analysis of Organic Waste Treatment Focusing on Composting Scenarios. *J. Clean. Prod.* **2017**, *155*, 229–237. [CrossRef]
7. de Sousa, M.H.; da Silva, A.S.F.; Correia, R.C.; Leite, N.P.; Bueno, C.E.G.; dos Santos Pinheiro, R.L.; de Santana, J.S.; da Silva, J.L.; Sales, A.T.; de Souza, C.C.; et al. Valorizing Municipal Organic Waste to Produce Biodiesel, Biogas, Organic Fertilizer, and Value-Added Chemicals: An Integrated Biorefinery Approach. *Biomass Convers. Biorefin.* **2022**, *12*, 827–841. [CrossRef]
8. Ihsanullah, I.; Alam, G.; Jamal, A.; Shaik, F. Recent advances in applications of artificial intelligence in solid waste management: A review. *Chemosphere* **2022**, *309*, 136631. [CrossRef]
9. Krogmann, U.; Woyczechowski, H. Selected Characteristics of Leachate, Condensate and Runoff Released during Composting of Biogenic Waste. *Waste Manag. Res. J. A Sustain. Circ. Econ.* **2000**, *18*, 235–248. [CrossRef]
10. de Guardia, A.; Brunet, S.; Rogeau, D.; Matejka, G. Fractionation and Characterisation of Dissolved Organic Matter from Composting Green Wastes. *Bioresour. Technol.* **2002**, *83*, 181–187. [CrossRef]
11. Fan, H.; Liao, J.; Abass, O.K.; Liu, L.; Huang, X.; Wei, L.; Li, J.; Xie, W.; Liu, C. Effects of Compost Characteristics on Nutrient Retention and Simultaneous Pollutant Immobilization and Degradation during Co-Composting Process. *Bioresour. Technol.* **2019**, *275*, 61–69. [CrossRef] [PubMed]
12. Onwosi, C.O.; Igbokwe, V.C.; Odimba, J.N.; Eke, I.E.; Nwankwoala, M.O.; Iroh, I.N.; Ezeogu, L.I. Composting Technology in Waste Stabilization: On the Methods, Challenges and Future Prospects. *J. Environ. Manag.* **2017**, *190*, 140–157. [CrossRef] [PubMed]
13. Siciliano, A.; Limonti, C.; Curcio, G.M.; Calabrò, V. Biogas Generation through Anaerobic Digestion of Compost Leachate in Semi-Continuous Completely Stirred Tank Reactors. *Processes* **2019**, *7*, 635. [CrossRef]
14. Farrell, M.; Jones, D.L. Critical Evaluation of Municipal Solid Waste Composting and Potential Compost Markets. *Bioresour. Technol.* **2009**, *100*, 4301–4310. [CrossRef] [PubMed]
15. Cadena, E.; Colón, J.; Artola, A.; Sánchez, A.; Font, X. Environmental Impact of Two Aerobic Composting Technologies Using Life Cycle Assessment. *Int. J. Life Cycle Assess.* **2009**, *14*, 401–410. [CrossRef]
16. Liu, J.; Zhong, J.; Wang, Y.; Liu, Q.; Qian, G.; Zhong, L.; Guo, R.; Zhang, P.; Xu, Z.P. Effective Bio-Treatment of Fresh Leachate from Pretreated Municipal Solid Waste in an Expanded Granular Sludge Bed Bioreactor. *Bioresour. Technol.* **2010**, *101*, 1447–1452. [CrossRef] [PubMed]
17. Roy, D.; Azaïs, A.; Benkaraache, S.; Drogui, P.; Tyagi, R.D. Composting Leachate: Characterization, Treatment, and Future Perspectives. *Rev. Environ. Sci. Biotechnol.* **2018**, *17*, 323–349. [CrossRef]
18. Amani, T.; Veysi, K.; Elyasi, S.; Dastyar, W. A Precise Experimental Study of Various Affecting Operational Parameters in Electrocoagulation–Flotation Process of High-Load Compost Leachate in a Batch Reactor. *Water Sci. Technol.* **2014**, *70*, 1314–1321. [CrossRef] [PubMed]
19. De Rosa, S.; Siciliano, A. A Catalytic Oxidation Process of Olive Oil Mill Wastewaters Using Hydrogen Peroxide and Copper. *Desalination Water Treat.* **2010**, *23*, 187–193. [CrossRef]
20. Siciliano, A.; Stillitano, M.A.; De Rosa, S. Increase of the Anaerobic Biodegradability of Olive Mill Wastewaters through a Pre-Treatment with Hydrogen Peroxide in Alkaline Conditions. *Desalination Water Treat.* **2015**, *55*, 1735–1746. [CrossRef]
21. Pistocchi, A.; Dorati, C.; Grizzetti, B.; Udias Moinelo, A.; Vigiak, O.; Zanni, M. *Water Quality in Europe: Effects of the Urban Wastewater Treatment Directive*; EUR 30003 EN, Publications Office of the European Union: Luxembourg, 2019. [CrossRef]
22. Pandis, P.K.; Kalogirou, C.; Kanellou, E.; Vaitsis, C.; Savvidou, M.G.; Sourkouni, G.; Zorpas, A.A.; Argirusis, C. Key Points of Advanced Oxidation Processes (AOPs) for Wastewater, Organic Pollutants and Pharmaceutical Waste Treatment: A Mini Review. *ChemEngineering* **2022**, *6*, 8. [CrossRef]
23. Zuriaga-Agustí, E.; Mendoza-Roca, J.A.; Bes-Piá, A.; Alonso-Molina, J.L.; Muñagorri-Mañueco, F.; Ortiz-Villalobos, G.; Fernández-Giménez, E. Comparison between Mixed Liquors of Two Side-Stream Membrane Bioreactors Treating Wastewaters from Waste Management Plants with High and Low Solids Anaerobic Digestion. *Water Res.* **2016**, *100*, 517–525. [CrossRef]
24. Khajouei, G.; Mortazavian, S.; Saber, A.; Zamani Meymian, N.; Hasheminejad, H. Treatment of Composting Leachate Using Electro-Fenton Process with Scrap Iron Plates as Electrodes. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 4133–4142. [CrossRef]
25. Hashemi, H.; Ebrahimi, A.; Khodabakhshi, A. Investigation of Anaerobic Biodegradability of Real Compost Leachate Emphasis on Biogas Harvesting. *Int. J. Environ. Sci. Technol.* **2015**, *12*, 2841–2846. [CrossRef]
26. Mahvi, A.H.; Feizabadi, G.K.; Dehghani, M.H.; Mazloomi, S. Efficiency of different coagulants in pretreatment of composting plant leachate. *J. Biodivers. Environ. Sci.* **2015**, *6*, 21–28.
27. Siciliano, A.; Limonti, C.; Curcio, G.M. Improvement of Biomethane Production from Organic Fraction of Municipal Solid Waste (OFMSW) through Alkaline Hydrogen Peroxide (AHP) Pretreatment. *Fermentation* **2021**, *7*, 197. [CrossRef]
28. Sun, Q.; Li, H.; Yan, J.; Liu, L.; Yu, Z.; Yu, X. Selection of Appropriate Biogas Upgrading Technology-a Review of Biogas Cleaning, Upgrading and Utilisation. *Renew. Sustain. Energy Rev.* **2015**, *51*, 521–532. [CrossRef]

29. Calabrò, P.S.; Fazzino, F.; Limonti, C.; Siciliano, A. Enhancement of Anaerobic Digestion of Waste-Activated Sludge by Conductive Materials under High Volatile Fatty Acids-to-Alkalinity Ratios. *Water* **2021**, *13*, 391. [CrossRef]
30. Barbera, E.; Menegon, S.; Banzato, D.; D'Alpaos, C.; Bertucco, A. From Biogas to Biomethane: A Process Simulation-Based Techno-Economic Comparison of Different Upgrading Technologies in the Italian Context. *Renew. Energy* **2019**, *135*, 663–673. [CrossRef]
31. Siciliano, A.; Limonti, C.; Curcio, G.M. Performance Evaluation of Pressurized Anaerobic Digestion (PDA) of Raw Compost Leachate. *Fermentation* **2022**, *8*, 15. [CrossRef]
32. Toledo-Cervantes, A.; Estrada, J.M.; Lebrero, R.; Muñoz, R. A Comparative Analysis of Biogas Upgrading Technologies: Photosynthetic vs Physical/Chemical Processes. *Algal. Res.* **2017**, *25*, 237–243. [CrossRef]
33. Siciliano, A.; Limonti, C.; Mehariya, S.; Molino, A.; Calabrò, V. Biofuel Production and Phosphorus Recovery through an Integrated Treatment of Agro-Industrial Waste. *Sustainability* **2019**, *11*, 52. [CrossRef]
34. Khanal, S.K. *Anaerobic Biotechnology for Bioenergy Production: Principles and Applications*, 1st ed.; Wiley-Blackwell: Ames, IA, USA, 2008; ISBN 978-0-8138-2346-1.
35. Ebrahimi, A.; Hashemi, H.; Eslami, H.; Fallahzadeh, R.A.; Khosravi, R.; Askari, R.; Ghahramani, E. Kinetics of Biogas Production and Chemical Oxygen Demand Removal from Compost Leachate in an Anaerobic Migrating Blanket Reactor. *J. Environ. Manag.* **2018**, *206*, 707–714. [CrossRef]
36. Mokhtarani, N.; Bayatfard, A.; Mokhtarani, B. Full Scale Performance of Compost's Leachate Treatment by Biological Anaerobic Reactors. *Waste Manag. Res.* **2012**, *30*, 524–529. [CrossRef]
37. Lim, B.S.; Kim, B.; Chung, I. Anaerobic Treatment of Food Waste Leachate for Biogas Using a Novel Digestion System. *Environ. Eng. Res.* **2012**, *17*, 41–46. [CrossRef]
38. Maleki, E.; Bokhary, A.; Liao, B.Q. A Review of Anaerobic Digestion Bio-Kinetics. *Rev. Environ. Sci. Biotechnol.* **2018**, *17*, 691–705. [CrossRef]
39. Borja, R.; Martín, A.; Banks, C.J.; Alonso, V.; Chica, A. A Kinetic Study of Anaerobic Digestion of Olive Mill Wastewater at Mesophilic and Thermophilic Temperatures. *Environ. Pollut.* **1995**, *88*, 13–18. [CrossRef] [PubMed]
40. Hu, W.C.; Thayanithy, K.; Forster, C.F. A Kinetic Study of the Anaerobic Digestion of Ice-Cream Wastewater. *Process Biochem.* **2002**, *37*, 965–971. [CrossRef]
41. Tchobanoglous, G.; Burton, F.L.; Stensel, H.D. *Wastewater Engineering, Treatment and Reuse*, 4th ed.; Metcalf & Eddy; McGraw-Hill: New York, NY, USA, 2003; ISBN 883866188-X.
42. Briggs, G.E.; Haldane, J.B.S. A Note on the Kinetics of Enzyme Action. *Biochem. J.* **1925**, *19*, 338–339. [CrossRef]
43. APHA. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; American Public Health Association: Washington, DC, USA, 1998.
44. Romero, C.; Ramos, P.; Costa, C.; Carmen Márquez, M. Raw and Digested Municipal Waste Compost Leachate as Potential Fertilizer: Comparison with a Commercial Fertilizer. *J. Clean. Prod.* **2013**, *59*, 73–78. [CrossRef]
45. Rao, A.G.; Naidu, G.V.; Prasad, K.K.; Rao, N.C.; Mohan, S.V.; Jetty, A.; Sarma, P.N. Anaerobic treatment of wastewater with high suspended solids from a bulk dark industry using fixed film reactor. *Bioresour. Technol.* **2005**, *96*, 87–153. [CrossRef]
46. Eslami, H.; Hashemi, H.; Fallahzadeh, R.A.; Khosravi, R.; Fard, R.F.; Ebrahimi, A.A. Effect of Organic Loading Rates on Biogas Production and Anaerobic Biodegradation of Composting Leachate in the Anaerobic Series Bioreactors. *Ecol. Eng.* **2018**, *110*, 165–171. [CrossRef]
47. Nayono, S.E.; Winter, J.; Gallert, C. Anaerobic Digestion of Pressed off Leachate from the Organic Fraction of Municipal Solid Waste. *Waste Manag.* **2010**, *30*, 1828–1833. [CrossRef] [PubMed]
48. Amin, M.M.; Hashemi, H.; Bina, B.; Ebrahimi, A.; Pourzamani, H.R.; Ebrahimi, A. Environmental Pollutants Removal from Composting Leachate Using Anaerobic Biological Treatment Process. *Int. J. Health Syst. Disaster Manag.* **2014**, *2*, 136. [CrossRef]
49. Pirsaheb, M.; Hossaini, H.; Amini, J. Operational parameters influenced on biogas production in zeolite/anaerobic baffled reactor for compost leachate treatment. *J. Environ. Health Sci. Eng.* **2021**, *19*, 1743–1751. [CrossRef]