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Anaerobic co-digestion in a liquid recirculation pilot-scale reactor: Thermal and hydraulic study

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Abstract

Morocco's economy relies heavily on agriculture, which leads to an abundance in the availability of both vegetal and animal waste. Different treatment and disposal methods have been proposed to produce energy. Anaerobic digestion, being one of them, is being extensively used due to its lower environmental impact. In this paper, we are studying a wet, mesophilic, anaerobic co-digestion of animal and vegetable waste, using a pilot-scale anaerobic digester with liquid recirculation and immersed solid waste. In fact, this study could be divided into two main parts, the first one being a thermal study aiming to investigate the influence of the liquid recirculation's flow rate and the substrate's presence/absence on the heat transfer to the digester, and a second part presents a Computational Fluid Dynamics analysis (CFD) using FLUENT software tool, allowing a better understanding of the fluid's behavior inside the digester. Simulations have been conducted and results show that a higher recirculation flow rate increases heat delivery to the effluent (from 0.18 to 0.66 kWh) but has a negative impact on pressure drop (from 429 to 1937.41 Pa). It was also observed that the liquid percolated more easily and through a larger portion of the waste at lower flow rates.

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Keywords: Anaerobic digestion; Biogas; Computational Fluid Dynamics analysis; Liquid recirculation; Thermohydraulic study

1. Introduction

Recently, global efforts are focused towards finding more efficient methods to dispose of organic waste issued from households and farms. Anaerobic digestion has emerged as a sustainable energy efficient technique with low environmental impacts. There are two types of anaerobic digesters: continuous and batch. For batch digesters, the feedstock is introduced once at the beginning and removed at the end of the digestion, as for the continuous type, the feedstock is fed as the digestion progresses and digested materials are removed to make room for new waste. Many

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parameters influence the biogas quality and yield, such as the total solid content (TS) which represents the fraction occupied by the solid (by weight) in the total mixture, as well as the inoculum fraction. The optimal percentage was found to be 30% inoculum source and 20% TS, as it allowed a faster start up time and a greater CH₄ production [1]. Furthermore, as TS is lower, it becomes easier to heat the digester, because a lower TS implies a higher liquid content, which leads to a greater thermal conductivity, meaning the used heating technique's efficiency is improved. Another crucial aspect is the temperature, as the microbial community's activity dramatically depends on the temperature of its environment [2]. In order to allow the anaerobic digestion to take place, it must be carried out within three operating temperature ranges: psychrophilic (under 20 °C), mesophilic (between 20 °C and 45 °C) and thermophilic (over 45 °C), each having its advantages and drawbacks. In fact, these temperature ranges influence methane's yield and composition, and while the anaerobic bacterial community is resilient to slight temperature changes, these variations should not exceed the maximum temperature at which the death rate surpasses the growth rate [3].

Furthermore, any anaerobic digester, regardless of its type, requires some degree of stirring in order to increase the contact area between the bacteria and the organic waste, therefore increasing the methane's yield [4]. Many types of stirred bioreactors are being used, mainly CSTRs or continuously stirred tank reactors. This technique of stirring is usually done by rotating a propeller within a reactor in contact with the substrate. Mechanical stirring time plays an important role in the biogas production, as a reduced stirring time contributed to a lower produced methane volume [5]. Singh et al. [6] have developed a novel approach in the bottom gas stirring injection technique, considerably diminishing the stirring time by 30%–35% while increasing the mass transfer rate by 30%. Both aspects are vital in anaerobic digestion, as they would simultaneously increase methane's yield and keep a relatively low energy consumption, meaning an implementation in anaerobic digesters is feasible and could be beneficial. Another stirring technique is performed by liquid recirculation (also called inoculum recirculation). This form of mixing works by pumping a liquid, being either tap water, liquid manure (co-digestion) or recycled leachate back into the digester. This liquid percolates through a layer of solid waste and is re-introduced into the reactor (closed loop). Leachate recirculation's importance is manifested in the substantial increase in the produced methane's volume by approximately three-folds [7]. Liquid recirculation could be performed continuously or periodically, but no difference has been reported between the two scenarios. However, the strength of the recirculation plays a role, as a flow that is too weak may hold back the biogas' production, and a flow too strong could lead to a methanation failure [8].

In this work, experimental tests and numerical simulations were carried out to determine the influence of the leachate recirculation's flow rate on heat transfer to the digester, and on the ability of the liquid to penetrate the waste layer. The remainder of the paper is structured as follows. Section 2 presents the used materials and methods. Experimental and simulation results are reported in Section 3. Conclusions and perspectives are given in Section 4.

2. Materials and methods

2.1. Anaerobic digester description

The used digester is a batch reactor with a capacity of 90 liters (11) as depicted in Fig. 1. The digester is hermetically sealed to prevent air from getting inside and biogas from leaking out. The solid waste is trapped by a fine stainless-steel mesh inside, and only liquid is allowed to pass through it. A recirculation pump (14) displaces liquid from the bottom of the digester to the top at a fixed flow rate. Two heating resistors of 1000 W each (13) are mounted on the reactor to heat up its external surface and, consequently, the effluent. Furthermore, a control system is included in order to keep a constant temperature and pH.

The heating belts (metering pump (8)) are activated whenever the temperature probe (7) (the pH probe (10)) indicates a temperature (a pH) below the set threshold and are off otherwise. Inside the electric enclosure (1), there is a display (4) showing an overview of the current state of all system's components, as well as a monitor (3) displaying real-time pH and temperature values. A gas analyzer (Siemens-ULTRAMAT 23) (2) is used to analyze the composition of the produced biogas.

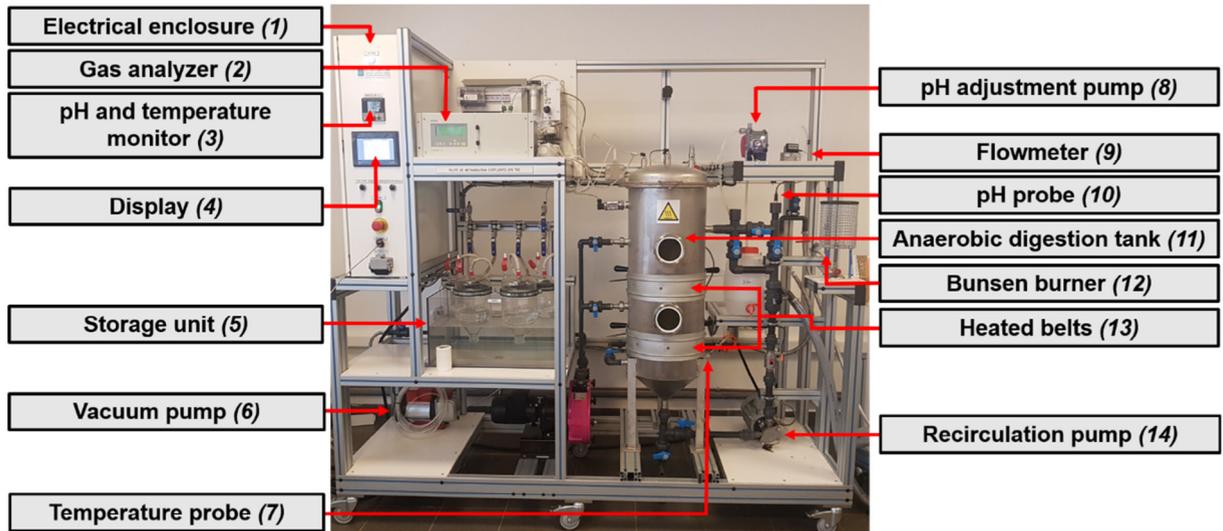


Fig. 1. Anaerobic digester description.

Table 1. Characterization of the solid and liquid phases of the waste.

	TS (%)	VS (%)	Weight (kg)	Thickness (mm)	ρ (kg/m ³)	ϵ (%)	k (m.day ⁻¹)
Solid waste		62 ± 0.7	8.5	50	230	75.33 ± 3.7	0.189 ± 0.01
Liquid	7.58 ± 0.5						

2.2. Waste characterization

The used waste is composed of potatoes, lettuce, onion, tomatoes and cow dung at an animal/vegetable waste weight ratio of 1:3. The organic waste is grinded and introduced in the reactor, forming a layer that gets held by a fine mesh and through which the liquid percolates. This deposit is called a porous zone and is characterized by its composition, weight, volatile solid content (VS), density (ρ), porosity (ϵ), permeability (k) and thickness. The liquid percolating through the solid layer is water that was added at the beginning of the digestion. It is characterized by its total solid content (TS). All characterization tests have been carried out three times (except density), and the standard deviation between the obtained results is presented. Table 1 summarizes the experimental values of these parameters.

2.3. Experimental and numerical simulation setup

Experimentations have been conducted and include thermal and hydraulic studies. For the thermal study, the aim was to determine the heat transfer to the digester under different liquid recirculation flow rates. To achieve that, the temperature had to be continuously measured at the top and the bottom of the reactor.

Regarding the hydraulic study, FLUENT software was used to investigate the liquid's behavior inside the digester under different operating conditions. In order to fully define the substrate (the solid phase), two coefficients, R_v and R_i , respectively representing the viscous and inertial pressure losses inside the digester, had to be calculated.

Lastly, in this study, we consider the assumption of a Newtonian flow (the recirculating liquid's viscosity is independent of the applied stress), and the interactions between the produced biogas and the effluent (liquid and solid phases) are also assumed negligible.

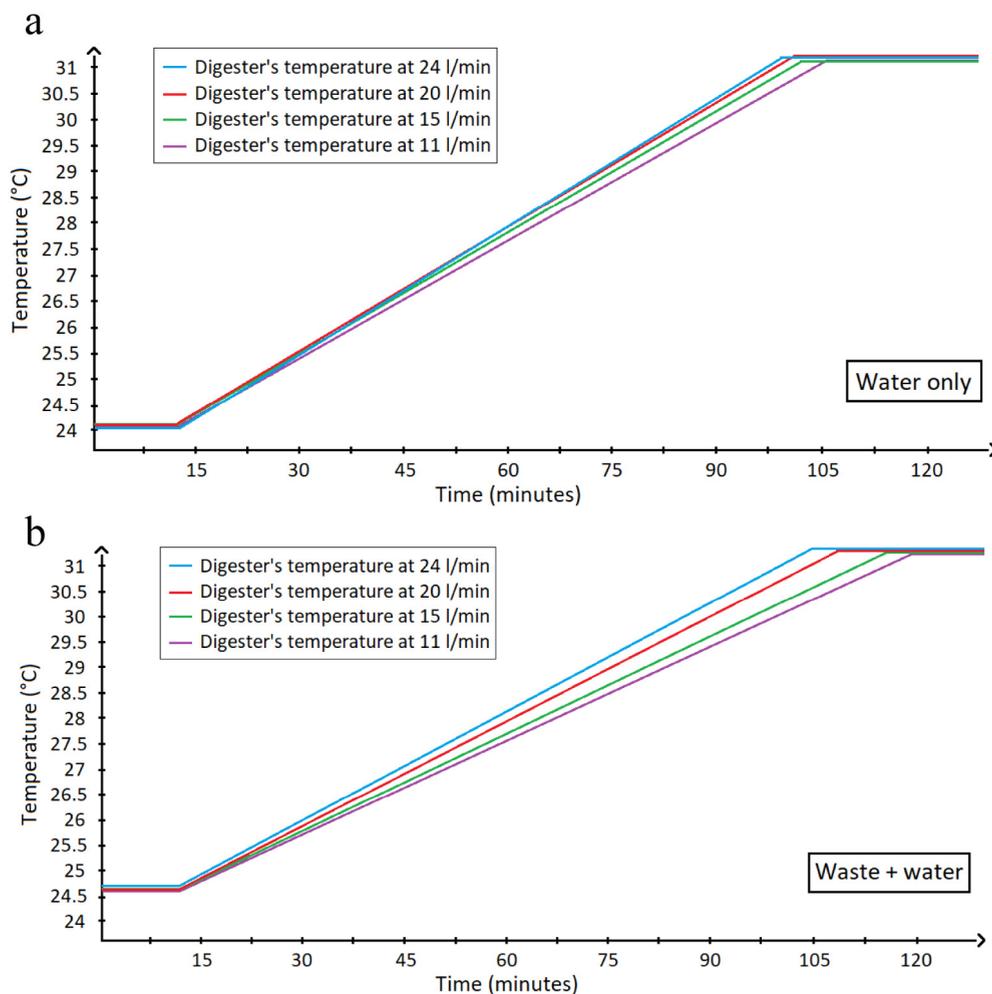


Fig. 2. Experimental temperature curves inside the digester (a) without solid phase (only water); (b) with solid phase (water + solid waste).

3. Results and discussions

3.1. Thermal study

The key focus of this section is to compare the heat transferred to the effluent under different leachate recirculation flow rates. Therefore, two experiments were carried out with four flow rates (11, 15, 20 and 24 l/min) with and without the presence of the solid phase. The digester is heated externally using the two heating resistors (2×1000 W) to a temperature of $\approx 30^\circ\text{C}$, then the obtained results are analyzed and discussed. The presented curves (Fig. 2) represent the average temperature measured in the top and bottom of the reactor.

As a first test, the reactor is only filled with liquid and no waste is added. This initial experiment served as a basis for investigating the effect of the waste quantity and composition on the energy transfer to the effluent. It is clear, from the obtained experimental curves (Fig. 2, a), that the necessary time to warm the effluent from ambient temperature ($\approx 24^\circ\text{C}$) to a fixed mesophilic temperature ($\approx 30^\circ\text{C}$) decreases as the recirculation flow rate increases; this is primarily caused by the improvement of the heat transfer coefficient (h_f) between the effluent and the digester's heated walls [9]. This finding will be further justified later on in the flow analysis section. After completing this first test, a more usual operation scenario is explored. In fact, the reactor is loaded with standard household waste, creating a solid layer inside the digester through which the liquid will leach. The same conditions as the first experiment are kept. Experimental curves (Fig. 2, b) show a similar trend to the first experiment, since

Table 2. Integrated experimental results without solid waste (only water).

Flow rate (m) [l/min]	Required heating time (t) [s]		Energy delivered to the effluent (Q) [kWh]		Total consumed energy (P) [kWh]		Thermal efficiency (η)	
	Water only	Water + waste	Water only	Water + waste	Water only	Water + waste	Water only	Water + waste
11	5656	6447	0.28	0.18	3.14	3.58	8.91%	5.22%
15	5505	6193	0.4	0.35	3.06	3.44	13.07%	10.1%
20	5407	5813	0.54	0.42	3	3.23	18%	13%
24	5243	5643	0.76	0.66	2.91	3.13	26.11%	21.3%

the heat delivery to the digester decreases at lower recirculation speeds. Nevertheless, it is notable that the required heating time is longer by up to 12%, and the energy losses increase by 12% as well. This goes on to show the negative effect of the solid waste layer's presence on heat delivery.

To determine the energy delivered to the effluent (Q), the power has been integrated at every instant (Eq. (1)), where Q is the energy (kWh), \dot{Q} is the power (kW), \dot{m} is the liquid's mass flow rate (kg/s), cp is the heat capacity ($\text{kJ K}^{-1} \text{kg}^{-1}$), T_{in} and T_{out} are the top and bottom temperatures respectively ($^{\circ}\text{C}$).

$$Q = \int \dot{Q} dt = \int \dot{m} \times cp \times (T_{in} - T_{out}) dt \quad (1)$$

The heat capacity value was taken as $4.187 \text{ kJ K}^{-1} \text{kg}^{-1}$ on the first test (only water) and $4.1 \text{ kJ K}^{-1} \text{kg}^{-1}$ on the second one when waste was introduced [10]. T_{in} and T_{out} were determined experimentally at every instant of the experiment. This allowed to integrate the power over time. Table 2 could then be completed, where P is the energy consumed by the $2 \times 1000 \text{ W}$ resistors, and η is the thermal efficiency defined as the ratio between the energy delivered to the effluent Q and the total consumed energy P .

It will be interesting to discuss the normal operation scenario with the presence of the solid waste (Fig. 2, (b) and Table 2. second columns of each row): the increase of the flow rate from 11, 15, 20 to 24 l/min induces a decrease in the heating time from 6447, 6193, 5813 to 5643 s respectively, showing the positive impact of higher flow rates on energy transfer. Also, the energy loss decreased from 3.4, 3.09, 2.81 to 2.47 kWh respectively, meaning the heating efficiency improved consistently with higher recirculation flow rates.

We conclude that a higher flow rate is beneficial from a thermal standpoint, and a smaller quantity of the solid waste would lead to a faster heating. While obtained results are promising, further studies must be carried out to determine the optimal solid waste quantity to allow an easier and less costly heating.

3.2. Flow analysis

Simulations have been carried out using Fluent software in order to better understand the flow fields in the digester under different leachate recirculation speeds. This CFD (computational fluid dynamics) analysis enabled to visualize the liquid's behavior and know where the recirculation zones are located, as well as the liquid's ability to percolate through the solid phase. The presented graphics in Fig. 3 are drawn on the midplane (the plane passing through the digester symmetrically), and all the vectors were normalized to 0.27.

As shown in Fig. 3 (b1, b2, b3 and b4), the liquid enters with a high velocity (red) and slows down (blue) inside the digester. This is because the leachate flows from a small diameter pipe into the large diameter reactor, generating a high velocity jet, leading to substantial dissipation of its energy at the entrance.

It is also observed, from Fig. 3 (a1, a2, a3 and a4), that a large liquid recirculation area forms near the wall while a weaker one occurs at the bottom of the digester. The main recirculation zone gets larger and closer to the substrate (solid layer) with the increase in recirculation flow rate. From the same figures, we notice the undesirable influence of the higher recirculation flow rates on the ability of the liquid to percolate through the solid waste layer. At lower flow rates (Fig. 3, a1 and a2) the liquid appears to penetrate the solid layer without difficulty, as opposed to higher flow rates (Fig. 3, a3 and a4) where the liquid seems to flow across the substrate's surface and only be able to percolate at a small area. This aspect is associated with the increase of the vortex's size with higher flow rates, causing the liquid to drag on the solid layer's surface while impeding its ability to penetrate it. Parameters,

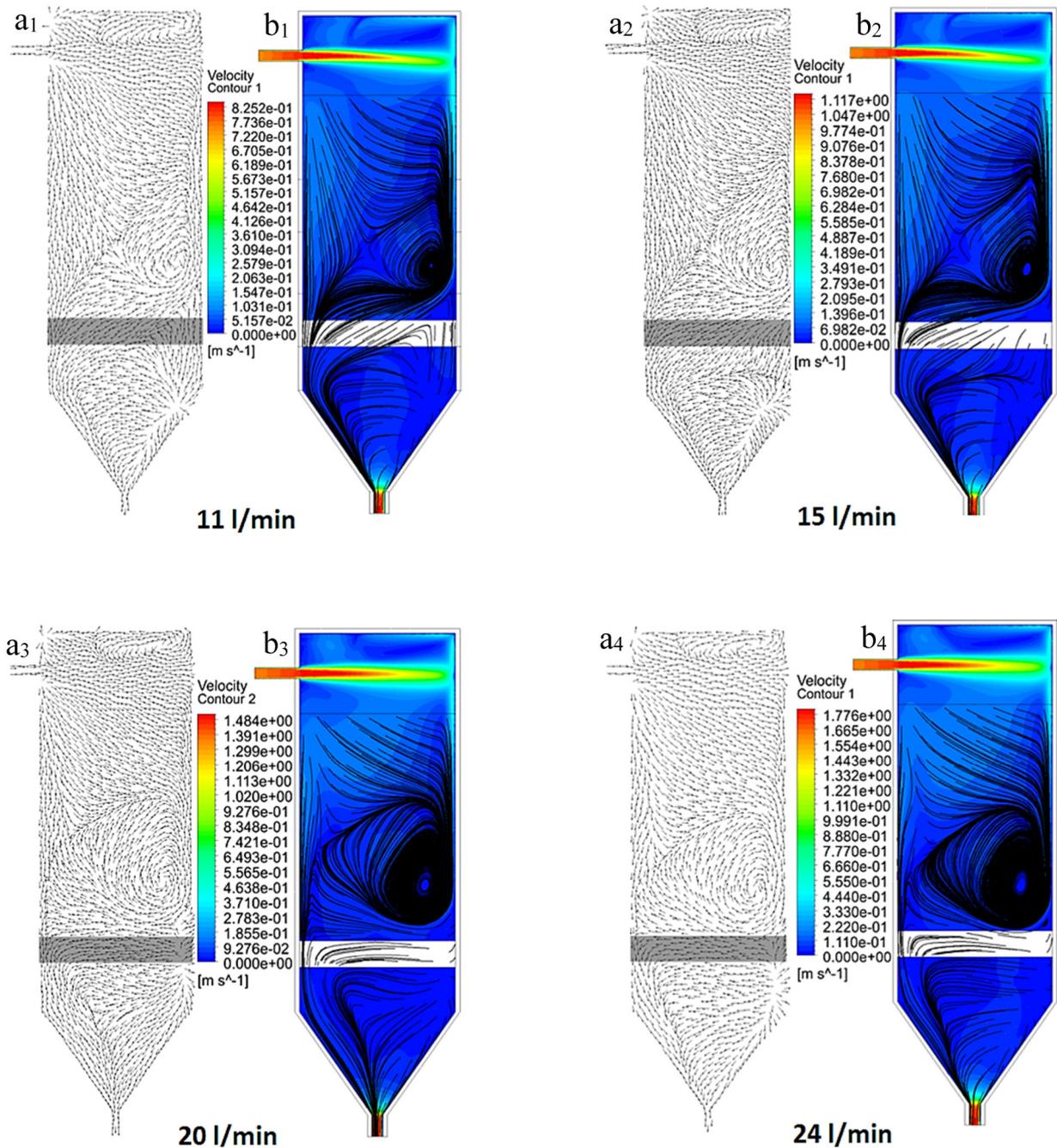


Fig. 3. Simulation results of the flow inside the digester under different flow rates: vectors distribution (left) and velocity magnitude contours (right). (a1) - (b1) 11 l/min, (a2) - (b2) 15 l/min, (a3) - (b3) 20 l/min and (a4) - (b4) 24 l/min.

such as the total pressure drop, were also calculated, ranging from 429, 778.58, 1346.74 to 1937.41 Pa for 11, 15, 20 and 24 l/min respectively. This increase indicates a higher pump power consumption. Another important factor is the strain rate, growing from 2.97, 4, 5.08 to 6.12 s^{-1} for flow rates of 11, 15, 20 and 24 l/min respectively, revealing that a higher and more effective degree of stirring takes place at higher leachate's recirculation flow rates.

After analyzing the obtained results, we find ourselves face to conflicting conclusions. In fact, the presence of the recirculation zones has a positive role on a thermal standpoint (more heat will be transferred through the walls of

the digester to the effluent), but has a negative impact on the pressure loss, as larger recirculation zones and higher maximal velocities usually produce an increase in frictional pressure drops, therefore increasing the pumping cost [11]. As for the liquid's percolation through the solid layer, it is in fact optimal for the leachate to penetrate the total volume of the solid waste in order to maximize the contact between the liquid phase and the solid phase. This phenomenon is more prominent at lower speeds, meaning the methane's yield would be superior.

4. Conclusions and perspectives

In this work, a thermo-hydraulic analysis based on experimental results and numerical simulations was carried out on a batch anaerobic digester. The aim was to investigate how the leachate's recirculation flow rate affects the thermal transfer to the effluent and the liquid's ability to percolate through the solid waste. We concluded that increasing the recirculation flow rates leads to an enhanced heat transfer to the reactor, which is validated by both thermal experiments and CFD analysis. Nevertheless, higher flow rates have a negative impact on the hydraulic performance, as they induce a greater pressure drop inside the digester, meaning the pump consumes much more power thus negatively impacting the total energetic efficiency.

An ongoing study aims to determine the effect of the recirculation flow rate on methane's yield, thus relating the discussed aspects (thermal and hydraulic) to biogas production, and consequently, establishing a tradeoff between biogas production and energy consumption.

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