

Article

UASB Performance and Perspectives in Urban Wastewater Treatment at Sub-Mesophilic Operating Temperature

Daniele Ceconet , Arianna Callegari and Andrea G. Capodaglio * 

Department of Civil Engineering & Architecture, University of Pavia, 27100 Pavia, Italy;
daniele.ceconet@unipv.it (D.C.); arianna.callegari@unipv.it (A.C.)

* Correspondence: andrea.capodaglio@unipv.it

Abstract: UASBs present several advantages compared to conventional wastewater treatment processes, including relatively low construction cost facilities, low excess sludge production, plain operation and maintenance, energy generation in the form of biogas, robustness in terms of COD removal efficiency, pH stability, and recovery time. Although anaerobic treatment is possible at every temperature, colder climates lead to lower process performance and biogas production. These factors can be critical in determining the applicability and sustainability of this technology for the treatment of urban wastewater at low operating temperature. The purpose of this study is the performance evaluation of a pilot-scale (2.75 m^3) UASB reactor for treatment of urban wastewater at sub-mesophilic temperature (25°C), below the optimal range for the process, as related to biogas production and organic matter removal. The results show that, despite lower methane production and COD removal efficiency compared to operation under ideal conditions, a UASB can still achieve satisfactory performance, and although not sufficient to grant effluent discharge requirements, it may be used as a pretreatment step for carbon removal with some degree of energy recovery. Options for UASB pretreatment applications in municipal WWTPs are discussed.



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Keywords: UASB; anaerobic processes; domestic sewage; biogas; low temperature

1. Introduction

After decades of unchanging traditional practices, new strategies and approaches to urban wastewater management are being proposed [1–3]. Wastewater treatment plants (WWTPs) based on current mainstream technologies are one of the major energy consumers at the municipal level worldwide [4], and energy use by utilities is expected to grow significantly in the next decade: it was reported that in Australia, due to expected population growth of 25% by 2030, energy use by water utilities would grow between 130% and 200% above existing levels [5]. The concept that wastewater contains resources that are already, or are soon due to become, limited is well established in the scientific community [6–9]. Resources include water itself [10], thermal and embedded chemical energy [11,12], and nutrients [13].

Among the so-called “New Sanitation” concepts [14] proposed to implement more efficient approaches to sustainability and circular economy principles achievement in the water sector, anaerobic sewage biodegradation could represent one of the main core technologies as it sports several advantages, including relatively low facilities construction costs, low excess sludge production, plain operation and maintenance, energy generation in the form of biogas, and robustness in terms of COD removal efficiency [15]. In addition to the absence of free (dissolved) oxygen, which is costly to supply and represents up to 60% of the energy demand in traditional WWTPs, anaerobic processes can partly convert the intrinsic energy embedded within wastewater organics (theoretically calculated in 3.86 kWh/kgCOD) [16] into usable energy (methane) form ($1\text{ mgCOD} \approx 0.35\text{ mLCH}_4$). The latter aspect is of particular relevance, given the current concerns and energy policies at

European and global level [17,18], the costs involved in excess biological solids management [19–21], and the drive to transform process residues into value-rich circular economy materials [22–26].

The main factors preventing generalized adoption of earlier anaerobic technologies in urban wastewater treatment are the relatively high sewage dilution, the slower anaerobic kinetics, requiring larger process volumes, and the need for high process temperature for optimal biogas production, as temperature influences the growth and survival of microorganisms and determines the characteristics of the process. Although anaerobic treatment is possible at every temperature, low temperatures lead to the decline of the maximum specific bacterial growth rate and of related methanogenic activity [27]. Optimal mesophilic digestion and biomethanation take place optimally at between 30 to 38 °C; at continental winter ambient temperatures, this may require high additional external heat input to maintain process conditions. Methanogenic activity at low temperature may be up to 10–20 times slower than at 35 °C, requiring a similar increase of total biomass in the reactor, operation at higher sludge (SRT), and hydraulic retention time (HRT) in order to maintain the same efficiency obtained at higher temperature.

The greatest breakthrough in anaerobic contact process technology was given by the development of the upflow anaerobic sludge blanket (UASB) reactor, first described by Lettinga et al. [28], in which high biomass concentration is achieved by the principle of autoflocculation through the generation of granular biomass. This specific biomass structure and an appropriate operational design allow the independent setting of SRT and HRT in the reactor, allowing processing of relatively diluted substrates. UASB reactors can now be considered a consolidated process technology that overcomes some of the limitations of conventional anaerobic processes and, as such, have found many applications in urban sewage treatment in tropical countries by virtue of favorable climatic conditions [29], and have been indicated as possible alternative, sustainable technology for decentralized treatment systems [30].

Typical COD removal efficiency of UASB reactors can reach 80%, and more in warm climates [31], because in those conditions they usually operate within the ideal (mesophilic) range. In cold-to-temperate regions (sewage temperature occasionally ranging from 10 to 20 °C), UASB suffers from some specific limitations: with temperature below 20 °C, undigested sludge may accumulate in the blanket, and processing performance could decrease considerably [32]. This may induce large seasonal variations in UASB-based WWTPs, with COD removal efficiency oscillating by up to 40% between summer and winter operations [33]. Many studies have been carried out to investigate UASB performance at below mesophilic conditions; however, most of them concern small-scale bench or pilot test reactors [34]. In order to integrate UASB technology in real WWTP facilities, the robustness and effectiveness of the process under suboptimal conditions must be proven beyond uncertainty.

The purpose of this study is the performance evaluation of a pilot-scale UASB reactor operated in real-life conditions for treatment of urban wastewater at sub-mesophilic temperature (25 °C), as related to biogas production and organic matter removal. After discussing the observed results, a discussion on possible strategies for application of UASB process in urban wastewater management follows.

2. Materials and Methods

2.1. System Configuration

The pilot plant (Figure 1) used for this study is installed on the grounds of a municipal, conventional WWTP plant (consisting of activated sludge and anaerobic sludge digestion processes) in Northern Italy, covering a service area of approximately 90,000 population equivalent (P.E.). The pilot is fed by raw wastewater influent diverted from the main line, after mechanical screening. A fine wire-mesh filter is placed prior to the pilot's inlet to remove excess nonbiodegradable solids that may adversely affect the distribution of the flow into the UASB reactor, clog the feeding systems, and accumulate into the biological

flocs. A mixing/equalization tank of 120 L follows the filter, to obtain homogeneous feed to the reactor, introduced by a precisely adjustable volumetric pump. A slow-turning mixer (0.35 kW) and heating elements (3.5 kW) are also installed in the tank. The latter are used to maintain the raw influent's target temperature of 25 °C for the duration of the study. The UASB reactor ($V = 2.75 \text{ m}^3$, $H = 3.5 \text{ m}$) is made of 1 m diameter HDPE pipe, with eight regularly spaced sampling ports (one every 40 cm, with the first positioned at 30 cm from the bottom of the tank) and a gas/liquid/solid separator (GLSS) with baffles and upper gas deflector to enhance biogas collection and avoid biosolids washout. An effluent collection tank with 80 L capacity is installed to allow visual examination of the effluent and allow collection of grab and composite samples (automatic sampler ISCO 1700/1710; Teledyne-ISCO, Lincoln, NE, USA).

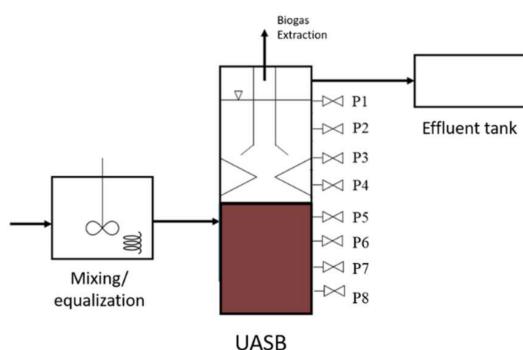


Figure 1. Pilot plant scheme.

2.2. Reactor Startup

The reactor was initially seeded with 500 L of sludge (40.8 g/L total suspended solids, TSS, and 22.4 g/L volatile suspended solids, VSS) from the facility's own mesophilic anaerobic digester. The seed amount was selected to maintain the biological loading rate during reactor startup within the 0.30 to 0.50 kgCOD/kgVSS·day range, which was suggested as appropriate according to previous experiences. The feed sludge was left to rest for one day prior to the introduction of raw wastewater up to half of the reactor's volume; then, after a further 24 h, the reactor was completely filled with wastewater, and pH and VFAs checked for acceptable values ($6.8 < \text{pH} < 7.4$, acetic acid $< 200 \text{ mg/L}$). When these parameters stabilized within the required ranges, continuous wastewater feeding of the UASB started. The study lasted 30 weeks in total (September to April).

During the startup period, HRT ranged from 11 to 24 h with influent heated to 30 °C to favor biomass acclimation. As the purpose of this study was to maximize UASB performance at operational temperature below optimal mesophilic range, a target process temperature of 25 °C, often observed in the wastewater of temperate regions [35], rather than within the 35–38 °C range commonly considered as the mesophilic optimum, was adopted. Influent wastewater below the target process temperature was heated in the upstream mixing/equalization tank by means of an electric resistance. Previous preliminary lab tests indicated that for UASBs treating domestic wastewater with relatively high alkalinity, at 25 °C, an HRT of 4 h would not negatively affect the reactor's performance; however, during this study, a minimum HRT of 8 h was maintained.

2.3. Influent Characteristics and Operational Parameters

Raw wastewater characteristics during the study period are summarized in Table 1. Detailed curves representing temporal variations are shown in the following Section 3.

Table 1. Influent wastewater characteristics during the study.

Parameter	Units	Range
Total COD	mg/L	602–866
Soluble COD	mg/L	147–183
TSS	mg/L	300–520
VSS	mg/L	274–467
VFA (as CH ₃ COOH)	mg/L	56–112
Alk (as CaCO ₃)	mg/L	892–1037

Table 2 summarizes the main operational parameters of the UASB reactor during the study, divided into five periods of different duration, during which flow conditions were kept stable, preceded by a startup period. Considering the unfavorable operational conditions (i.e., temperature) of the process, it was decided to limit the applied hydraulic load and organic loading rate (OLR), compared to the maximum values normally selected for this type of process [34]. Influent wastewater pH was measured by an online pH-meter in the upstream mixing tank and controlled prior to entering the reactor within the desired range (6.5–8) using an automated PID-time proportional control system developed and tested in previous studies [36].

Table 2. Process conditions in the UASB reactor.

Period	Duration (weeks)	Temperature (°C)	Hydraulic Load (m/h)	Influent Flow (L/h)	HRT (h)	OLR (kgCOD/m ³ ·day)	SRT (days)
Startup	8	30	0.22–0.36	185–280	11–24	0.4–2.3	40
I	4	25	0.27	210	11.2	0.8–1.8	22
II	1	25	0.29	230	10.5	1.5–2.0	12
III	1	25	0.32	255	9.5	1.9–2.3	6
IV	2	25	0.35	275	8.8	0.5–2.5	8
V	14	25	0.33	185	13	0.7–3.0	30

2.4. Monitoring and Analytics

Sampling was carried out daily (with exceptions on weekends and holidays) as follows: influent and effluent were drawn by automatic samplers every 15 min to obtain a final daily composite sample; the UASB mixed liquor was manually sampled daily by taking 600 mL samples after purging 500 mL of liquid to eliminate the liquor trapped in the piping of each port (P1–P8 in Figure 1, P1 being the uppermost and P8 the bottom one). Qualitative parameters COD, volatile fatty acids (acetic acid), alkalinity, sulfate, total N (TN), ammonium, total P (TP), and phosphate were determined according to Standard Methods in our laboratory. Total biomass present in the reactor was estimated from the observed vertical solids profile (TSS and VSS) integrated over the entire height of the unit.

Turbidity and TSS monitoring in the upstream feeding tank and in the effluent collection tank were monitored online; the latter, in particular, was necessary to verify any biomass losses from the reactor. Biogas production was metered by a gas flow meter and IR gas analyzer (Fresenius GA210/220, Herten, Germany) to determine CH₄ and CO₂ fractions within. Biogas production is an important parameter representative of overall process performance; however, it is a poor indicator of any ongoing imbalances. Low biogas production in fact may result not only from process inhibition, but also from low OLR and from low or changing temperature; furthermore, it is often observed when the process has already undergone performance degradation [37]. Hence, stability of the process was further assessed by monitoring pH, alkalinity, and VFAs (as CH₃COOH), the most immediate indicators to reflect its ongoing status. VFA, in particular, is widely used for this purpose because it is the main intermediate product prior to methane production, and its accumulation in the reactor indicates process imbalance and can induce pH decrease. In such instance, alkalinity constitutes the ultimate buffer to offset acidification. The VFA/alkalinity ratio can thus be considered a better early warning sign of anaerobic

process stability compared to pH, which may not indicate an operating problem until it is too late [38]. pH was measured continuously with an online probe in the reactor. The same instrument also measured redox potential, which remained at an almost constant value (-250 ± 11 mV) for the entire period of the study, indicating absence of dissolved O₂ in the reactor's influent (data not shown).

As the study had the eminently practical nature of preliminary evaluation of UASB performance, no microbiological determinations, save for the study of the biomass' vertical distribution in the reactor, were foreseen. Table 3 summarizes the average influent and effluent characteristics of treated wastewater during the study.

Table 3. Average quality and process parameter values during the five study periods.

Period		Total COD (mg/L)	Soluble COD (mg/L)	TSS (mg/L)	VSS (mg/L)	VFA (as CH ₃ COOH) (mg/L)	Alk (mg CaCO ₃ /L)	Biogas Production (L/day)	COD Conv. to CH ₄ (%)
Startup	Influent	617	147	300	276	58	894		
	Effluent	324	130	121	138	66	1002	279	26
	Removal, %	45.3	10.5	62.5					
I	Influent	659	179	423	388	98	959		
	Effluent	391	108	255	231	53	1109	484	31
	Removal, %	41.4	38.6	41.8					
II	Influent	745	180	479	434	108	982		
	Effluent	506	79	209	229	36	1094	560	28
	Removal, %	31.3	55.6	54.6					
III	Influent	820	153	562	468	86	969		
	Effluent	631	79	516	397	39	1094	643	26
	Removal, %	23	45.7	8.2					
IV	Influent	653	158	425	320	85	1034		
	Effluent	518	110	326	215	50	1108	519	25
	Removal, %	22.1	38.7	27.1					
V	Influent	756	160	458	383	97	932		
	Effluent	234	62	142	120	34	1024	427	28
	Removal, %	66.4	59	66.8					

3. Results

3.1. COD and Solids Removal

Results from the 30 weeks of operation are summarized in the following graphs. Figure 2 reports observed total and soluble COD values (TCOD and SCOD, respectively). Influent wastewater is a typical urban complex mixture with relatively high SS content (50–65% of total COD), resulting in low SCOD/TCOD ratios.

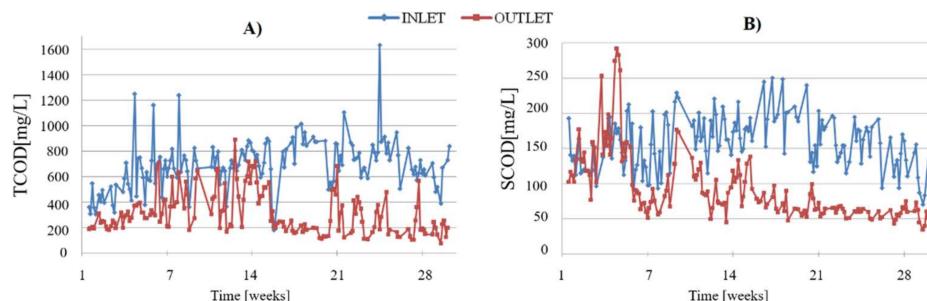


Figure 2. Total (A) and soluble (B) COD in the influent and effluent of the reactor.

Influent daily average TCOD over the entire period of the study ranged from about 300 to over 1600 mg/L, while it was observed to be generally between 80 and 400 mg/L

in the effluent. Occasional fluctuations of effluent TCOD concentration up to 900 mg/L could be linked to punctual TSS losses, likely due to entrapment of gas bubbles. Despite a general trend of increasing influent TCOD from week 1, effluent values seem stable in the second half of the study, decreasing to values between 100 and 200 mg/L level. Easily biodegradable organic matter (SCOD) varies from about 70 to 250 mg/L in the influent, while the effluent curve follows the influent one, stabilizing in the range between 50 and 80 mg/L level in the final period.

Removal of solid COD begins with its entrapment within the sludge blanket; the observed effluent SCOD pattern is more stable than TCOD's, which confirms that the latter is affected significantly by biosolids losses from the reactor. The wide influent SCOD fluctuations are damped in the effluent, suggesting that steady and relatively efficient uptake of the easily available organic substrate is taking place. At startup, effluent SCOD values are high and exceed the inlet concentrations: this represents the accumulation of organic matter in the reactor, suggesting some initial converting difficulties by the anaerobic microorganism in the reactor, which are then overcome by their gradual adaptation to the low process temperature.

TSS and VSS trends are reported in Figure 3. TSS content in raw water varied from 100 to 1000 mg/L; the effluent presents variable solids concentrations, affected by the frequent peaks that could be likely attributed to gas entrapment in the flocs, with maximum removal observed at 66.8%. VSS in the effluent ranged from 70 to over 95% of TSS (Figure 4). The peaks in Figure 4 represent biomass washout from the system.

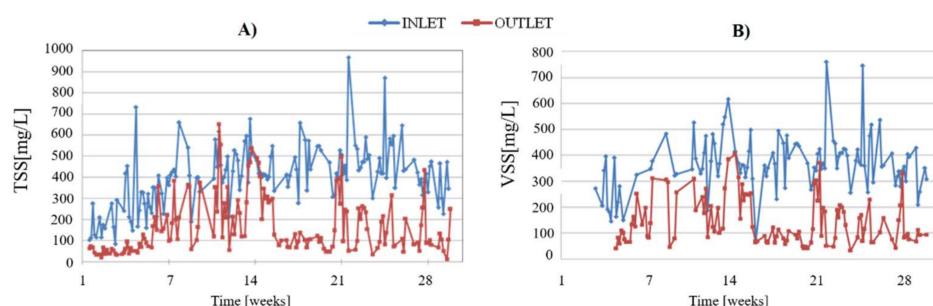


Figure 3. Total (A) and volatile (B) suspended solids in the UASB influent and effluent.

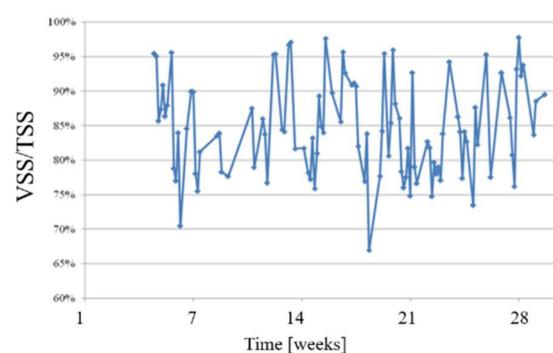


Figure 4. VSS/TSS ratio in effluent.

3.2. Process Stability and Biogas Production

VFAs (mainly acetic, propionic, and butyric acids) are intermediate products in the digestion process, produced from its first two steps, i.e., hydrolysis and acidogenesis. VFA monitoring (Figure 5) yields an effluent pattern with behavior very similar to SCODs: in fact, VFAs represent the major component of the easily biodegradable organic matter during the process. Therefore, similarly to SCODs, effluent VFAs accumulate initially during the startup period, reaching the maximum value of 180 mg/L in the liquor. This

represents a high production of VFA intermediates not readily consumed by anaerobic bacteria. After the initial period, VFA concentration in the effluent decreases, stabilizing in the range of 20–50 mg/L, a sign of stable, though limited in efficiency, methanogenic activity.

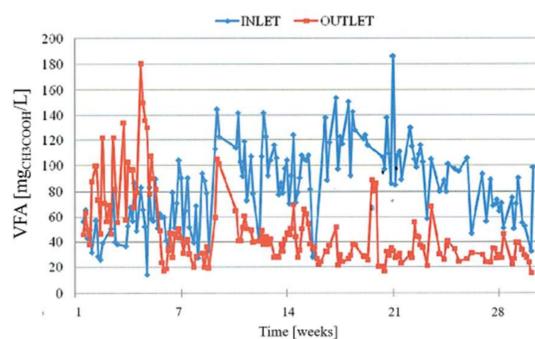


Figure 5. VFA monitoring in influent and effluent.

Overall, notwithstanding the increasing upflow velocities during the various study phases, COD and TSS removal do not seem to be significantly affected by this change. Figure 6 shows SCOD removal efficiencies that, despite significant variability ($\pm 15\%$), seem to stabilize around the 60% level after the startup phase.

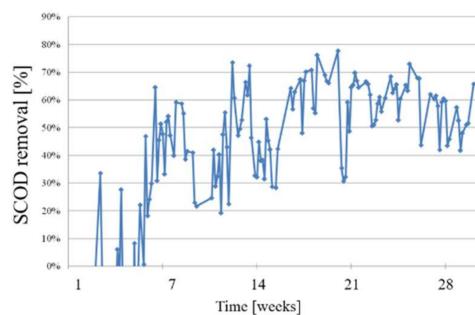


Figure 6. SCOD removal trend.

Figure 7 summarizes the evolution of total biogas and CH_4 production in the process and the overall COD fractions balance around the UASB reactor. As seen in Figure 7A, CH_4 represents about 70% of total biogas volume, a fraction in the upper range commonly observed in anaerobic processes. Figure 7B shows the fractional COD distribution in the reactor output. After an initial lag period, conversion of influent COD into CH_4 is fairly stable in a 20–40% efficiency range, with average value of 28%. These values represent the methane collected from the GLSS of the unit, and therefore do not measure the biogas lost in the effluent, which was not measured. It should be considered that CH_4 water solubility at 25 °C (22 mg/L) is about 37% higher than solubility at 38 °C, the optimal mesophilic operational range, and a considerable amount of biogas is therefore likely to escape the reactor in the liquid effluent. Values that exceed 100% of total COD inflow (green line) represent material losses due to biological solids washout from the reactor, due to punctual hydraulic transient conditions or to gas entrapment in the flocs, which may lower apparent solids density and increase solids' buoyancy.

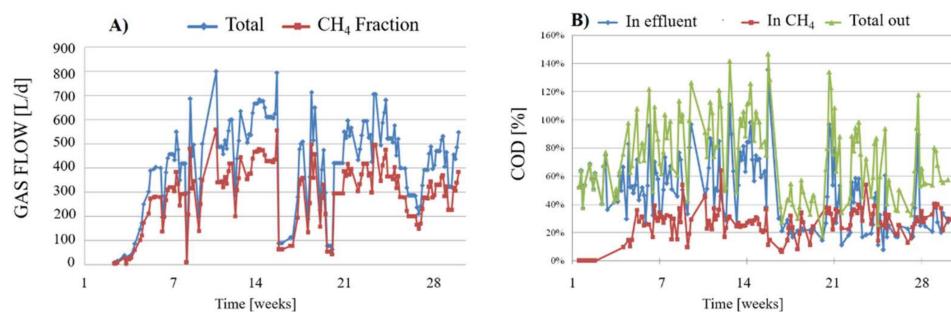


Figure 7. Biogas production (A) and overall COD fractions balance (B).

In addition to the rate of biogas production, anaerobic processes stability indicators include the VFA/alkalinity ratio. Under mesophilic conditions, VFA/alkalinity ratio in the range of 0.23–0.3 indicates stable digestion, a ratio <0.23 is an indication of stable but underfed digester, whereas values >0.3 are indication of process overloading and poor stability [38]. The reactor showed VFA–alkalinity ratio normally below 0.1, a sign of process stability, but also an indication that OLR could be further increased if operating at higher temperature. Effluent alkalinity is always higher than influent (Figure 8A), indicating that no alkaline buffer capacity was used up to contrast acidification, an index of possible process stability problems, as VFA accumulation was only observed during the startup phase. pH (Figure 8B) oscillated in the range 7.5–8, which is appropriate for process conditions, although higher than the usual range from 6.6–7.4.

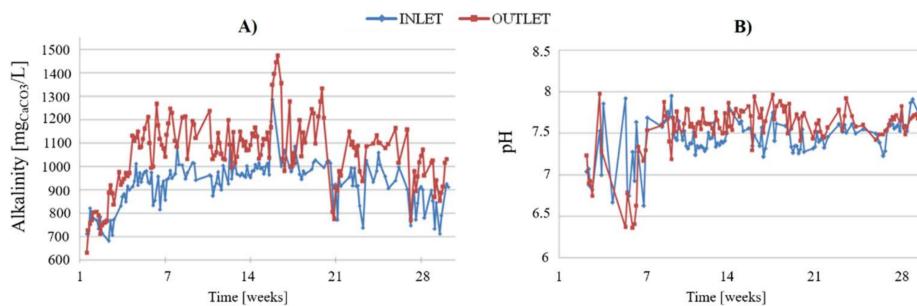


Figure 8. Alkalinity (A) and pH (B) monitoring in the reactor.

Finally, vertical biomass distribution in the unit is summarized in Figure 9. Only VSS concentrations related to sampling ports 1, 5, and 8, (highest, middle, and lowest) are shown for simplicity. Sludge concentration, represented by VSS, decreases from the bottom of the reactor to the top. Progressive increase of upflow velocity during the study induces rising sludge concentration at P1 and a corresponding decrease at P8.

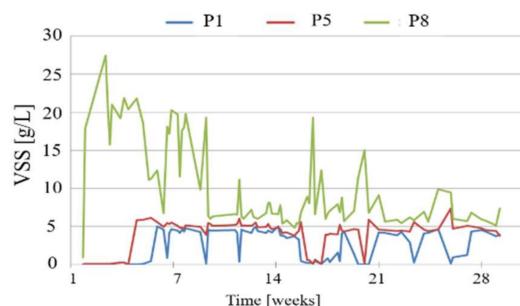


Figure 9. Vertical biomass distribution in the reactor.

Average nutrient concentrations in the reactor's influent and effluent are summarized in Table 4. Values were nonlimiting for anaerobic biomass. No ammonia inhibition could be detected to the process.

Table 4. Average observed macronutrients concentrations.

Parameter	Units	In	Out
Ammonia	mg _{N-NH₄} /L	48	61
Total N	mg _N /L	69	76
Phosphate	mg _{P-PO₄} /L	3.3	7
Total P	mg _P /L	9	8.5

4. Discussion

Process temperature has a great influence on the performance of a UASB reactor as it not only affects methanogenic activity, but also hydrolysis, solids settling, and gas transfer rates. Low COD conversion efficiency under low-temperature conditions and reduced SRT has been attributed to incomplete sludge granulation and insufficient volume of settled solids, reducing microorganisms' methanogenic activity [39]. A similar trend is observed in this study.

A common feature of domestic wastewater consists of the presence of suspended solids: while particulate influent organic matter is effectively removed by entrapment in the UASB sludge bed, its hydrolysis rate is significantly affected by temperature. Uemura and Harada [35] observed that just 58% of the entrapped organic particulate in UASB blankets was liquefied at 25 °C, rapidly decreasing to 33% at 13 °C. Particulate accumulation in the sludge blanket may lead to bed thickness increase, solids buildup around sludge granules, lower sludge digestion, and gradual decrease of sludge activity, with lower ultimate COD conversion efficiency. Although granular sludge remains such even at decreasing temperature, in these conditions, the granules tend to undergo a process of autolysis, with partial breakdown.

TSS losses suggest that the UASB reactor may be affected by a series of issues, not limited to the above-described granular morphology and size, but also including hydrodynamic issues, such as internal turbulence, incomplete mixing of biological sludge with the incoming flow, and possible gas entrapment within flocs. Dynamics of liquid flow-and-sludge movement influence the performance of the process: upflow velocity, and rising biogas bubbles are the main factors influencing internal fluid flow and the resulting mixing pattern. A commonly reported problem related to UASB treatment of municipal sewage, especially under suboptimal conditions, is limited internal mixing due to low biogas production, a major contributing factor to effective mass transfer, resulting in hindered liquid–biomass contact [40].

Despite suboptimal operational conditions, results showed a satisfactory performance, achieving total and soluble COD conversions of 66 and 60%, respectively. Sewage treatment efficiencies by UASB processes of any size reported so far range from 7 to 90% of total COD removals within a process temperature range of 7–32 °C [41]. Results obtained in this study at large pilot-scale and field conditions show a relatively good performance compared to others. They also indicate the feasibility of UASB process technology for sewage treatment at low temperatures with limited, but still significant, suspended solids and dissolved organic material removal. In winter conditions, municipal wastewater temperatures may be even lower than the one tested herein, and bacterial hydrolytic activity could therefore be even lower than observed, with greater solids accumulation in the reactor and lower COD removal performance. Internally accumulated sludge from the colder periods would subsequently be digested in the subsequent warmer ones, with partial recovery of the missed gas production. Sludge disintegration and washout issues observed during the study, however, would require special considerations in process and reactor configuration, perhaps introducing improved GLSS design.

Although the UASB process alone, as tested, would not comply with current discharge requirements, especially under a low operating temperature, it may, however, be considered an efficient preliminary treatment step for domestic sewage to improve the sustainability of current practices, still mostly based on conventional activated sludge (CAS) technology.

4.1. Strategies for UASB Application for Enhanced Sustainability of Municipal WWTPs

A suitable strategy for increased WWTP operational sustainability could envision the introduction of UASB units as pretreatment, prior to CAS units in existing municipal facilities. The advantages of such combination for the treatment of municipal wastewater, especially for temperate climate applications, have been previously proposed, but in spite of the foreseeable benefits deriving from their interaction, little investigation has been conducted in different settings at global level [42]. COD reduction of about 60% in the cold season, observed in this study, and up to 80% in the warm one [43], would add substantial benefits to a traditional treatment scheme. If UASB pretreated effluent were fed to a CAS unit, the following effects would be achieved: lower energy consumption for aeration; lower chemical consumption for sludge dewatering, and lower disposal costs; lower O&M requirements and higher operational simplicity and, not least, a much lower overall carbon footprint due to biogas recovery and reduced energy inputs [42]. In UASB–CAS systems, steadier operational performance was observed compared to CAS-only schemes, which produced effluents with wider-quality variability [44]. While additional costs would be needed for the addition of UASB units to existing facilities, higher treatment capacity and substantial overall savings could be obtained by year-round O&M cost reduction and energy recovery, especially during the warm season [34].

In CAS-based systems without an anaerobic sludge digestion line (e.g., extended aeration systems), excess aerobic sludge could be returned to the UASB reactor, where biological solids would undergo final stabilization, simplifying sludge treatment, with wastage from the UASB reactor only. Anaerobic sludge would then be directly sent for dewatering, disposal, or other productive reuse [45].

Finally, it should be noted that UASB technology could become even more effective, even at low temperatures, if new paradigms concerning domestic water use and disposal, i.e., stream separation and differential treatment, would be adopted at widespread level in urban systems [46,47].

4.2. Circular Economy Implications of UASB Wastewater Treatment

UASB processes may have relevant impacts both on local circular economy (CE) and on the water/energy/food (WEF) nexus. In UASB systems, nutrients are removed to a lesser degree than in CAS or other aerobic processes, due both to the lower stoichiometric C:N:P ratio in anaerobic biomass, and lower biomass production. Although this may require corrective actions under current discharge regulations, it may set optimal conditions in the case of agricultural fertigation reuse of effluents, with substantial benefits to local and global sustainability in terms of water resources availability and nutrient cycle optimization [48].

The production and exploitation of wastewater-generated biogas should be regarded as an important tassel capable of closing the WEF in a modern bioeconomy's wastewater cycle, capable of opening new developments. Methane in biogas could be directly used as a fuel or reformed to hydrogen by various processes [49], and CO₂, which is also contained in biogas, could also be converted to bio-oil by new biorefinery technologies being developed [50]. In addition to energy savings and recovery, UASBs reduce the amount of excess sludge generated in WWTPs' water line, reducing its disposal costs; however, the biostabilized sludge can also be exploited in the CE cycle by being further transformed into usable resources, such as soil-fertilizing or enrichment products [51,52] or biofuels [25,53].

5. Conclusions

A UASB reactor was operated for 30 weeks at a set temperature of 25 °C under different operating conditions. Although nowhere near to the ideal optimum for mesophilic anaerobic biomass, the UASB process worked regularly, with overall acceptable organic conversion rate. In particular, methanogenic activity converted an average 30% of the influent COD load into methane, this being a typical value of bioconversion for this type of reactors, even in more ideal conditions. Solids and biodegradable organic matter removal were highly influenced by the presence of transient peaks, representing TSS losses from the reactor, which considerably reduced solids removal efficiency. In order to comply with EU-wide discharge regulations, such a UASB system would generally need to be supplemented by a post-treatment system. In order to improve overall wastewater efficiency, UASB and CAS units (as pre- and post-treatment) may be combined in existing facilities as an integrated setup with the perspective of positive operative returns. This approach could bring substantial benefits (quantifiable on a case-by-case basis) and improved sustainability to WWTPs' management, especially considering the second-order impacts on local circular economy and WEF nexus.

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