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Planar Mixing Tool for Enhanced Performance of Covered Anaerobic Pond Systems

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Abstract Pond systems are the simplest and most widespread technology for the treatment of high-strength wastewater containing biodegradable suspended solids. When covered, they offer significant advantages such as odour control, intensification of the decomposition process, and the potential to capture methane as a bioenergy fuel. However, process performance is challenged by occurrence of unmixed (dead) zones, as well as the formation of floating and sinking layers lowering residence times, degradation rates, and biogas yields. Here we aimed at the integration of a novel mixing concept for covered anaerobic pond systems to overcome these problems. A lab-scale pond (V = 330 L) was manufactured from transparent PVC. The effect of the substrate's apparent viscosity (1, 100 and 1,000 mPa s; at 1 s^{-1}), hoist speed (6 and 12 cm/s) and three alternative mixing tool designs on the mixing process was evaluated in dye and conductivity tracer experiments. Results show that mixing time strongly increases with increasing substrate viscosity and could be reduced (factor 4) by doubling the hoist speed of the mixing system. The design of the mixing tool largely affects the flow conditions and needs to be adjusted to the viscosity of the substrate. **Keywords:** Biogas, mixing, wastewater, anaerobic digestion

1. Introduction

Anaerobic pond systems (APS) are the simplest and most widespread applied technologies for the treatment and storage of agricultural and industrial wastewaters, worldwide. Typical waste streams comprise domestic wastewater, piggery, dairy manure, and a diversity of (agro-)industrial process wastewaters (Ewing et al. 2014; Mccabe et al. 2013). APS are particularly effective in treating high-strength wastewaters containing biodegradable dissolved organics and total suspended solids (Rajbhandari and Annachhatre 2004). Thus, APS serve the dual purpose of sedimentation of particulate matter as well as of anaerobic conversion of organics. Due to the latter, APS may release considerable amounts of greenhouse gases (GHGs) and there is great potential for energy recovery (Park and Craggs 2007). In recent years considerable progress has been made towards the use of covered APS, which offer significant advantages such as odor control, intensification of the decomposition process and BOD removal, an increase in feed rate and the reduction in GHGs (McCabe et al. 2014). Several researchers successfully applied covered APS for the treatment of red meat, dairy, and piggery wastewater (Schmidt et al. 2018; Park and Craggs 2007). One major challenge for the process performance is related to formation of floating and sinking layers, which hamper treatment efficiency and gas release (Harris and McCabe 2020; Mccabe et al. 2013). In addition, design criteria for APS are poorly defined and are mainly experience-based (McCabe et al. 2014). Several investigations focused on process optimization of APS in terms of biogas recovery, mixing, pond geometry, in and outlet design (Park and Craggs 2007; Harris and McCabe 2020; Coggins et al. 2018) and suggested that efficiency may be improved by enhancing mixing within the pond volume (Peña et al. 2000). However, to the best of our knowledge, there are no systematic studies regarding the possible improvements on APS performance by mechanical mixing.

Here we aimed at the integration of a novel mixing tool for covered APS to overcome problems related especially to the formation of floating and sinking layers. Dye and conductivity tracer experiments were performed in a lab-scale pond to evaluate the effect of digestate viscosity, mixing tool design, and hoist speed on the mixing time. The mixing tool design (MTD) was also considered in terms of the resulting tractive force by tensile tests and operation conditions.

2. Material and Methods

2.1. Model substrate

Input substrates for APS cover a wide range of total solids content (1 – 20 wt.%, Chen 1986). Most substrates and digestates have been described as non-Newtonian fluids with a shear-thinning behavior (Mbaye et al. 2014;

Annas et al. 2018). In our experiments, we used Xanthan gum (Cosphaderm® X 34) to establish distinct viscosities of model substrates. Xanthan solution are non-Newtonian and highly pseudoplastic (Katzbauer 1998). Model substrates (250 L) were prepared as follows: Xanthan gum (0, 0.15 and 0.43 g/L) was dissolved in tap water by mechanical agitation. Subsequently, the xanthan gum solution (XGS) was pumped in circuit for homogenization and was finally transferred into the pond. The amount was verified by weighing. Tracer solutions were prepared by adding sodium chloride to the XGS to increase the electrical conductivity relative to the background value. To compensate the concomitant increase in density due to the salt addition, 25 % of the water in the XGS was replaced by ethanol. In addition to the salt tracer, different dye tracers (Patent Blue V, Merck and Rose Bengal, Sigma Aldrich) were added to visualize the mixing process. All model substrates (XGS and tracer/XGS mixtures) where rheologically characterized using a stress-controlled rheometer (Thermo Haake RS300) equipped with wide gap coaxial cylinders.

2.1. Experimental setup

To study the mixing process, a pilot-scale pond (V_{total} = 0.33 m^3) was manufactured from transparent PVC (see Fig. 1). The transverse back and forth motion of the mixing tool through the pond was achieved by a rail guide system fixed above the pond. The mixing tool was attached to a wire rope hoist which was driven by an electric motor. The hoist speed could be continuously adjusted by a potentiometer. To evaluate the mixing process 7 conductivity cells (DuraProbe 4-Electrode, Thermo Scientific) were placed at different positions in the pond (see Fig. 1) the electrical conductivity (EC) was logged in intervals of 5 or 15 seconds, depending on the experimental duration, with two benchtop meters (Versa Star Pro, Thermo Scientific).

2.1. Experiment design

Mixing experiments were conducted for each mixing tool design at two hoist speeds and with three substrate viscosities as indicated in Table 1. All runs were performed at a filling volume of 250 L (80 % of Vtotal). Tracer solutions (1 % of Vtotal) were injected at the front side of the pond as indicated in Figure 1. To avoid longitudinal spreading of the tracer a shielding plate was attached lengthwise to the pond. After tracer addition the mixing tool was continuously moved back and forth until complete mixing was achieved. Complete mixing was defined as the state where the normalized EC measured by each of the 7 cells was within a range of >0.9 to <1.1. The normalized EC was independently determined by mixing the model substrate and tracer solution in a beaker at the same ratio as used in the experiments. All experiments were conducted at room temperature (20 ± 3 °C). Hoist speeds of 0.06 m/s and 0.12 m/s were tested. These are comparable to slowly running paddle agitators which require up to 70 % less energy than fast running agitators (Lemmer et al. 2013).

Table 1. Overview of the experimental conditions (hoist speed: L = 0.06 m/s and H = 0.12 m/s; XGS = Xanthan Gum solution). For the mixing tool design please refer to Figure 1.

Indication	Mixing tool design	Hoist speed	Model substrate
1.L/H.H_2O	1	L / H	Water
1.L/H.XGS-1	1	L / H	XGS-1
1.L/H.XGS-2	1	L / H	XGS-2
2.L/H.H_2O	2	L / H	Water
2.L/H.XGS-1	2	L / H	XGS-1
2.L/H.XGS-2	2	L / H	XGS-2
3.L/H.H_2O	3	L / H	Water
3.L/H.XGS-1	3	L / H	XGS-1
3.L/H.XGS-2	3	L / H	XGS-2

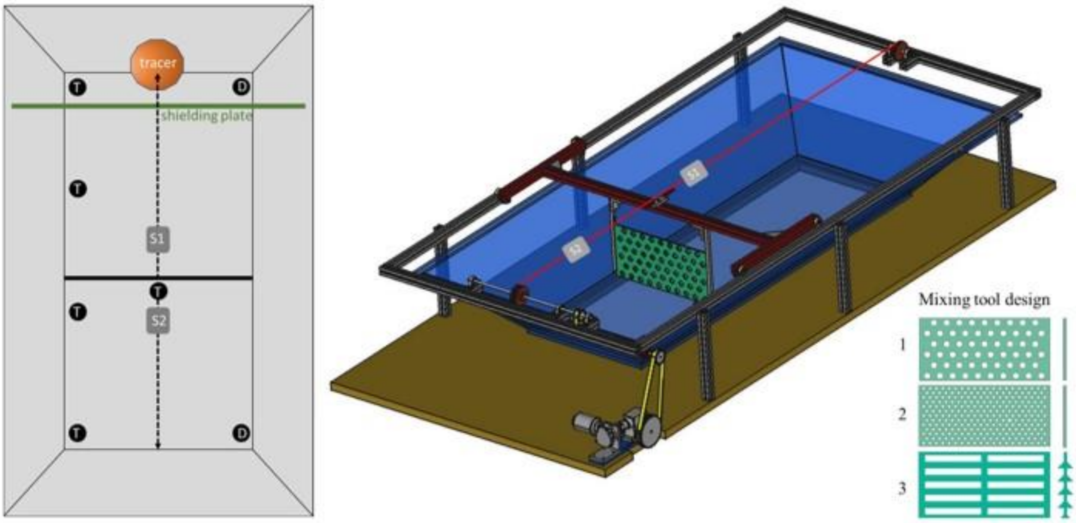

Figure 1. Schematic of the lab-scale pond. Left: top view indicating the position of the tracer addition, shielding plate and EC cells (T: Top position, D: Deep position); middle: schematic of the experimental setup indicating the position of the load dose sensors (S1 and S2); right: front and side view of the mixing tool 1-3.

2.2. Tensile tests

The force necessary to pull the mixing tool through the pond was evaluated in tensile tests with each of the three mixing tools. Therefore, two load dose sensors (racelogic PSD-S1) were attached to the wire rope hoist in front and behind the mixing tool (see Fig. 1). For each configuration (Table 1), the pull force was recorded. The pull force was also measured with a blank hoist without mixing tool to correct the measurements for the base load related to the drive unit and system inherent friction (Figure 2). From each hoist interval, a period of constant pulling force was selected for further analysis (see indicated field in Fig. 2). This was done to eliminate inaccuracies and fluctuations in the pulling force, caused by the acceleration and deceleration. The length of each time period was selected depending on the hoist speed.

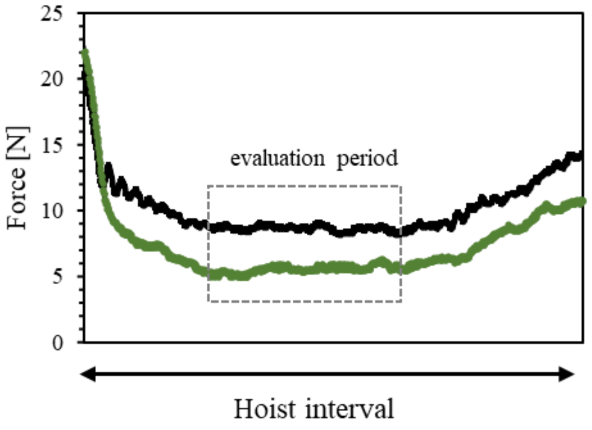

Figure 2. Exemplary course of the tensile tests.

3. Results and Discussion

Figure 3a-c shows the course of the normalized EC as the mean of all 7 cells for a selected set of experiments. Substrate viscosity had a considerable effect on the mixing time as can be seen in Figure 3a. The mixing time increased with increasing substrate viscosity from 5 minutes (water) to 77 minutes (XGS-1) and 884 minutes (XGS-2). Furthermore, for the XGS-2 a more complex mixing course was observed (oscillating characteristic). The effect of the hoist speed was less significant and resulted in similar mixing characteristics. Mixing time decreased from 77 minutes to 18 minutes (factor 4) by doubling the hoist speed.

The mixing times observed for the different MTDs fall into two categories: 71 and 77 minutes for MTD 2 and MTD 1, respectively and 194 minutes for MTD 3. In the latter the openings were designed as oblong holes while in the former the same opening area was provided by round holes. The opening geometry strongly impacted the flow pattern. Particularly the smaller hole size of MTD 2 induced a flow around the mixing tool while hampering a flow through the holes. This resulted in a longer mixing time compared to MTD 1.

The tensile tests showed a strong variation in the pull force for the different mixing tool designs. Selected results of experiments with water XGS-2 are shown in Fig. 4. In case of a pure water the highest pull force was measured round 20 mm openings (MTD 1) and the lowest with the oblong holes (MTD 3). The effect of the velocity was most striking as indicated by a strong decrease in pulling force with decreasing velocity. These findings are of relevance in view of energy demand. For the high viscosity substrate (XGS-2) an almost identical pattern was observed for the different mixing tool designs. Surprisingly, the pull force decreased for mixing tool design 1 (20 mm holes), while for the other designs a slight increase was observed. One possible reason for this discrepancy is the occurrence of counterflows within the pond as a result of the specific flow pattern caused by each mixing tool. Formation of counterflow may have been inhibited for higher viscosities.

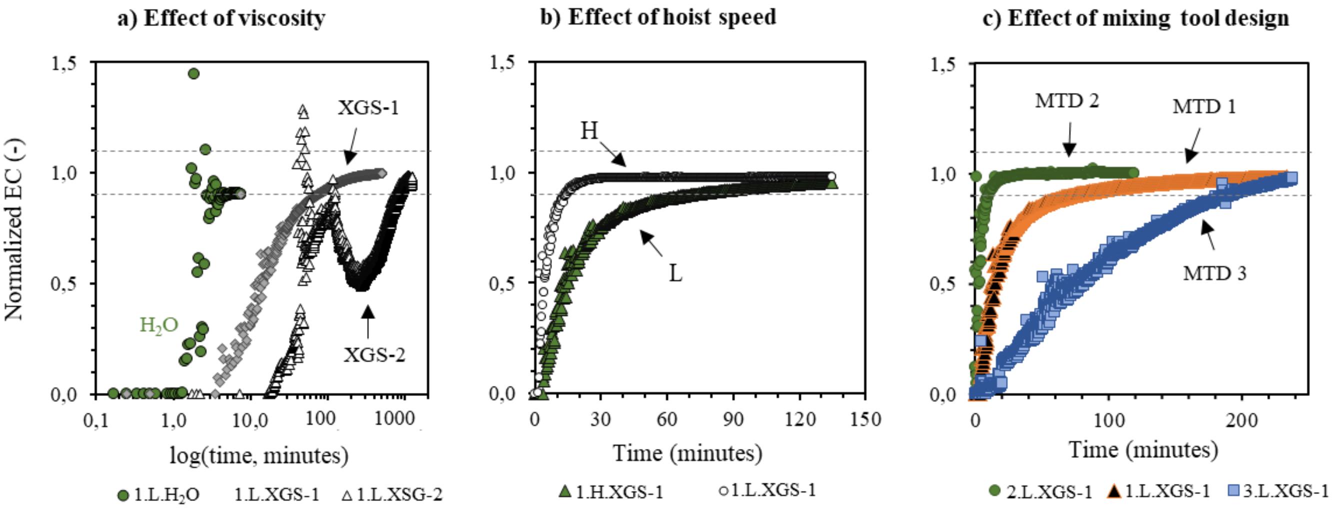

Figure 3. Comparison of selected mixing experiments for a) three substrate viscosities, b) two hoist speeds (H: 0.12 m/s and L 0.06 m/s) and c) mixing tool designs (1-3, see Figure 1).

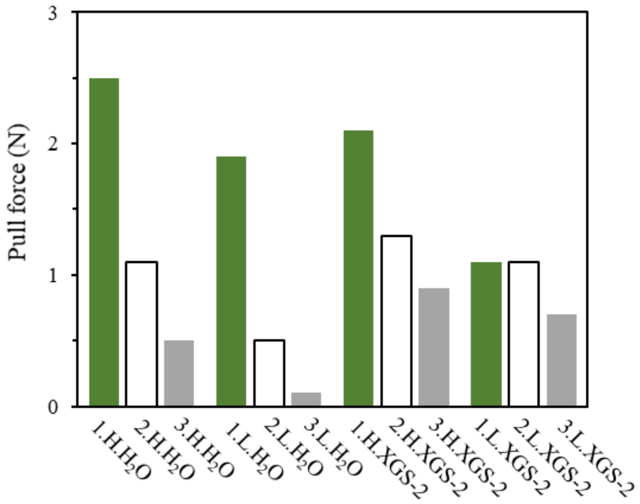

Figure 4. Tensile test results.

4. Conclusion

Results of the mixing experiments and the tensile tests indicate that low mixing times favored by mixing tools with a higher pull force requirement. In high viscosity substrates mixing times increase and the influence of the mixing tool on the mixing time as well as on the required pull force is lessened.

Mixing tool 3 (oblong openings) was selected for further experiments. It represents a compromise between mixing time and energy demand. In addition, larger openings are less prone to clogging thereby favoring continuous operation of the system. Future work with the current system will focus on performance tests with real food-waste substrates in terms of biogas yield and scale-up issues.

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