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Short Communication

Novel system configuration with activated sludge like-geometry to develop aerobic granular biomass under continuous flow

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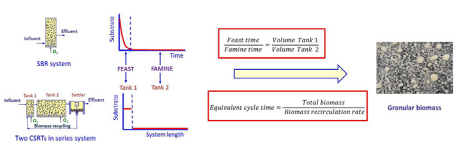
GRAPHICAL ABSTRACT



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ABSTRACT

A novel continuous flow system with “flat geometry” composed by two completely mixed aerobic tanks in series and a settler was used to promote the formation of aerobic granular sludge. Making similarities of this system with a typical sequencing batch reactor (SBR), for aerobic granules cultivation, the value of the tank 1/tank 2 vol ratio and the biomass recirculation rate would correspond with the feast/famine length ratio and the length of the operational cycle, respectively, while the settler upflow liquid velocity imposed would be related to the settling time. From the three experiments performed the best results were obtained when the tank 1/tank 2 vol ratio was of 0.28, the sludge recycling ratio of 0.25 and the settler upflow velocity of 2.5 m/h. At these conditions the aggregates had settling velocities between 29 and 113 m/h, sludge volume index at 10 min (SVI_{10}) of 70 mL/g TSS and diameters between 1.0 and 5.0 mm.

1. Introduction

In the last years, research focused on obtaining stable aerobic granular sludge under continuous flow conditions is gaining attention. This is due to the fact that existing wastewater treatment plants operate normally in continuous mode and as a consequence upgrades based on aerobic granular biomass are easily applicable if they are developed in continuous systems too (Sarma and Tay, 2018). Most of the attempts carried out to develop granular biomass or maintain its stability under a continuous flow regime were done using airlift reactors or columns type reactors (Kent et al., 2018). At laboratory scale these reactors are characterized by a height to diameter ratio (H/D) greater than 6–8, which helps to maximize the hydraulic shear forces. Nevertheless, until now, only few studies have reported on the achievement of aerobic granulation using systems with “flat geometries” (H/D ≤ 1), similar to those of conventional activated sludge systems (Morales et al., 2012; Devlin and Oleszkiewicz, 2018).

Already, “accidental granulation” has been reported in continuous flow activated sludge systems but the operational conditions which promote granulation phenomena are still unknown (Bruce et al., 2014). As a first step to understand accidental granulation, a recent survey was conducted in North America, to help to identify full-scale facilities

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achieving very low sludge volume index (SVI) values, which may indicate the presence of granular biomass or the potential for granulation (Martin et al., 2016).

An interesting system to maintain granular sludge with continuous flow was proposed by Li et al. (2016). These authors used a two reactors configuration (anaerobic/aerobic) to keep granular sludge for biological phosphorus removal. However, they used as inoculum already formed granules and the granulation process was not studied from the beginning. Furthermore, as these authors stated, the granules stability for biological phosphorus removal is easier to maintain than for the traditional aerobic granular sludge comprising organic matter removal.

Based on these observations, the aim of the present research work is to define a novel reactor configuration with two serial tanks to promote aerobic granulation, from conventional activated sludge, using a continuous flow system with "flat geometry" for organic matter removal.

2. Materials and methods

2.1. System description and operational conditions

In order to obtain the formation of aerobic granular sludge a continuous flow system composed of two completely stirred tanks in series, with an overall height/width/length ratio of 1/0.8/1, was used (Fig. 1). The purpose of the first tank (tank 1, useful volume of 0.6 L) was to allow the contact between biomass and substrate during a short period of time to promote its conversion into intracellular storage compounds (feast period) while, in the second tank (tank 2), substrate concentration should be almost zero (famine period). Therefore, the tank 1/tank 2 vol ratio served to determine the feast/famine ratio of the configuration proposed (Eq. (1)). This ratio was changed during the experiment to achieve a suitable feast/famine length ratio by changing the useful volume of tank 2 from 4.0 to 2.1 L (Table 1). To retain the biomass, a settler operated at an upflow liquid velocity higher than 1 m/h (values assayed 1.4 and 2.5 m/h) was used to carry out the wash-out of biomass that did not have suitable sedimentation properties. The settled biomass was recirculated to the first tank by means of a peristaltic pump with a large diameter tubing to minimize the possible disintegration of the granules. This peristaltic pump was activated 15 min each hour and the biomass recycling ratio was of 0.25. The passage of the biomass present in tank 1 to the tank 2 occurred only during the periods in which the recirculation pump was activated, due to the increase in the flowrate that tank 1 receives. In this way, the recycling rate of biomass serves to control the time it takes for the total biomass to suffer an alternation between conditions of feast and famine and an equivalent cycle time can be determined according to Eq. (2).

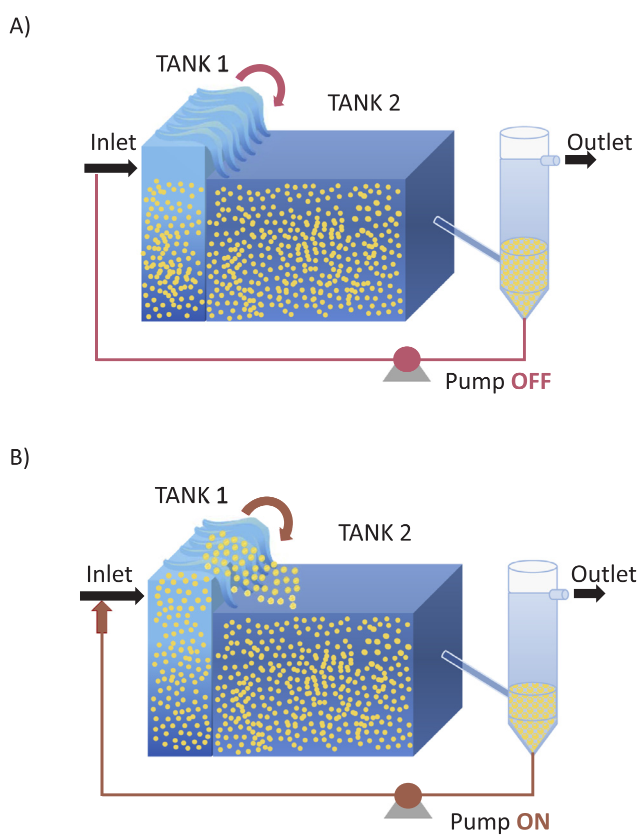

Fig. 1. Schematic system performance: A) recirculation pump stopped: biomass does not pass from tank 1 to tank 2, only liquid does; B) recirculation pump in operation: biomass passes from tank 1 to tank 2.

Table 1
Operational conditions and configurations of the system during the different stages of the experiment.

	Stage I	Stage II	Stage III
Operational period (d)	60	40	30
Tank 1/tank 2 vol ratio (-)	0.15	0.15	0.28
HRT of the whole system (h)	6.5	6.5	3.8
OLR of the whole system (g COD/(L·d))	2.2	2.2	4.4
Tank 1 conditions*	Anoxic	Aerobic	Aerobic
Upflow velocity in the settler (m/h)	1.4	1.4	2.5
Equivalent cycle time (h)	11.9	11.9	4.5

* Tank 1 was mixed by a mechanical stirrer when operated under anoxic conditions.

$$\frac{\text{Volumetank1}}{\text{Volumetank2}} = \frac{\text{Feasttime}}{\text{Faminetime}} \quad (1)$$

$$\text{Equivalentcycletime(h)} = \frac{\text{Totalbiomass(gVSS)}}{\text{Biomassrecirculationrate(gVSS/h)}} \quad (2)$$

2.2. Feeding composition

The system was fed with a synthetic medium simulating the composition of domestic wastewater containing 0.55–0.65 g COD/L (Jungles et al., 2011). The experiments were divided in three stages according to the different conditions assayed (Table 1). At the beginning of each operational stage, the system was inoculated with floccculent biomass taken from the municipal wastewater treatment plant of Curacaví (Chile) characterized by a sludge volume index at 30 min (SVI_{30}) of 200 mL/g TSS. The system operated at 20 °C and without pH control (pH value was between 8.1 and 8.3). The dissolved oxygen concentration in the aerobic tanks was around 7.8 mg O_2/L during the operational period.

(Table 1)

2.3. Analytical methods

The pH value, the dissolved oxygen, nitrate, nitrite, ammonium and Total Suspended Solids (TSS) concentrations, and the SVI at 30 (SVI_{30}) and 10 min (SVI_{10}) were determined according to the Standard Methods (APHA-AWWA-WPCF, 2005). The concentration of soluble chemical oxygen demand (COD_S) was determined by a semi-micro method from the sample filtered through 0.45 µm pore size filters (Soto et al., 1989). The size distribution of the granules was measured regularly by using an Image Analysis procedure (Tijhuis et al., 1994) with a stereo-microscope (EZ24 HD, Leica). The settling velocity of granules was calculated in a 40 cm long column.

Table 2
Main operational results obtained throughout the different stages of the experiment.

	Stage I	Stage II	Stage III
Organic matter removal efficiency of Tank 1 (%)	36	70	80
Overall organic matter removal efficiency (%)	85	93	95
Overall biomass concentration (g VSS/L)	0.26	0.43	2.05
Overall F/M ratio (g COD/(g VSSd))	8.3	5.1	2.1
Solids in the effluent (g TSS/L)	0.19	0.16	0.14
Diameter of the biomass particles (mm)	0.8–3.0	0.5–10.0	1.0–5.0
SVI_{10} (mL/g TSS)	n.d.	110	70
SRT (d)	0.4	0.8	2.7
Biomass yield coefficient (g VSS/g $COD_{consumed}$)	0.33	0.29	0.24

n.d.: not determined.

3. Results and discussion

3.1. Configuration change from anoxic/aerobic (Stage I) to aerobic/aerobic (Stage II)

During Stages I and II the tank 1/tank 2 vol ratio was of 0.15 and the upflow velocity imposed in the settler of 1.4 m/h. In the first stage the tank 1 was operated under anoxic conditions and although filamentous biomass and small flocs were predominant, on day 56, some granule-like particles appeared. As the organic matter removal efficiency in tank 1 was low (around 36%) and the most part was removed in the tank 2, the feast/famine regime being not fulfilled.

Therefore, in Stage II the tank 1 mode was changed to aerobic conditions (Table 2). In this way, its organic matter removal efficiency increased up to 70%, achieving the approximation to a feast period in tank 1. On day 10 of Stage II, the formation of granule-like particles was observed but, in few days, these particles were covered by filamentous biomass. Later, on 29 day of Stage II, rounded aggregates, whose surface was still covered with filaments, started to predominate. However, these aggregates were unstable and broke within a week of their formation. During the rest of Stage II several episodes of formation and break-up of this type of aggregates were observed. The appearance of filaments on the surface of the aggregates and their break-up would indicate substrate limitation conditions (Mosquera-Corral et al., 2005). Since dissolved oxygen concentration in both tanks was around 7.8 mg O_2/L, the possible substrate limitation could be attributed to the low presence of organic matter.

3.2. Optimization of the feast/famine ratio and settling velocity

In Stage III, to avoid the substrate limitation, the volume of the second tank was reduced in order to decrease the period where biomass was exposed to a very low organic matter concentration (famine) and, therefore, to achieve a proper feast/famine balance (Corsino et al., 2017). Furthermore, the imposed upflow liquid velocity in the settler was increased from 1.4 to 2.5 m/h. Under these operating conditions, the formation of aggregates with settling velocities between 29 and 113 m/h, SVI_{10} of 70 mL/g TSS and diameters between 1.0 and 5.0 mm was observed. The formation of the aggregates was associated with the appearance of translucent structures (similar to alginate spheres) that turned compact over the time of operation. These aggregates, contrary to those formed during Stage II, maintained their integrity during the entire period of operation.

3.3. Organic matter and nitrogen removal

In terms of COD removal the system performed better in Stage III when the treated OLR was up to 4.4 g COD/(L·d) with an overall removal efficiency of 95% (Table 2). In the three stages, the ammonia removal efficiency was between 15 and 30%. This removal can be totally attributed to biomass assimilation since nitrification did not take place (nitrite or nitrate was never detected) due to the low sludge retention time (SRT) achieved (between 0.4 and 2.7 days, Table 2). These low SRT values are attributed to the washout in the effluent of small granules, embedded in the fraction of flocculent and/or filamentous biomass, that presented unsuitable settling velocities to be retained inside the system. Although, this washout diminished from Stage I to Stage III, decreasing the solids concentration in the effluent and increasing the SRT values (Table 2). As it was observed, short SRT values limit nitrogen removal efficiency but have not a negative effect on the granulation process (Li et al., 2008). In fact, if the purpose of the system is only to remove organic matter, the results obtained in Stage III indicate that could be possible to operate at SRT of approximately 3 days, obtaining aggregates with acceptable settling properties, to maximize the production of highly biodegradable sludge and, therefore, the subsequent methane generation (Ge et al., 2017).

3.4. Drivers for granulation with the configuration proposed

Generally, aerobic granules obtained in continuous flow systems with "tall geometry" have lower SVI (23–60 mL/g TSS) and diameters ($<$ 2 mm) (Kent et al., 2018) than the aggregates obtained in Stage III. This fact can be probably to the higher shear forces obtained in this kind of systems. In spite of the influence of shear forces on the physical properties of the granules, high shear forces are no always essential for granulation under continuous flow (Devlin et al., 2017) and other type of strategies can be considered, as it can be in the case of the settling velocity-based selection pressure (Zou et al., 2018) and/or the application of alternating feast/famine conditions (Kent et al., 2018).

The strategies used in the proposed reactor configuration with continuous flow to achieve the granulation can be correlated to those of SBRs. First, the tank 1/tank 2 vol ratio corresponds to the feast/famine length ratio typical in SBRs. Second, the recirculation rate of biomass serves to control the time it takes for the total biomass to be exposed to alternating feast/famine conditions, which equals the duration of a cycle of operation in a SBR. Third, the imposed upflow liquid velocity in the settler served to set the settling time like in a SBR.

Other factor that affects the physical properties of granules is the food to microorganisms (F/M) ratio applied. Wu et al. (2018) observed that the SVI_{10} value corresponding to aerobic granules cultivated in SBR systems is of 40 mL/g TSS when F/M ratios of 0.4–0.5 g COD/(g VSS·d) are applied, but when the applied F/M ratio is of 0.9 g COD/(g VSS·d) the granules formed have an SVI_{10} value of approximately 72 mL/g TSS, similar to that obtained in this research work (Table 2).

In this way, taking into account the operational conditions imposed during Stage III, the formation of aerobic aggregates with adequate settling velocities (29–113 m/h) and SVI_{10} (70 mL/g TSS) was achieved at a feast/famine length ratio, operational cycle length equivalent, minimum settling velocity and F/M ratio of 0.28, 4.5 h, 2.5 m/h and 1.8, respectively. Therefore, the novel reactor configuration proposed with two tanks in series approximates with success the concepts of continuous flow and development of aerobic granules. However, further research is needed to optimize the operational conditions to decrease the solids concentration in the effluent and to fulfill the effluent disposal requirements.

4. Conclusions

It is possible to form aerobic aggregates (SVI_{10} of 70 mL/g TSS and settling velocities of 29–113 m/h), for organic matter removal in continuous flow systems, operating under hydrodynamic conditions that simulate those obtained in a discontinuous reactor. The novel configuration of the proposed system is very similar to the "flat geometry" of the activated sludge systems usually used, so it would be relatively easy to convert them into aerobic granular systems.

Pictures of biomass morphology evolution along the operating stages can be found in the Appendix A of supplementary data.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.biortech.2018.07.146.

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