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Influence of carrier media physical properties on start-up of moving attached growth systems

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ABSTRACT

Five carrier media with different shapes (spherical and cylindrical), sizes, voidage and protected surface areas (112–610 m^2/m^3) were studied in a pilot scale moving bed biofilm reactor (MBBR). This study aimed at assessing start-up duration using biofilm formation rates. Results indicated that the spherical media required shorter periods to achieve stable biofilm formation rates associated with chemical oxygen demand (COD) (15–17 days), compared to cylindrical high surface area media (23–24 days). Protected surface area presented weaker correlations with the biofilm formation rate for COD (R^2 = 0.83) and ammonia removal (R^2 = 0.76). However, good correlations were observed with a combination of the media physical factors: dimensionality (Di), voidage (Voi), and hydraulic efficiency (HE) strongly correlated with biofilm formation rates for heterotrophic (R^2 = 0.95) and nitrifying bacteria (R^2 = 0.92). This study proposes that the media physical properties can contribute to shortening start-up, contributing to improved removal rates and fast commissioning of MBBRs.

1. Introduction

The need to meet increasingly stringent discharge limits has made biofilm processes popular for the removal of organic pollutants and nitrogen in wastewater treatment plants (WWTPs) (Barwal and Chaudhary, 2016). Moving bed biofilm systems, such as submerged aerated filters (SAFs) (structured or random packed) (Holloway and Soares, 2018), moving bed biofilm reactor (MBBRs) and integrated fixed film activated sludge (IFAS) use buoyant carrier media as a biofilm growth support material. MBBRs have been established in the past 25 years as robust, versatile and compact solutions and have been successfully implemented in municipal and industrial wastewater treatment (Leyva-Díaz et al., 2013; Ødegaard, 2016).

The initial biofilm adhesion plays a crucial role on attached growth systems (Mao et al., 2017; Tang et al., 2017). Due to the nature of the process the time required to achieve a well-established biofilm can vary considerably from 1 to 6 weeks (Bassin et al., 2016; Dong et al., 2015; Leyva-Díaz et al., 2013; Tang et al., 2016). Start-up duration has been a major drawback on full-scale applications especially in nitrification processes (Lackner et al., 2009) due to the slow growth rate of nitrifiers (Habouzit et al., 2014; Rikmann et al., 2018; Zekker et al., 2016).

Bacterial adhesion to support surfaces has been extensively studied, and physical (size, shape, density, roughness) and chemical properties (surface materials: plastic, foam, woven, ceramic, glass, etc. and chemical modified polymer) have been shown to strongly affect early stages of biofilm formation (Deng et al., 2016; Eldyasti et al., 2012). Biofilm formation occurs after initial cell adhesion to the surface of the carrier media that then leads to bacteria accumulation and extracellular polymeric substances (EPS) production. This helps bacteria bind and form the biofilm (Zhu et al., 2015). However, bacterial adhesion and subsequent biofilm development is a dynamic process that can be affected by external factors such as operating conditions, organic and nutrient loading and hydrodynamics within the reactor (Liu and Tay, 2002; Pellicer-Nàcher and Smets, 2014). The latter plays a critical role during start-up as it controls biofilm detachment caused by shear forces (superficial air velocity) and abrasion (carrier media concentration) (Goel et al., 2011; Mao et al., 2017). To ensure a fast-start up and stable biofilm formation a balance has to be achieved between biofilm growth and detachment processes (Lackner et al., 2009).

To date, there have been limited studies on start-up of moving attached growth systems (Zekker et al., 2012). Most studies identified in the literature are performed at the laboratory scale, and focus on strategies to accelerate the adhesion of the microorganisms, to the carrier reducing the start-up duration. Zhu et al. (2015) fed a 9 L laboratory scale reactor with easy biodegradable substrates (synthetic wastewater) inoculated with activated sludge from a secondary clarifier. The reactor was used to describe different start-up stages in biofilm systems with a cylindrical shape carrier media with a protected surface area of 460 $m^2/$

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m^3 (no information provided about the carrier media material). Stable COD and ammonia removals of 92% and 50% were achieved after 6 and 14 days of start-up respectively (Zhu et al., 2015). The same strategy was used by Bassin et al. (2016) on the start-up using two different carrier media; a cylindrical (high density polyethylene) and chip shaped (virgin polyethylene with additives) media with 500 and 3000 m^2/m^3 at 50 and 8.3% filling ratio. Twenty to thirty days were necessary for a constant attached biofilm to be achieved. Seeding sludge and synthetic wastewater was also used in Mao et al. (2017) where start-up was compared using three high density polyethylene (HDPE) carriers (two modified and one unmodified). Modified material using PQAS-10 polyquaternium-10 and cationic polyacrylamides (CPAM) resulting in 13, 19 and 27 days, respectively. Batch feeding and prolonged hydraulic retention times were adopted as a start-up strategy in Tang et al. (2016) using a round polyethylene ball and start-up was achieved in only 6 days. These studies mainly demonstrate the dynamic nature of the process but also highlight the variation of how start-up is interpreted and defined. Start-up in moving attached growth systems has been described in a multitude of parameters, including: biofilm growth, time to form a fully developed biofilm, biofilm activity and reactor performance (i.e. substrate removal efficiencies) (Bassin et al., 2016; Mao et al., 2017; Tenno et al., 2016; Zekker et al., 2017; Zhu et al., 2015).

Research on moving attached growth system start-up has been limited so far and to date, no studies have investigated the relationships between carrier media physical properties and start-up. The significance of this is emphasised in the importance of start-up towards achieving low commission periods and treatment robustness during steady state (Rikmann et al., 2014; Zekker et al., 2012).

This in turn can lead to improvement of the economic competitiveness of the moving attached growth system technology. Therefore, this study aims to investigate how carrier media physical properties influence process start-up using real wastewater. The expected outcome of this work is intended to provide guidance for design and start-up of a full-scale moving attached growth system plant. Furthermore, the fast biofilm formation rate, can be of benefit for operation conditions modification (increased flow and organic loading) as well as for upgrade of existing wastewater treatment plants contributing to the extended application of moving attached growth systems.

2. Material and methods

2.1. Pilot plant setup and operation conditions

A 2 m^3 rectangular shaped pilot plant divided into three separate aerobic cells of equal volume (1.0 m width × 1.5 m length and 1.30 m height), was designed to study process start-up. Medium bubble aeration was utilised to supply the required aeration and mixing. The pilot was designed to cope with variable air velocities 3.6–18.7 m^3/m^2.h and wastewater flows, ranging from 2.5 to 18 m^3/day. Air and wastewater flows were normalised per protected surface area of media. Wastewater distribution was enhanced by the instalment of two baffles on the cells. The five carrier media with different physical properties investigated were supplied by Warden Biomedia (Table 1). Media 1, 2 and 3 were spherical media with a protected surface area of 112, 149 and 220 m^2/m^3 respectively whilst Media 4 and 5 were cylindrical in shape with a protected surface area of 350 and 610 m^2/m^3 (Table 1). The pilot plant was fed with settled wastewater from Cranfield University wastewater treatment plant (Cranfield, UK) during 2016–2018. Each media was study for 60 days, covering a total of 300 days for the 5 media. The organic and nutrient loading per surface area was kept constant by fixing the media filling ratio at 60%, within the values recommended in literature (McQuarrie and Boltz, 2011), by varying the wastewater flow rate. The pilot-plant was designed to keep stable dissolved oxygen levels by delivering variable air flow velocities (between 3.6 and 18.7 m^3/m^2.h) and variable wastewater flow (between 2.5 and 18.0 m^3/day). The start-up was done with clean media directly transferred to the tank. No foam formation was observed.

2.2. Chemical analysis

The wastewater of the influent and effluent was sampled three times a week during process start-up.

Samples were analysed for total 5-day carbonaceous biochemical oxygen demand (BOD_5) and soluble BOD_5, total and volatile suspended solids (TSS and VSS) according to standard methods (APHA, 2005). Total and soluble chemical oxygen demand (tCOD and sCOD), ammonium-nitrogen (NH_4^+-N), and nitrate-nitrogen (NO_3^--N) were analysed using Merck cell tests kits (Merck KGaA, Darmstadt, Germany) and measured with a NOVA60 photometer (VWR, UK). Temperature, dissolved oxygen (DO) and pH were measured onsite daily using portable meters (HACH HQ40d; Camlab, Cambridge, UK).

Statistical analysis was completed using the software IBM SPSS Statistics 23 and results checked for normality using Shapiro-Wilk tests. ANOVA tests were applied for the normal distributed data. Statistical differences were based on 95% of the confidence level ($p < 0.05$).

Attached growth biofilm on the carriers was analysed two to three times a week following the procedure described in Regmi et al. (2011). Carriers were sampled and dried at 105 °C overnight and weighed. The biofilm was removed by placing the carriers in a H_2SO_4 solution (2N) and stirred vigorously for 24 h. The carriers were washed with tap water then biofilm brushed off and dried at 105 °C. The total attached biofilm was calculated based on the difference in media dry weight before and after removing all biofilm attached. The results were expressed as grams of total solids per metre square of protected surface area of carrier media (g TS/m^2). Carriers were sampled from the three cells of the pilot plant (10 carriers of Media 1, 2 and 3 and 40 carriers of Media 4 and 5).

Protected surface area was defined in this study as the area of carrier covered with biofilm. The protected surface area was calculated for each media. Individual carriers were cut and separated into small pieces and photographed. Comparisons were made between the area covered with biofilm and the area without biofilm attached. All the images were analysed using ImageJ Software and biofilm coverage area determined.

Organic removal performance was evaluated according to Ødegaard (2006). An “obtainable removal rate” was calculated based on 100%

Table 1
Media characteristics used in this study. Media 1 (Biofil), Media 2 (Bioball), Media 3 (Biomarble), Media 4 (Biopipe) and Media 5 (Biotube). Media was supplied by Warden Biomedia (http://www.wardenbiomedia.com).

Media	Total surface (m^2/m^3)	Protected surface area (m^2/m^3)	Shape	Dimensions		Voidage (%)	Material	Density (g/cm^3)
				Length (mm)	Diameter (mm)			
1	135	112	Spherical	65	95	95	Recycled polypropylene (PP)	0.97
2	220	148	Spherical	53	65	92		
3	310	220	Spherical	36	46	90		
4	600	348	Cylindrical	13	21.5	82.5		
5	1000	610	Cylindrical	8	12	80		