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Impact of carrier media on oxygen transfer and wastewater hydrodynamics on a moving attached growth system

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ABSTRACT

This study investigated the impact of five different carrier media on oxygen transfer efficiency and flow mixing in a 2 m^3 moving attached growth system pilot-plant. The five media studied varied in shape (cylindrical and spherical), size, voidage and protected surface area (112-610 m^2/m^3). In clean water tests, the media enhanced the overall oxygen transfer efficiency by 23-45% and hydraulic efficiency (HE) by 41-53%, compared with operation with no media. When using spherical media (Media 1, 2 and 3), the presence of biofilm increased the HE to 89, 93 and 100%, respectively. Conversely, Media 4 and 5 with biofilm contributed to a reduction in HE to 74 and 63%, respectively. The media protected surface area, the parameter traditionally selected to design biofilm processes, did not correlate with HE or with oxygen transfer efficiency in clean water tests. This study provides clear evidence that other media physical properties play a role in the mixing and oxygen transfer in moving attached growth systems. A correlation (R^2) of 0.89 and 0.90 was obtained between the media dimensionality times voidage (Di x Voi) and HE, with and without biofilm development, respectively. The combination of parameters (Di x Voi / HE) also correlated well with oxygen transfer efficiency in clean water (R^2 of 0.92 without biofilm and R^2 of 0.88 with biofilm). Dimensionality and voidage should be utilised to design and optimise media size and shape, to enhance mixing and oxygen transfer, ultimately contributing to energy savings and higher removal efficiencies.

Keywords: Aeration efficiency, carrier media, dimensionality, hydraulic efficiency, voidage.

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1. Introduction

Aeration of secondary processes requires high energy consumption in wastewater treatment plants (WWTPs), which can account for 20-60% of the total energy demand, depending on the plant configuration [1].The energy requirements to operate activated sludge processes (ASPs) are estimated to be in the order of 0.18-0.8 kWh/m^3 in the UK [1], 0.16-0.45 kWh/m^3 in the United States (US), 0.46 kWh/m^3 in Australia, and 0.43-2.07 kWh/m^3 in Japan [2].The increasing cost of energy in the UK, and worldwide, have made ASP less attractive to the water industry. Furthermore, in Europe, the *Urban Wastewater Treatment Directive 91/271/EEC*, is tightening the ammonium-nitrogen (mg NH_4^+-N/L) discharge consent level from 5 mg NH_4^+-N/L to 3 mg NH_4^+-N/L, and in certain sensitive areas down to 1 mg N-NH_4^+/L [3]. In the US, as authorised by the Clean Water Act, the National Pollutant Discharge Elimination System (NPDES) effluent limit for mg NH_4^+-N/L ranges from 0.1 to 1.0 mg NH_4^+-N/L. The energy requirements to treat the wastewater to this level are expected to increase, as the oxygen requirement for nitrification is 4.6 kg O_2/kg mg NH_4^+-N/L [4].

Moving attached growth system, such as submerged aerated filters (SAF) moving bed biofilm reactors (MBBR) and integrated fixed film activated sludge (IFAS), have been increasingly used as cost effective processes and alternatives to ASP, to meet the more-stringent nutrient/ammonia consents [5,6]. Moving attached growth systems make use of buoyant carrier media, which support and allow biofilms to grow promoting high biomass concentrations. The use of carrier media promotes the development of slow growing bacteria such as nitrifiers, preventing wash out and enhancing the nitrification efficiency [7]. The constant movement of the carrier media increases biofilm/bulk liquid oxygen levels and substrate mass transfer, compared with fixed media processes. Moving attached growth systems maximise the loading capacity and efficiency of the conventional biological processes at reduced footprints due to high biomass retention [8]. Sufficient air needs to be provided for the degradation of organic matter, endogenous respiration, nitrification as well as mixing and scouring of the biofilm [8]. In moving attached growth systems, dissolved oxygen (DO) set points are usually high (3-5 mg/L), compared to conventional ASP (1-2 mg/L) [4]. Thus, it is important to optimise aeration efficiency, thereby minimising energy consumption and operational costs, while ensuring good process performance [9].

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Different studies have investigated the impact of plastic carrier media on oxygen transfer efficiency and have demonstrated consistent results on the enhancement of oxygen transfer with different media and filling ratios [10–13]. An increase of 15-32% in standard oxygen transfer efficiency (SOTE) has been described when the media filling ratio was 25% [10], and an increase in SOTE of 50% was observed with a media filling ratio of 50% [11]. A 48-61% enhancement on the volumetric mass transfer coefficient (k_La) was reached using a lab scale reactor filled with 40% of media [12]. Other studies stated a 10% increase with a 50% filling ratio [13]. Results generated indicated that air bubbles were sheared into small bubbles through contact with the carriers, thereby increasing the gas-liquid interfacial area. Carrier media also promoted bubble dispersion increasing bubble retention time within the reactor. Nevertheless, only a small number of studies compared different sizes and shapes of carriers. Two media with ring shape (500 and 650 m^2/m^3 of protected surface area) and a plane surface (1200 m^2/m^3) were studied by Collignon [14]. Results generated indicated that little difference was observed in standard oxygen transfer efficiency (SOTE) using fine bubble aeration with and without media. A more pronounced impact was observed using coarse bubble aeration. With regards to size, shape and density of the media, the ring shape media helped the break-up of coarse bubbles. This in turn increased k_La by 6-22% at a 40% filling ratio and the circular flat shape encouraged bubble coalescence.

The hydraulic characteristics of moving attached growth systems have a significant impact on system performance. Hence, different size and shape carriers can influence flow pathways and hydraulic velocities with an impact on oxygen and substrate mass transfer [15] and biofilm dynamics including growth, thickness and detachment [7]. Little is known about the impact of plastic carrier media on hydraulic flow patterns and mixing conditions. Tracer studies are frequently used to characterise hydraulic profiles and mixing behaviour in reactors. These studies help to identify hydraulic limitations, such as inactive volume (stagnant flow), hydraulic short circuiting and preferential flow paths, channelling [16]. Dead volume or stagnant zones reduce the actual volume available for chemical and biochemical reactions, reducing the treatment capacity [17]. Tracer analyses are also vital in illustrating the influence of aeration in a reactor. Often, well aerated reactors have a maximum use volume for biological treatment [18].

Although there are different studies on the effect of plastic carriers on oxygen transfer and a few studies on moving attached growth systems hydrodynamics,

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physical media properties appear to have been overlooked. To the best of the authors' knowledge, no studies have correlated media physical properties with oxygen transfer and moving attached growth systems hydrodynamics. Therefore, in this study, five media with different physical properties (surface area, voidage, shape and size) were used to study their impact on reactor hydrodynamics and oxygen transfer efficiency in a moving attached growth systems pilot plant. The study was performed with and without biofilm, from which correlations between physical properties of the media and hydrodynamic and oxygen transfer parameters were obtained.

2. Material and methods

2.1. Experimental setup

The experimental tests were conducted at Cranfield University WWTP (Cranfield, UK), treating 600 m^3/day of municipal wastewater. The pilot plant consisted of a reactor divided into three aerobic cells of equal volume with a total volume of 2 m^3 (1.0 m width x 1.5 m length and 1.30 m height) (Fig. 1). The wastewater was introduced at the bottom of the tank and exited at the top, with narrow vertical baffles included to improve wastewater distribution to all of the cells. The media was retained within each cell by flat perforated sieves with 6 mm openings. A medium bubble aeration grid made of a 25 mm diameter PVC pipe drilled with 4 mm diameter holes, was fitted into each section of the tank. Air distribution was adjusted and controlled using three individual air flow rotameters installed in each of the cells and flow regulated by valves. Three recycled polypropylene spherical shape carrier media (Media 1, 2 and 3) with a protected surface area of 112, 148, 220 m^2/m^3 and two recycled polypropylene cylindrical shape media (Media 4 and 5) with a protected surface area of 348 and 610 m^2/m^3 were tested (Table 1). Protected surface area for the spherical and cylindrical shape carrier media was defined in this study as the area of carrier covered with biofilm. The five carrier media were provided by Warden Biomedia (Luton, UK). The organic and nutrient loading per surface area was kept constant by fixing the media filling ratio at 60%, within the values recommended in the literature [8]. Influent wastewater characteristics of 285±58 mgO_2/L of COD,112±54 mgO_2/L of BOD and of 42±4 mg NH_4^+-N/L ammonium-nitrogen at loading rates were 6.1±0.2 g COD/m^2.day, 3.0±0.4 g BOD/m^2.d and 0.6±0.1 g NH_4^+-N/m^2.day were fed to the reactor. The pilot-plant was designed to deliver variable air

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flow velocities (between 3.6-18.7 $m^3/m^2.h$) and variable wastewater flow (between 2.5-18.0 m^3/day).

2.2. Tracer studies

Tracer studies were performed using Rhodamine (Rhodamine WT 20%; Fisher Scientific, Loughborough, UK). The tracer was injected in the reactor by the "pulse input technique" as described by Levenspiel [19]. A volume of 5 ml of Rhodamine was injected instantaneously into the inlet of the reactor. The Rhodamine concentration was then monitored in the effluent using a submersible fluorometer (Cyclops-7; RS Aqua Ltd, Hampshire, UK) and data collected was recorded on a data logger (Databank Handheld Dataloggers; RS Aqua Ltd, Hampshire, UK). Measurements were taken every 30 seconds over a period equivalent to 3 to 4 hydraulic retention time (HRT) to ensure 100% of tracer recovery. A first set of tests was completed without media, with and without aeration and a second set of tests included media with and without aeration at a wastewater flow of 4 and 9 m^3/day and two air flow velocities of 2.2 and 9 $m^3/m^2.h$ (a total of 72 tracer studies). All tests were carried out in triplicate.

2.2.1. Determination of the residence time distribution (RTD) curves

Residence time distribution function ($E(t)$) curves were obtained from the tracer concentrations measured at the outlet of the reactor ($C(ti)$) as function of time (t_i) and calculated using Eq. (1) as described by Levenspiel [19].

Based on the $E(t)$, the average time that the tracer remained in the reactor (mean residence time - t_m), and the distribution variance ($\boldsymbol{\sigma}^2$) were calculated using Eq. (2) and Eq. (3). To allow for a comparison between RTD profiles, tracer concentration $E(\theta)$ and time (θ) were normalised, where θ is the ratio between HRT and t_i. An analytical dispersion model was used to represent non-ideal flows (between Plug Flow and Mixed Flow) as described by Levenspiel [19]. Dispersion number $(\boldsymbol{\delta} = D/uL)$ and variance ($\boldsymbol{\sigma_\theta}^2$) were calculated based on iterative calculations and used as mixing indicators, where D is the axial dispersion coefficient (m^2/s), L is the axial distance of the reactor (m) and u is the velocity (m/s) Eq. (4). Peclet number is the inverse of the dispersion number ($Pe = 1/\boldsymbol{\delta}$).

RTD curves can be interpreted and quantified in different ways. Brannock et al. [20] stated a number of relationships commonly used to evaluate RTD curves, such as dead zones, or short-circuiting flow. Dead zones (V_d) and hydraulic efficiency (HE) were calculated according to Eq. (5) and Eq. (6) [21,22]. Hydraulic efficiency (HE)

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was used to measure the hydraulic behaviour of the reactor (wastewater flow distribution and mixing) and calculated based on the ratio between mean residence time and hydraulic retention time (t_{m}/HRT). The effective volume was calculated based on total volume correction (V_t), considering the HE and bed voidage (Voi) and Eq. (7).

$$E(t) = C(t_i) \Big/ \sum_{0}^{\infty} C(t_i).d(t_i) \tag{1}$$

$$t_m = \sum_{0}^{\infty} t_i C(t_i).\Delta t_i \Big/ \sum_{0}^{\infty} C(t_i).\Delta t_i \tag{2}$$

$$\sigma^2 \cong \sum_{0}^{\infty} (t_i - t_m)^2 C(t_i).\Delta t_i \Big/ \sum_{0}^{\infty} C(t_i).\Delta t_i \tag{3}$$

$$\sigma_\theta^2 = 2(D/uL) - 2(D/uL)^2\left[1 - e^{-uL/D}\right] \tag{4}$$

$$HE\ (\%) = t_m/HRT \tag{5}$$

$$V_d(m^3) = \left(1 - (t_m/HRT)\right) \tag{6}$$

$$V_{effective} = V_t.Voi.HE \tag{7}$$

2.3. Clean water oxygen transfer tests

Oxygen transfer was assessed using the procedure described in the standard methods “Measurement of Oxygen Transfer Capacity in Clean Water” [23]. Batch trials were performed in one of the three reactor cells at three air flow velocities: 2.2, 9.0 and 16.2 m^3/m^2.h. A first set of tests was completed without media, then with media at a 60% filling ratio. The DO concentrations were measured using two DO portable metres (HACH HQ40d; Camlab, Cambridge, UK). The DO probes were placed at two fixed positions in the tank 0.2 m and 0.8 m below the water level. All tests were completed in triplicate to assess reproducibility.

2.3.1. Determination of the oxygen transfer parameters

The data collected for each test was analysed using DO versus time data. The volumetric oxygen mass transfer coefficient (k_La) (1/h), was calculated based on Eq. (8) and Eq. (9), where C_0 is the initial dissolved oxygen concentration, C_t bulk oxygen concentration at time t and C^*_∞ the oxygen saturation concentration (mg/L). All the values collected were adjusted to standard conditions (zero DO, 20 ˚C, and 1 atm)

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[23]. The standard oxygen transfer rate (SOTR, kgO_2/h) and the standard oxygen transfer efficiency (SOTE, %/m) were also determined in Eq. (10) to (13), where W_{O_2} is calculated based on the mass fraction of oxygen into dry air, the flow rate (Q) and ρ air density.

$$ - (C_{\infty}^{*} - C_0).\, e^{(-k_L\, a.(t-t_0))} \qquad (8)$$

$$ - C_0) = K_L\, a_{20}.\, t + ln\,(C_{\infty}^{*} - C_0) \qquad (9)$$

$$.\, C_{20}^{*} \qquad (10)$$

$$K_L\, a_{(T)} = K_L\, a_{20}\, .\, \theta^{T-20} \qquad (11)$$

(12)

$$\frac{SOTR}{{}_{D} \times Q \times 0.299} \qquad (13)$$

Standard aeration efficiency (SAE, kgO_2/kWh) for each media was also calculated based on the power requirements (P_w) from air flow rates (2.2, 9.0 and 16.2 $m^3/m^2.h$) and on compressor efficiency (e=60%), where R is the gas constant for air, P_2 and P_1 absolute inlet and outlet pressure, respectively Eqs. (14) and (15).

$$/29.7\, n.\, e\, [(P_2/P_1)^{0.283} - 1] \qquad (14)$$

$$SAE = SOTR/P_w \qquad (15)$$

2.4. *Oxygen transfer and hydrodynamic behaviour under operational conditions*

To study the effect of biofilm development in the hydrodynamic behaviour, tracer studies were conducted when the operation reached steady state and the biofilm was fully attached to each media. Oxygen transfer efficiency during operation was measured using off-gas techniques according to the ASCE [24]. A plastic cover with two layers was used to cover each cell, a sealed hose was used to collect the off-gas released (gas flow rates were measured using rotameters and DO. Temperature, and COD at inlet and outlet were also measured. A portable gas analyser (Geotech's BIOGAS 5000, Leamington Spa, UK) was used to measure the percentage of O_2 (0-25%) and CO_2 (0-100%) from the off-gas. The oxygen transfer efficiency was

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calculated based on a mass balance between the gas feeding and the off-gas Eq. (16). The operation standard oxygen transfer efficiency (*αSOTE*) was then calculated using Eq. (17), where, *θ* is the temperature correction factor (*θ=1.024*) for wastewater temperature (T_w), *β* beta factor, $C_{s,20}$ concentration of oxygen at 20 degrees (mg/L), DO concentration of dissolved oxygen (mg/L), and $C_{s,T}$ oxygen concentration under operational conditions. The α value was determined by the ratio between *αSOTE* and the clean *SOTE* [24].

$$OTE = (Oxygen\,air, \%) - (Oxygen\ \ off - gas, \%)/(Oxygen\,air, \%) \qquad (16)$$

$$\alpha SOTE = C_{s,20}.\,OTE.\,\theta^{(20-Tw)}/\beta.\,C_{s,T} - DO \qquad (17)$$

3. Results and discussion

3.1. Hydrodynamic behaviour without biofilm growth

Residence time distribution (RTD) curves were investigated in clean media (without biofilm) and wastewater. Hydraulic efficiency (t_m/HRT) was calculated for each condition studied, with and without media (with and without aeration) at a wastewater flow rate of 4 and 9 m^3/day and two air flow velocities of 2.2 and 9 m^3/m^2.h (Table 2).

Differences between HRT and t_m indicated that the reactor deviated from the ideal plug-flow behaviour. The results obtained (with and without media) demonstrated that the hydraulic efficiency was always inferior to 100%. When aeration was off, the mean residence time varied from 3.15-5.85, 3.32-7.51, 3.92-7.66, 3.40-8.07, 3.45-7.61, 3.39-7.43 h, without media and with Media 1, 2, 3, 4 and 5, respectively, for a theoretical value of 5.30-11.80 h. When aeration was on, the mean residence time varied from 3.22-9.00, 4.00-9.51, 4.85-10.07, 4.83-10.09, 3.58-10.23, 3.60-10.94h without media and with Media 1, 2, 3,4 and 5, respectively (Table 2). The mean residence time was always shorter than the theoretical value. These results indicated that the occurrence of hydraulic short circuits or dead zones, reduced the effective volume of the reactor [22].

The average hydraulic efficiency was found to improve by 5-28% when the results obtained were compared for when the aeration was off and in the presence of media. Without media, values of hydraulic efficiency varied from 40-52% compared with 63-64% with Media 1, 66-74% with Media 2, 64-68% with Media 3, 64-65% with Media 4 and 63-64% with Media 5, for the two HRTs studied (Table 2). Once aeration was

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introduced, hydraulic efficiency increased from 25-38% without media compared with 14-25% with Media 1, 19-24% with Media 2, 8-30% with Media 3, 4-27% with Media 4 and 6-32% with Media 5. Other studies also observed the positive effect of aeration and media on hydraulic efficiency. This is because the reactor behaviour tended to be completely mixed due to agitation promoted by the air [16,25]. Morgan-Sagatume and Noyola [25] demonstrated that the presence of media (volcanic scoria media) increased the hydraulic efficiency by 72% when compared with the aerated filter without media. Other studies revealed that the introduction of 100% media filling ratio in a submerged aerated filter, improved the hydraulic efficiency by 48% [16].

Comparing the hydraulic efficiency results statistically, using paired *t* tests, was verified that hydraulic efficiency for Media 1 was statistically different ($p<0.05$) from all the other media. Between Media 2 and 3 and between Media 4 and 5 there was no statistical difference in the hydraulic efficiency results. However, there was a statistical difference between the spherical (1, 2 and 3) and the cylindrical (4 and 5).

Results indicated a decrease of dead zones from 28 to 77% for both air flow rates and with media. In this study, the dead volume percentages varied from 17-26%, 8-20%, 8-26%, 11-32% and 7-37% with Media 1,2, 3, 4 and 5, respectively (Table 2). Aeration has been shown to have a greater impact on mixing. The presence of media and aeration held the tracer for a longer period inside the reactor, reducing dead zones. Similar results were obtained by Morgan-Sagastume and Noyola [25] demonstrating that dead zones were decreased by 53% when aeration and media were used.

Mixing patterns (back-mixing) were analysed based on dispersion number ($D/\mu L$). Tomlinson and Chambers [26] defined a low degree of mixing when $D/\mu L \leq 0.02$ and a large degree of mixing when $D/\mu L \geq 0.2$. For an ideal plug-flow reactor, the dispersion coefficient $D/\mu L = 0$, whereas $D/\mu L = \infty$, is expected in a perfectly mixed reactor. The values of dispersion coefficient (Table 2) varied from 0.16 to 0.25 suggesting a moderate to high degree of mixing. An average Peclet number, the inverse of dispersion number ($1/\boldsymbol{\delta}$), of 5.1±0.4 also confirmed the large degree of dispersion $Pe<5$, as stated by Fogler [27]. The presence of media did not increase the dispersion coefficient values, rather, the same results were verified in the studies by Morgan-Sagastume and Noyola [25]. Back mixing can also be characterised by the value of *N*-CSTR, with an $N \leqslant 3$ indicating higher back mixing [27]. The values varied from 2.11 and 3.53 within the media.

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3.2. Hydrodynamic behaviour under operational conditions (with biofilm growth)

To study the impact of biofilm growth in the hydrodynamic behaviour of the reactor, tracer studies were conducted when heterotrophs and nitrifiers biofilm was formed (Fig 6). Values of mean residence time of 16.90±0.29h, 11.20±0.65h, 8.69±0.29h, 5.25±0.34h and 3.02±0.65h were obtained at operation conditions for Media 1, 2, 3, 4 and 5, respectively (Table 3). The hydraulic efficiency achieved with Media 1 and 2 was 89±2% and 93±5%, respectively. With Media 3 the mean residence time exceeded the theoretical value of 8h, 8.69±0.29h (tracer retention within the biofilm). The same observation was verified in Holloway and Soares, [16], where t_m exceeded by 27-40% the HRT. The presence of biofilm in Media 1, 2 and 3 led to an increase in the residence time, reducing channelling, increasing reactor effective volume and back mixing. Effective volume of 1.34±0.02, 1.33±0.05 and 1.68 ±0.02 m^3 were registered with Media 1, 2 and 3. The same effect was observed in Holloway and Soares [16] where biofilm growth increased tracer retention and back mixing by 33%, at 50% media filling ratio. A 5% increase on tracer retention was also reported by Morgan-Sagastume and Noyola [25]. For Media 4 and 5, the biofilm contributed to a reduction in mean residence time, 5.25±0.34h and 3.02±0.65h compared to theoretical values of 6.8 and 4h. Hydraulic efficiency of 74±1 and 63±2% were registered for Media 4 and 5, respectively, with effective volumes of 1.14±0.02 and 1.10±0.05 m^3 (Table 3). Dispersion coefficient values were very similar within the media value of 0.22; this value was indicative of intermediate to high dispersion. The parameter, N- CSTR, also exhibited similarities within the media, with values of 2.81±0.05 were calculated for Media 1, 2.98±0.01 for Media 2 and 2.78±0.05 for Media 3. Media 4 and 5 shifted the flow behaviour towards a plug flow with values of N-CSTR of 3.0±0.23 for Media 4 and 3.0±0.01 for Media 5 [22].

3.3. Clean water oxygen transfer

The results obtained for k_La for each media are presented in Fig. 2. The results demonstrated that aeration mass transfer in clean water was enhanced by the presence of the media. The k_La values without media varied from 3.07, 9.53 and 15.44 1/h at aeration rates of 2.2, 9.0 and 16.2 $m^3/m^2.h$, respectively. When the media was introduced the k_La increased from 3.97 and 25.57 1/h. The k_La in clean water was significantly different for all the media ($p<0.05$). Media 1 improved k_La from 23-37%, Media 2 from 35-45%, Media 3 from 36-45%, Media 4 from 37-44%

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and Media 5 from 31-36%, when compared with clean water. Comparing the results obtained within the media, statistical analysis using the paired *t* tests was performed and this demonstrated that k_La for Media 1 and 5 were statistically different ($p<0.05$) from Media 2, 3 and 4.

A k_La increase from 21-55% has been reported by different authors that studied the influence of carrier media on aeration [12,14].The presence of carrier media had been shown to influence bubble break-up, decreasing bubble size, increasing gas hold-up and hence the contact time between the gas and liquid. Limited studies have been conducted on the impact of media physical properties on oxygen transfer in moving attached growth systems. Using different packing material properties (size, density and shape), Fujie et al. [28], found that physical properties play an important role in gas-liquid oxygen transfer, by bubble hold up and dispersion. Among the materials studied, smaller material promoted bubble coalescence, reducing k_La, while larger materials increased k_La by bubble hold-up. Three plastic carrier media, two cylindrical and a circular flat shaped, were studied by Collignon [14] using coarse bubble aeration. The results confirmed an improvement in oxygen transfer by 6-22% in the presence of cylindrical media at a 40% filling ratio, whereas the addition of circular flat shaped media affected the k_La negatively. The different reactor designs (water depth), type of dispersed air system, media carrier and filling ratios used, make comparisons between studies challenging [29]. Considering the clean water k_La data in more detail, and comparing against other studies, the values registered in this study were higher. However, when the influence of water depth was considered, the values were lower (15.67 g O_2/m^3.m) than the ones obtained by Collignon [14] 21.18 g O^2/m^3.m . The aeration efficiency (g O_2/m^3 water per meter of submergence) was calculated following Al-Ahmady [30]; considering the air flow velocity and the oxygen transfer capacity of the system (gO_2/m^3.hr). Ødegaard [31] presented values of 10 g O_2/m^3 water per meter of submergence in clean water, 13 and 15 g O_2/m^3.m when a 500 m^2/m^3 media was used at 30 and 50% filling ratio.

The SOTE (%/m) with media at 2.2 m^3/m^2.h ranged from 5.01-6.56 %/m, 3.62-5.56 %/m at 9.0 m/h and 3.02-4.85 %/m at 16.2 m^3/m^2.h (Fig. 2). Lower values were registered by Collignon [14] at a 40% media filling ratio and 17 m^3/m^2.h, 2.27 and 2.41%/m and Pham et al. [10] at a 50% filling ratio registered values of SOTE of 2.6 %/m at an air flow velocity of 9.9 m^3/m^2.h. The values of SOTE obtained were also slightly higher compared to the theoretical design values used in MBBRs with coarse bubble diffusers that are usually around 2.5 to 3.5 %/m [8]. The addition of media

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improved the SOTE (%/m) by 10 to 44%. SOTE enhancement in Collignon [14] was 22% compared to the results achieved without media. In Sander et al. [11] the addition of carrier media increased SOTE from 2.9%/m (without media) to 5.6%/m (at 50% filling ratio) using a coarse bubble aeration.

3.4. Oxygen transfer under operational conditions (with biofilm growth)

To estimate the impact of the media with biofilm on oxygen transfer efficiency (OTE), off gas tests were conducted under steady-state conditions. Values of α factor of 0.80±0.10, 0.59±0.17, 0.63±0.17, 0.62±0.20 and 0.63±0.03 were attained with Media 1, 2, 3, 4 and 5, respectively (Table 3). The α factors obtained were within the typical values for coarse bubble aeration, 0.55 and 0.94 [32] and consistent with an alpha value of 0.63 calculated in Sander et al. [11]. A high variability in α factors was registered during the sampling. This was mainly due to the natural variability of the influent and operation limitations such as reactor depth and operation with no defined DO set point. The αSOTE obtained were 3.98±0.10, 3.65±0.17, 2.83±0.17, 2.72±0.20, and 1.58±0.03%/m for Media 1, 2, 3, 4 and 5, respectively (Table 3). These values are consistent with the ones achieved by Pham et al. [10] of 2.9%/m and α value of 0.6 with plastic carrier media and fine bubble aeration. A SOTE in the range of 3.79 and 3.88 %/m using fine bubble aeration was achieved in a full scale IFAS, with flat shaped carrier media with α values varying from 0.57 up to 0.85 [33]. An αSOTE of 3.72 %/m with medium bubble aeration was also reported by Sander et al. [11], respectively.

The energy efficiency values at operation conditions were 3.65, 2.85, 2.75, 2.28 and 1.7 kg O_2/kWh for Media 1, 2, 3, 4 and 5, respectively. The values were higher than the ones described for coarse bubble 0.6-1.5 kg O_2/kWh in Stenstrom and Rosso [34] and similar to the ones specified by Kappel [33] for an IFAS within 1.5-3.6 kg O_2/kWh using fine bubble aeration. The values of oxygen consumption per cubic metre of wastewater treated ranged from 0.14-0.23 kWh/m^3, the lower range values were registered with Media 5 and the higher value in Media 1. Compared with the literature, the aeration energy consumption registered by Belloir et al. [35] in two oxidation ditches was 0.95 kWh/m^3 and 0.64 kWh/m^3. Values in the order of 0.15-0.7 kWh/m^3 were estimated for ASP in Bodik and Kubaska [2]. An MBBR operated with oxygen had been supplied continuously registered a 0.25 kWh/m^3 [36]. Other studies presented values of 0.17 kWh/m^3 [37].

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3.5. Influence of media physical properties on hydrodynamics and oxygen transfer

3.5.1. Without biofilm growth

The results obtained on hydraulic efficiency (HE) and on oxygen transfer efficiency (SOTE) were correlated with the carrier media protected surface area (Fig. 3). A linear fitting of R^2=0.67 and R^2=0.48 suggested that the protected surface area does not correlate with hydraulic efficiency and SOTE.

Other physical parameters, such as porosity, have been mentioned in the literature as more suitable, compared to the specific surface area, to describe hydraulic behaviour and performance on an upflow biofilter [38]. Others suggested that additional media properties should be considered and not only surface area, such as voidage [39]. Physical properties (length to diameter ratio) were indicated as an influential parameter on the fluidization velocity Zhong et al. [40].

To gain a better understanding, other physical properties of the five media studied were investigated and correlated with HE and SOTE. Parameters such as: diameter, length to diameter ratio (L:D), sphericity, Sauter mean diameter, shape factor and voidage were considered and correlated with HE and on oxygen transfer efficiency (SOTE) (Table S1). Due to the complexity of the media shape (three-dimensional geometry), calculations applied to geometric properties of particles were also used to normalise the carrier media shape. Dimensionality (Di) was calculated based on the work of Jones, [41].

The parameters that fitted the data on HE were a combination of Di and voidage (Voi) (Fig. 4A), giving a strong correlation (R^2) of 0.89. Regarding the results achieved during the oxygen transfer tests in clean media, a strong correlation was attained when comparing SOTE with Di, Voi and hydraulic efficiency (R^2=0.92) (Fig. 4B).

The spherical shape media with high voidage (90-95%) promoted a better use of the reactor effective volume (1.33-1.44 m^3) compared with the cylindrical shape media, with lower voidage (80-82.5%) (reactor effective volume of 0.93-0.96 m^3). The lower voidage (80-82.5%) and the smaller size of the cylindrical media (Ø 21.5 and 12 mm) compared with larger spherical size media (Ø 95,65 and 46 mm) influenced the flow path when the air flow velocity was 2.2 m^3/m^2.h, and this later improved the reactor effective volume by 29%. At higher air flow velocity (9 m^3/m^2.h) the difference between media was not significant, effective volume in spherical media was 5%

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higher than cylindrical media. Increasing aeration velocity from 2.2 to 9 $m^3/m^2.h$ promoted greater turbulence that had a positive effect on the hydraulic efficiency when cylindrical media was used 87±7% compared to 68±1%.

When spherical media were added to the reactor, SOTE improved by 38±10% compared with cylindrical shape media; 16±6%. Large voidage and the shape of Media 1 appeared to break up the bubbles enhancing the SOTE by 27% when compared with no media in the reactor. However, the shearing effect and bubble hold up was insufficient to promote greater oxygen transfer when compared with 44% and 43% enhancement obtained with Media 2 and 3, respectively. Media 2 and 3, on the other hand, promoted higher enhancement in SOTE (43-44%). Once the larger number of media inside the tank was coupled with the smaller voidage they appear to break up the bubbles, retaining them for longer in the tank. When the voidage was smaller with Media 4 and 5, a 20% and 12% enhancement in SOTE was achieved, respectively. The increased number of media and mixing promoted higher collision within the bubbles, hindering the oxygen transfer by aggregating the smaller bubbles into larger bubbles reducing the contact between the gas and the liquid. Dean and Webb [42] demonstrated that a solid fraction up to 0.10 (1-Voi) increased the oxygen transfer, however a further increase in solid hold up, decreased the oxygen transfer due to the bubble coalescing effect. The same negative influence in k_La was observed by Ferreira et al. [43] when a high concentration of solids promoted bubble collision and subsequent coalescence.

3.5.2. *Operational conditions with biofilm growth*

The same data analysis was performed when biofilm was developed in the media. Considering the same combination of parameters, as in clean conditions, dimensionality and voidage. Nevertheless, voidage reduction was considered and calculated based on the biofilm growth (thickness) and total surface area correction. For the spherical media, Alonso et al. [44] and Dumont et al. [45] equations were used. For the cylindrical shape, the equation presented in Goode [46], was used. Thickness values when the biofilm was fully developed were considered. For the spherical media, Media 1, 2 and 3 the thickness was of 426±88, 375±45 and 328±70 µm, respectively. For the cylindrical media, an average biofilm thickness of 449±82 µm for Media 4 and 268±79 µm for Media 5 were measured. Taking into consideration the voidage reduction, hydraulic efficiency was compared with dimensionality and voidage for each media, and a correlation of R^2 =0.90 was obtained (Fig. 5A).

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Due to the media physical structure, the biofilm growth (thickness) in Media 1, 2 and 3 did not significantly impact the media voidage (Fig. 6). However, for Media 4 and 5, the increased biofilm thickness, due to the overgrowth of heterotrophic biofilm in the inner areas led to a reduction in voidage of 6 to 14%, respectively [47]. Biofilm accumulation in the internal parts of Media 4 and 5, reduced the hydraulic diameter for water to flow through, creating preferential flow paths, accelerating short-circuiting due to media clogging, and therefore decreasing hydraulic efficiency by 74±1 and 63±2%, respectively (Fig. 6). It was estimated that voidage could achieve a further 12 and 26% if the biofilm thickness reaches 1000 µm, for example under operation with high organic loads. Thus, affecting substrate and oxygen transport and diffusion within the biofilm, having a significant impact on the overall treatment performance. In this study, the amount of suspended solids were measured in the pilot plant effluent, varied between 100.9±29.5, 75.2±30.4, 74.9±14.3, 124.9±23.1, 120.7±18.8 mg TSS/L during operation with Media 1, 2, 3, 4 and 5, respectively. Values of TSS and VSS in the effluent were within the range stated in the literature (150-250 g SS/m3)[48] (Bassin et al., 2016) therefore their activity was not considered.

Regarding the oxygen transfer, a higher correlation was achieved when comparing the αSOTE with corrected voidage and hydraulic efficiency, R^2 of 0.88 (Fig. 5B). Furthermore, the SOTE correlated well with protected surface area after biofilm growth (R^2= 0.95). The strong correlations between hydraulic efficiency, dimensionality and voidage (R^2= 0.90) presented within this study demonstrate that carrier physical properties do have an impact in the reactor hydraulic regime. The findings support the importance of shape and voidage on the carrier design, which has been neglected in favour of an increase in surface area of media per volume. The conventional cylindrical shaped media, with smaller open voids are more likely to clog as biofilm thickness increases, thereby not allowing efficient contact between the biofilm and wastewater. The poor mixing, associated with channelling and short-circuiting make this media less efficient hydraulically. Similar observations were performed in other studies, where a larger and flat shaped media with small pore spaces were also affected by clogging. This is especially when used at high loading conditions due to high biofilm growth, and despite their high specific surface area [49]. These results are also in line with Show and Tay, [38], where a decrease in media voidage, induced clogging and dead spaces, resulting in lower hydrodynamic and treatment performance. The poor mixing and the slightly negative effect on

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oxygen transfer of large and flat shaped media was also observed by Collignon [14], by decreasing bubble retention time and increasing bubble coalescence. Information obtained from this work is expected to develop into a useful reference for media size and shape optimisation. These will act to improve process performance providing opportunities for capital and operational cost savings, making this process more competitive with alternative technologies.

4. Conclusions

The presence of media and aeration had a positive impact on the reactor effective volume increasing hydraulic efficiency (HE) by 41-53%, compared with no media, holding the tracer for longer period inside the reactor, and reducing the amount of short-circuiting and dead zones. The presence of media had improved aeration performance in comparison to results achieved without media. In clean water tests, the media enhanced the overall oxygen transfer efficiency by 23-45%. The biofilm developed on the carrier media increased HE when spherical media (Media 1, 2 and 3) was used by 89±3, 93±5 and 100%, respectively. For Media 4 and 5, the biofilm contributed to a reduction in HE, with values of 74±1 and 63±2%, respectively. Physical properties, dimensionality and voidage were highly correlated with HE without and with biofilm (R^2 0.89 and 0.90), in comparison to protected surface area (R^2 0.48, without biofilm and R^2 0.76 with biofilm growth). Physical properties, dimensionality and voidage, associated with hydraulic efficiency also correlated with oxygen transfer efficiency without (R^2 0.92). and with biofilm (R^2 0.88), in comparison to protected surface area (R^2 0.76, without biofilm and R^2 0.95 with biofilm growth). The combination of parameters: dimensionality and voidage, can be used to optimise media size and shape, enhancing mixing and oxygen transfer; and ultimately contributing towards energy savings and higher removal efficiencies.

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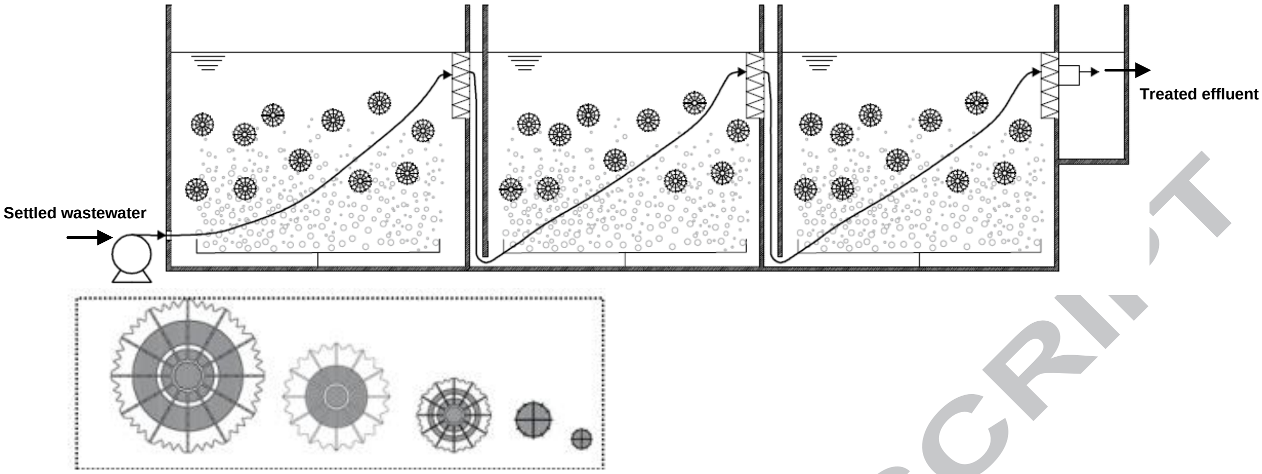

Figure 1. Schematic side view of the pilot-plant used to study hydrodynamic behaviour and aeration efficiency of 5 carrier media.

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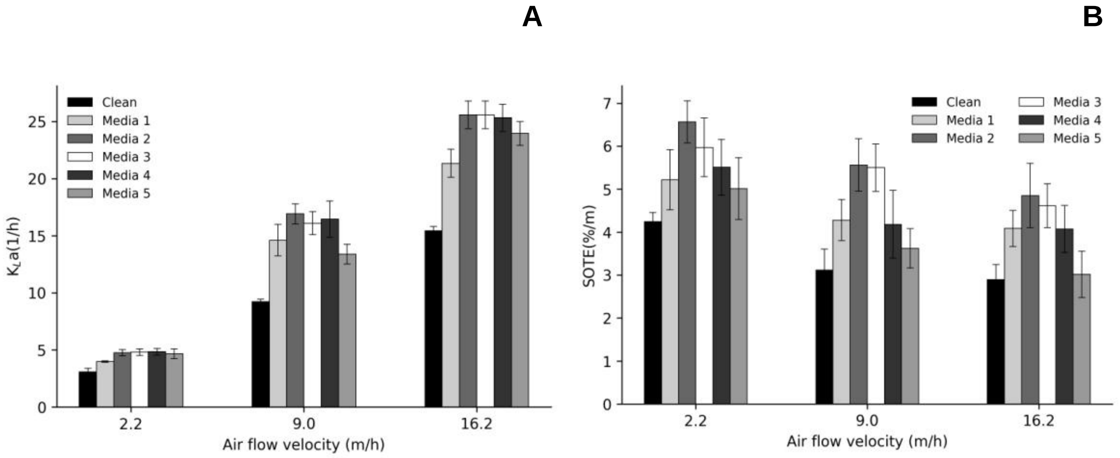

Figure 2. k_La (A) and SOTE (%/m) (B) measurements in clean water and with 5 different media at three air flow velocities. Media 1 (Biofil), Media 2 (Bioball), Media 3 (Biomarble), Media 4 (Biopipe) and Media 5 (Biotube). Media was supplied by Warden Biomedia (http://www.wardenbiomedia.com/).

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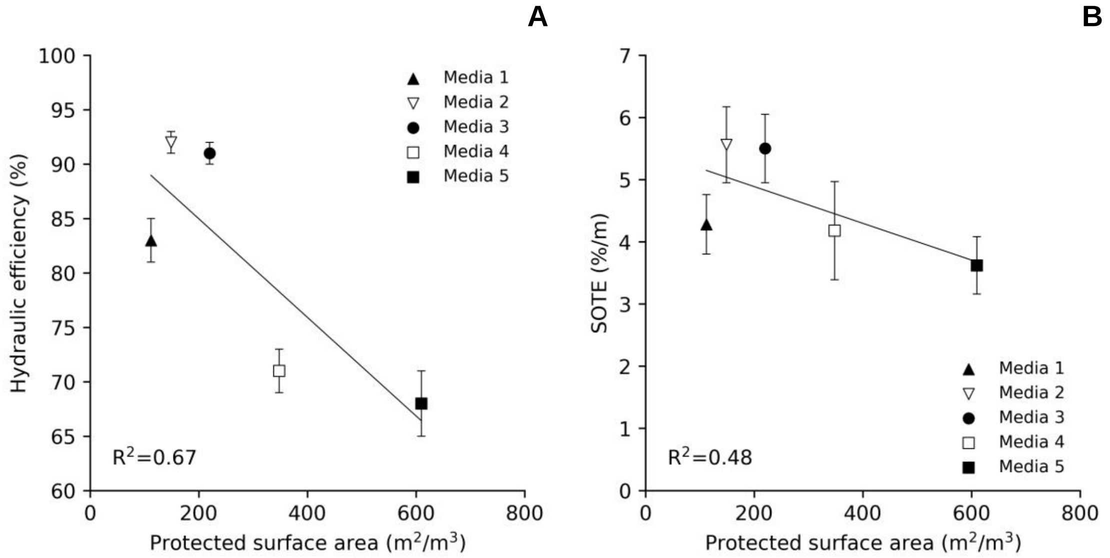

Figure 3. Correlation between hydraulic efficiency (A) and SOTE (%/m) (B) with the media protected surface area (m^2/m^3). Media 1 (Biofil), Media 2 (Bioball), Media 3 (Biomarble), Media 4 (Biopipe) and Media 5 (Biotube). Media was supplied by Warden Biomedia (http://www.wardenbiomedia.com/).

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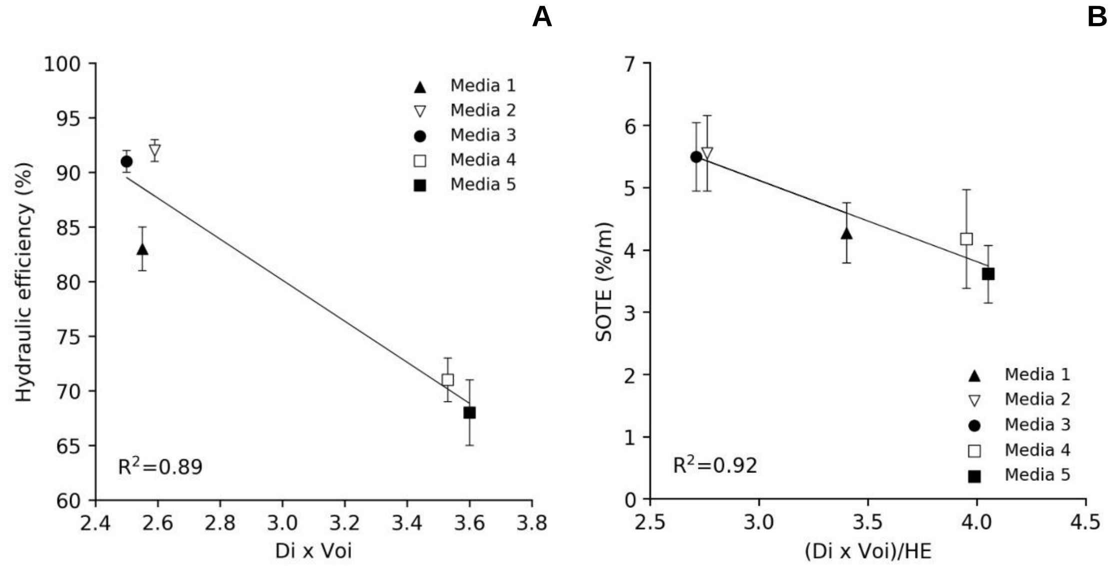

Figure 4. Correlation between hydraulic efficiency and Di x Voi (A) and correlation between SOTE (%/m) and (Di x Voi)/HE (B) without biofilm growth. Media 1 (Biofil), Media 2 (Bioball), Media 3 (Biomarble), Media 4 (Biopipe) and Media 5 (Biotube). Media was supplied by Warden Biomedia (http://www.wardenbiomedia.com/).

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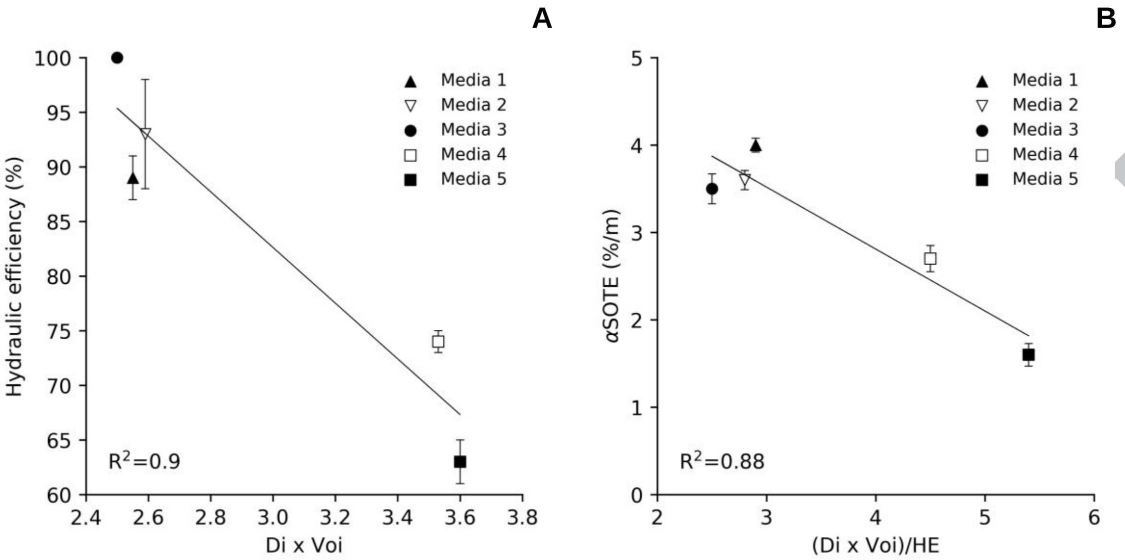

Figure 5. Correlation between hydraulic efficiency (A) and αSOTE (B) with biofilm developed on the carrier at steady state. Media 1 (Biofil), Media 2 (Bioball), Media 3 (Biomarble), Media 4 (Biopipe) and Media 5 (Biotube). Media was supplied by Warden Biomedia (http://www.wardenbiomedia.com/).

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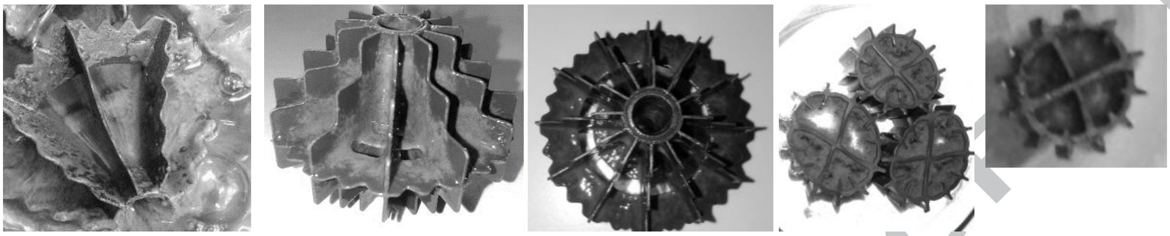

Figure 6. Pictures showing carrier media physical properties and biofilm attached to Media 1 (Biofil), Media 2 (Bioball), Media 3 (Biomarble), Media 4 (Biopipe) and Media 5 (Biotube) (left to right).

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Table 1

Characteristics of the carrier media tests in the moving attached growth systems. 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		

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Table 2

Summary of the hydraulic parameters determined based on two wastewater flow rates (4 m^3/day and 9 m^3/day). 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/).

Air Flow velocities	**No air**						**Air flow rate 2.2 m^3/m^2.h**						**Air flow rate 9 m^3/m^2.h**					
	Clean		**Media 1**		**Media 2**		**Clean**		**Media 1**		**Media 2**		**Clean**		**Media 1**		**Media 2**	
HRT (h)	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30
t_m (h)	5.8±0.5	3.2±0.2	7.5±0.2	3.3±0.3	7.7±0.3	3.9±0.9	8.2±0.1	3.2±0.1	9.5±0.2	4.4±0.1	9.4±0.6	4.8±0.1	9.0±0.3	3.5±0.1	8.7±0.1	4.0±0.2	10.1±0.4	4.9±0.3
V_d (m^3)	0.44±0.01	0.59±0.04	0.58±0.03	0.60±0.05	0.55±0.02	0.41±0.02	0.36±0.02	0.37±0.00	0.31±0.02	0.27±0.01	0.31±0.05	0.092±0.04	0.16±0.3	0.272±0.01	0.43±0.96	0.4±0.03	0.35±0.03	0.17±0.04
HE (%)	52	40	64	63	64	77	69	61	81	83	79	92	76	65	73	75	77	94
Dispersion $\boldsymbol{\delta}$	0.21±0.12	0.20±0.08	0.22±0.03	0.18±0.01	0.22±0.04	0.23±0.04	0.18±0.01	0.17±0.01	0.22±0.04	0.21±0.01	0.19±0.0	0.21±0.00	0.18±0.02	0.20±0.03	0.20±0.01	0.21±0.02	0.20±0.01	0.198±0.01
N-CSTR	3.4±0.1	2.3±0.4	3.2±0.1	3.4±0.1	3.2±0.5	2.9±0.3	3.4±0.1	3.4±0.14	2.9±0.4	2.1±0.1	3.2±0.2	3.0±0.1	3.5±0.3	3.2±0.3	3.1±0.1	3.0±0.2	3.1±0.1	3.0±0.2

Air Flow velocities	**No air**						**Air flow rate 2.2 (m^3/m^2.h)**						**Air flow rate 9 m^3/m^2.h**					
	Media 3		**Media 4**		**Media 5**		**Media 3**		**Media 4**		**Media 5**		**Media 3**		**Media 4**		**Media 5**	
HRT (h)	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30	11.8	5.30
t_m (h)	8.1±0.6	3.4±0.2	7.6±0.3	3.5±0.7	7.3±0.6	3.4±0.6	10.1±0.2	4.8±0.4	10.2±0.1	3.6±0.1	10.9±0.1	3.6±0.7	8.8±0.5	4.9±0.1	8.9±0.1	4.7±0.3	7.4±0.6	4.7±0.3
V_d (m^3)	0.49±0.01	0.56±0.04	0.52±0.01	0.51±0.05	0.54±0.02	0.54±0.02	0.23±0.01	0.19±0.01	0.20±0.02	0.34±0.01	0.11±0.05	0.36±0.01	0.40±0.02	0.07±0.01	0.36±0.01	0.05±0.03	0.05±0.03	1.50±0.04
HE (%)	66	62	59	60	57	58	83	91	80	71	84	68	72	92	76	89	63	89
Dispersion $\boldsymbol{\delta}$	0.18±0.12	0.18±0.08	0.16±0.03	0.16±0.01	0.22±0.02	0.22±0.01	0.18±0.01	0.20±0.01	0.18±0.04	0.20±0.01	0.19±0.01	0.21±0.00	0.19±0.02	0.20±0.03	0.21±0.01	0.25±0.02	0.19±0.01	0.188±0.01
N-CSTR	3.2±0.3	3.1±0.2	3.5±0.3	3.0±0.1	3.4±0.5	2.8±0.2	3.2±0.1	3.1±0.1	3.4±0.3	3.1±0.2	3.3±0.1	3.1±0.2	3.3±0.2	3.1±0.3	3.0±0.1	2.8±0.2	3.0±0.2	3.0±02

HRT theoretical retention time, t_m mean residence time, V_d volume of dead zones, HE hydraulic efficiency, $\boldsymbol{\delta}$ dispersion number, *N*-CSTR number of Continuous Stirred Tank Reactors

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Table 3
Summary of the hydraulic parameters and aeration efficiency at operation conditions with biofilm attached. 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 1	**Media 2**	**Media 3**	**Media 4**	**Media 5**
t_m (h)	16.9±0.3	11.2±0.6	8.7±0.3	5.2±0.3	3.0±0.6
$\boldsymbol{\delta}$	0.22±0.03	0.22±0.04	0.22±0.03	0.21±0.04	0.22±0.04
N-CSTR	2.81±0.05	2.98±0.01	2.78±0.05	3.0±0.23	3.0±0.01
V_e (m^3)	1.34±0.02	1.33±0.05	1.68 ±0.02	1.14±0.02	1.10±0.05
HE (%)	89±2	93±5	100±2	74±1	63±2
α factor	0.80±0.10	0.59±0.17	0.63±0.17	0.62±0.20	0.63±0.03
αSOTE (%/m)	3.98±0.10	3.65±0.17	3.50±0.17	2.72±0.20	1.58±0.03
αKla (1/h)	4.71	5.94	8.64	11.02	12.82
αSAE (kgO_2/kWh)	3.65	2.85	2.75	2.28	1.70
kWh/$kgO_{2\ consumed}$	0.6	0.6	0.5	0.5	0.4
kWh/$m^3_{wastewater}$	0.23	0.19	0.19	0.17	0.14

Impact of different carrier media on oxygen mass transfer and wastewater hydrodynamics on moving bed biofilm systems

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- All the carrier media enhanced oxygen mass transfer and hydraulic efficiency (HE)
- Spherical shaped media reduced the amount of short-circuiting and dead zones
- Cylindrical shaped media with low voidage reduced HE
- Protected surface area did not correlate with oxygen mass transfer or HE
- Dimensionality and voidage were highly correlated with oxygen mass transfer and HE

Impact of different carrier media on oxygen mass transfer and wastewater hydrodynamics on moving bed biofilm systems

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Graphical abstract