Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1140681

57 (2016) 24210–24221
November

Taylor & Francis
Taylor & Francis Group

Potential of engineered biomedia for the innovative purification of contaminated river water

L. Sidek[a], H.A. Mohiyaden[a], L.K. Lee[b], K.Y. Foo[c,*]

[a]*Centre for Sustainable Technology and Environment (CSTEN), Universiti Tenaga Nasional, (UNITEN), Jalan IKRAM-UNITEN, 43000 Selangor, Malaysia, Tel. +60 389217289; Fax: +60 389287166; email: Lariyah@uniten.edu.my (L. Sidek), Tel. +60 389212020; Fax: +60 389287166; email: Hairun@uniten.edu.my (H.A. Mohiyaden)*
[b]*Food Technology Programme, School of Industrial Technology, Universiti Sains Malaysia, 11800 Minden, Penang, Malaysia, Tel. +60 46532222; Fax: +60 46536375; email: l.k.lee@usm.my*
[c]*River Engineering and Urban Drainage Research Centre (REDAC), Engineering Campus, Universiti Sains Malaysia, Seri Ampangan, 14300 Nibong Tebal, Penang, Malaysia, Tel. +60 45945874; Fax: +60 45941036; email: k.y.foo@usm.my*

Received 5 October 2015; Accepted 2 January 2016

ABSTRACT

The performance of a laboratory scale bioreactor was investigated for the biological pretreatment of contaminated river water over the operation period of 6 months. The biofilters were constructed as four identical 5.75 L tanks filled with different carrier supports. The physiochemical properties of the biomedia, including the specific surface area, void fraction, adsorption of methylene blue, and morphological characteristics were examined. The biofilters responded effectively for chemical oxygen demand, biological oxygen demand, ammonical nitrogen, and total suspended solids removal, reaching the maximum removal of 94, 88, 85, and 98%, respectively. The variation of morphological development and biofilm densities revealed the existence of different growth rates and microbial activities under different biomedia supports. The operation is significantly correlated to the unique features of the biomedia. These new engineered structural biomedia are expected to be a potential option to govern the successful water purification process under steady and transient state operations.

Keywords: Adsorption; Biofilm; Biomedia; Bioreactor; River water

1. Introduction

Concern about environmental protection has increased over the years from a global viewpoint [1]. Biofilm reactor, a unique design which employs an inert support medium to immobilize large amounts of biomass through natural attachment, has emerged to be a promising alternative to conventional activated sludge treatment technology for the effective remediation of various industrial effluents [2]. These carrier supports provide a high biofilm surface area per unit volume of reactor, which leads to high volumetric conversion capacities [3]. The intrinsic tendency of micro-organisms to adhere to, and grow on surfaces in contact with the aqueous systems is the principal concept of biofilm formation. These reactors

*Corresponding author.

would benefit from the development of biofilm with long sludge age, high biomass concentrations, compact size, improved settling characteristics, low head loss, reduced sludge production, better oxygen transfer, shorter hydraulic residence time, better organic loading rates, and a higher stability of operation [4]. Specifically, a fully submerged biofilm could offer the treatment system with a higher treatment potential, without the cost and space requirement for additional treatment units [5].

Biofilm accumulation is net result of growth and the dynamic detachment process, primarily affected by several external factors, including composition and concentration of the feed, velocity of the liquid phase (shear stress), concentration of particles, particle–particle collisions, and particle–wall collisions [6]. During the operation, the right balance between the parameters that contribute to biofilm growth and those which affect the detachment from the surface should be attained to obtain the steady-state thicknesses. The fundamental importance of the biofilm reactor is the specially designed biofilm carriers, for which the geometry, sizing and materials of construction, density, durability, specific surface area, surface roughness, porosity, percentage of the bed void spaces and sorption properties that have to be carefully considered [7]. Proper selection of a suitable support media is critical to both technical and economical success for the biomass development. This would offer the flexibility for future treatment capacity upgrades without requiring the construction of additional reactors [8].

Media size and surface area have often dictated the maximum feed loading rate on the biofilters. The carrier media geometry which promotes attached growth has included smooth cylinders [9], cylinders with internal crosses and external fins [10], rectangles, cubes, and spheres [11]. Although it is generally accepted that a smaller media with higher specific surface area would perform relatively more efficient or yield better pollutant removal, there exists a large disconnection in the research community concerning the media geometry, material and filling fraction for nutrient removal, microbial biocenosis and fouling propensity in the bioreactors. In this sense, this study was carried out to evaluate the performance of four engineered biomedia for the effective purification of contaminated river water during a 6-month operation. The physiochemical properties including the specific surface area, void fraction, and adsorption capacities of methylene blue (MB) of the biomedia were examined. Additionally, the biofilm structure, biomass concentration, and the feasible implication for the water quality improvement were outlined.

2. Materials and methods

2.1. Design of the treatment setup

The biofilm reactor was made of acrylic tanks with 30 cm in length, 35 cm in height, and 15 cm in width, contributed to an effective tank volume of 5.75 L. The treatment system consists of four separate tanks, each preinstalled with different biomedia. Water from the culture tank was fed through the standpipe slots to the reactor by means of a peristaltic pump and air was up-lifted continuously into the biofilter, through the custom-built air diffusers. A schematic illustration of the laboratory scale bioreactor used in this study is shown in Fig. 1.

2.2. River water

The water samples were collected from the nearby river, and stored in darkness at 4℃ prior to use to minimize the chemical and biological changes. The chemical oxygen demand (COD) of the river water varied between 150 and 200 mg/L, while the biological oxygen demand (BOD_5) was less than 120 mg/L. The pH of the river water ranged within 7.5–7.9, and the dissolved oxygen (DO) level was approximately 5.5 mg/L.

2.3. Experimental protocol

The system was in operation with varying numbers and biomass of red drum juveniles five months prior to the start of the experimental trial. Four types of submerged fixed bed filters were operated (Table 1). These biofilm carriers are made of polypropylene, polyvinyl chloride and high-density polyethylene, and shaped as bottle, spawning brush, biocage, and fill media. The specific weight was approximately 0.50–0.96 g/cm^3, while the filling fraction was ranged from 50 to 60%. Each of the biofilters were contained in identical reactor, and evaluated in triplicates with regard to their capability for COD, BOD_5, ammonical

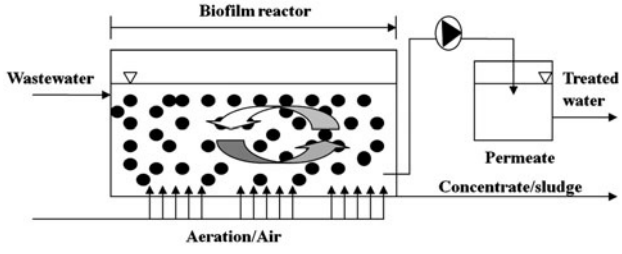

Fig. 1. Schematic illustration of the laboratory scale bioreactor.

Table 1
Specifications for the four types of engineered biomedia evaluated for BOD_5, COD, AN removal, and overall quality improvement in the biofilm reactor

Type	Name	Material	Shape	Surface area (m/m)	Void fraction	Condition
1	Structured bottle	High density polyethylene	Net-caged	140	92%	Fixed
2	Spawning brush	Polypropylene	Brush	49.4	>95%	Fixed
3	Biocage	Polypropylene	Spherical	500	>80%	Fixed
4	Fill media	Polyvinyl chloride	Corrugated layer surface	243	>90%	Fixed

nitrogen (AN) and total suspended solids (TSS) removal, and overall water quality index (WQI) improvement derived as:

$$\mathrm{WQI} = 0.22\,\mathrm{SIDO} + 0.19\,\mathrm{SIBOD} + 0.16\,\mathrm{SICOD} + 0.16\,\mathrm{SISS} + 0.15\,\mathrm{SIAN} + 0.12\,\mathrm{SIpH} \quad (1)$$

where WQI = Water quality index; SIDO = Sub-index of DO; $SIBOD_5$ = Sub-index of BOD_5; SICOD = Sub-index of COD; SIAN = Sub-index of AN; SISS = Sub-index of TSS; SIpH = Sub-index of pH

Sub-index for DO (in % saturation):

$$\mathrm{SIDO} = 0 \quad \text{for DO} < 8 \quad (1.1a)$$

$$= 100 \quad \text{for DO} > 92 \quad (1.1b)$$

$$= -0.395 + 0.030\,\mathrm{DO}^2 - 0.00020\,\mathrm{DO}^3 \quad \text{for } 8 < \mathrm{DO} < 92 \quad (1.1c)$$

Sub-index for BOD_5:

$$\mathrm{SIBOD} = 100.4 - 4.23\,\mathrm{BOD_5} \quad \text{for } \mathrm{BOD_5} < 5 \quad (1.2a)$$

$$= 108\,\mathrm{e}^{-0.055\,\mathrm{BOD}} - 0.1\,\mathrm{BOD_5} \quad \text{for } \mathrm{BOD_5} > 5 \quad (1.2b)$$

Sub-index for COD:

$$\mathrm{SICOD} = -1.33\,\mathrm{COD} + 99.1 \quad \text{for COD} < 20 \quad (1.3a)$$

$$= 103\,\mathrm{e}^{-0.0157\,\mathrm{COD}} - 0.04\,\mathrm{COD} \quad \text{for COD} > 20 \quad (1.3b)$$

Sub-index for AN:

$$\mathrm{SIAN} = 100.5 - 105\,\mathrm{AN} \quad \text{for AN} < 0.3 \quad (1.4a)$$

$$= 94\,\mathrm{e}^{-0.573\,\mathrm{AN}} - 5[\mathrm{AN} - 2] \quad \text{for } 0.3 < \mathrm{AN} < 4 \quad (1.4b)$$

$$= 0 \quad \text{for AN} > 4 \quad (1.4c)$$

Sub-index for TSS:

$$\mathrm{SISS} = 97.5\,\mathrm{e}^{-0.0067\,\mathrm{SS}} + 0.05\,\mathrm{TSS} \quad \text{for TSS} < 100 \quad (1.5a)$$

$$= 71\,\mathrm{e}^{-0.0016\,\mathrm{SS}} - 0.015\,\mathrm{TSS} \quad \text{for } 100 < \mathrm{TSS} < 1000 \quad (1.5b)$$

$$= 0 \quad \text{for TSS} > 1000 \quad (1.5c)$$

Sub-index for pH:

$$\mathrm{SIpH} = 17.2 - 17.2\,\mathrm{pH} + 5.02\,\mathrm{pH}^2 \quad \text{for pH} < 5.5 \quad (1.6a)$$

$$= -242 + 95.5\,\mathrm{pH} - 6.67\,\mathrm{pH}^2 \quad \text{for } 5.5 < \mathrm{pH} < 7 \quad (1.6b)$$

$$= -181 + 82.4\,\mathrm{pH} - 6.05\,\mathrm{pH}^2 \quad \text{for } 7 < \mathrm{pH} < 8.75 \quad (1.6c)$$

$$= 536 - 77.0\,\mathrm{pH} + 2.76\,\mathrm{pH}^2 \quad \text{for pH} > 8.75 \quad (1.6d)$$

For each treatment, experiments were carried out over a period of 6 months at the hydraulic residence time of 4 h. The technical concept of the biofilm reactor is shown in Fig. 2. The removal rate, R (%) was determined by:

$$R = \frac{(C_0 - C_t)}{C_0} \times 100\% \quad (2)$$

where C_0 and C_t (mg/L) are the liquid-phase concentrations at initial and time t (d), respectively.

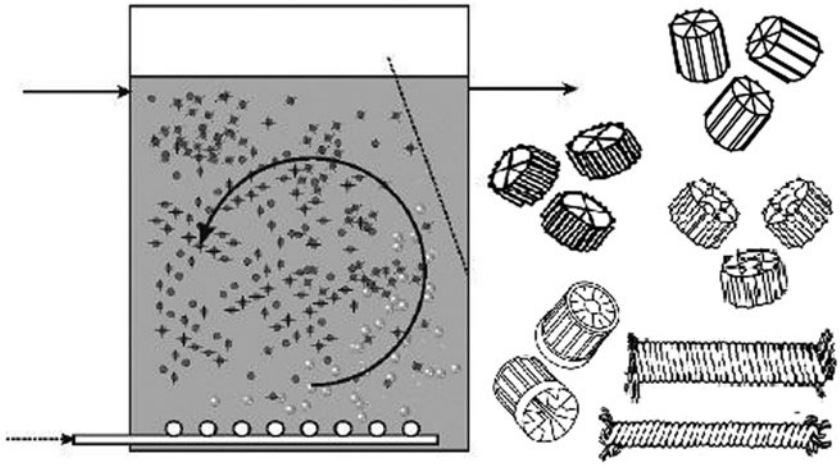

Fig. 2. The technical concept of biofilm reactor.

2.4. Water quality analysis

Water sampling was scheduled at least twice per week. Chemical analysis was performed according to the Standard Method of Water and Wastewater [12]. The analytical determination of BOD_5, COD, AN, and TSS concentration was determined according to the Luminescence Measurement, closed reflux colorimetric, Salicylate, and Gravimetric standard methods, using a spectrophotometer (HACH DR3900). The temperature, DO level, and pH were measured using a handheld multiparameter instrument (YSI 6920). The replicate of each biofilters was performed similarly in all conditions. All measurements were undertaken in triplicates.

2.5. Adsorption of MB

MB, a recognized probe molecule for assessing the adsorption performance of a specific biomedia from aqueous phase, especially for moderate size pollutant molecules with an average pore size ≥ 1.5 nm, was selected as the model assessment in this study [13]. The batch adsorption experiments were conducted using 1 g of biomedia and 200 mL of MB solutions with the concentration range of 5, 10, 15, and 20 mg/L, respectively. The solution mixtures were agitated in a water bath shaker at 30˚C and the shaking speed of 120 rpm for 24 h. The dye concentration in the supernatant was analyzed using a double beam UV–vis spectrophotometer (UV-1801 Shimadzu, Japan) at 668 nm. The MB uptake at equilibrium, q_e (mg/g), was calculated by:

$$q_e = \frac{(C_0 - C_e)V}{W} \tag{3}$$

where C_e (mg/L) is the liquid-phase concentrations equilibrium, V (L) is the volume of the solution, and W (g) is the mass of biomedia.

2.6. Morphological characterization

The surface morphology of the biomedia before and after the 6-month operation was visualized using a scanning electron microscope equipped with W-Tungsten filament (Lanthanum-Hexabonde Field Emission) operated at 10–15-KV speed voltage, 155-eV resolution and orientation of 35˚C, with Mn K_α as the energy source.

2.7. Biofilm mass

The biofilm mass was determined as the dry weight concentration on the carriers. These carriers were dried to a constant weight at 105˚C. The removal of biomass from the carriers was undertaken by soaking in a concentrated sulfuric acid with potassium dichromate for 16 h; following which the carrier was again dried and reweighed. The biofilm concentration was calculated by the difference between the weights of carriers before and after biomass removal, based on the number of carriers used and their volume in the bioreactors.

2.8. Statistical analysis

Descriptive statistics were used to report the feasibility of the experimental biomedia for the removal of BOD_5, COD, AN, and TSS. Generalized linear model (GLM) was performed to explore the effectiveness of the chosen biomedia for the improvement of water quality parameters. All statistical tests were analyzed using SPSS version 17.0 software (SPSS, Chicago, IL, USA), with significance level (α) of 5% was applied unless otherwise indicated.

3. Results and discussions

3.1. BOD_5 and COD removal

BOD_5 and COD are two different surrogate parameters measuring the oxygen content of water to the recipients [14]. BOD_5 quantifies the potential of oxygen consumption by bacteria to break down organic carbon in the water, characterized by DO [15]. Conversely, COD does not differentiate between biologically available and inert organic matters, and is a measurement of the total quantity of oxygen required to oxidize the amount of organic and inorganic oxydizable compounds in the water samples [16]. The daily variation of the BOD_5 and COD concentrations of the treated effluents, and the removal efficiency of different biomedia in the bioreactor during the operation period of 6 months is provided in Figs. 3 and 4. Along the study, the BOD_5 and COD concentrations of the influent river water varied between 63 and 112 mg/L, and between 150 and 195 mg/L, with an average concentration of 80.72 and 184.16 mg/L, respectively. The BOD_5 level of the treated effluents ranged within 3.61 and 78.36 mg/L, and the corresponding COD was 23.17–164.01 mg/L in all experiments.

The BOD_5 and COD removal efficiency fluctuated considerably throughout the study, ranging from 31 to 94%, and 27 to 90%, respectively, except for the first months of trial operation when the removal efficiency was very low due to the new start-up of the bioreactors. High fluctuation of the removal efficiency was due to the variations of influent concentration, as well as with the changes in biodegradability of organic compounds [17]. However, no obvious relationship between variation of influent concentrations with the COD and BOD_5 removal in the bioreactors was detectable, even though the influent BOD_5 levels, on average, showed a greater fluctuation than the COD concentration. The performance of the biomedia for BOD_5 and COD removal followed the order: Type 3 > Type 4 > Type 2 > Type 1 ($F = 11.123$; $\eta p^2 = 0.287$, $p < 0.0001$ for BOD_5; $F = 12.207$, $\eta p^2 = 0.306$, $p < 0.0001$ for COD). The deviation was probably ascribed to the difference in material, structure, shape, surface area, void fraction, and nature of the biomedia carriers, as presented in Table 1.

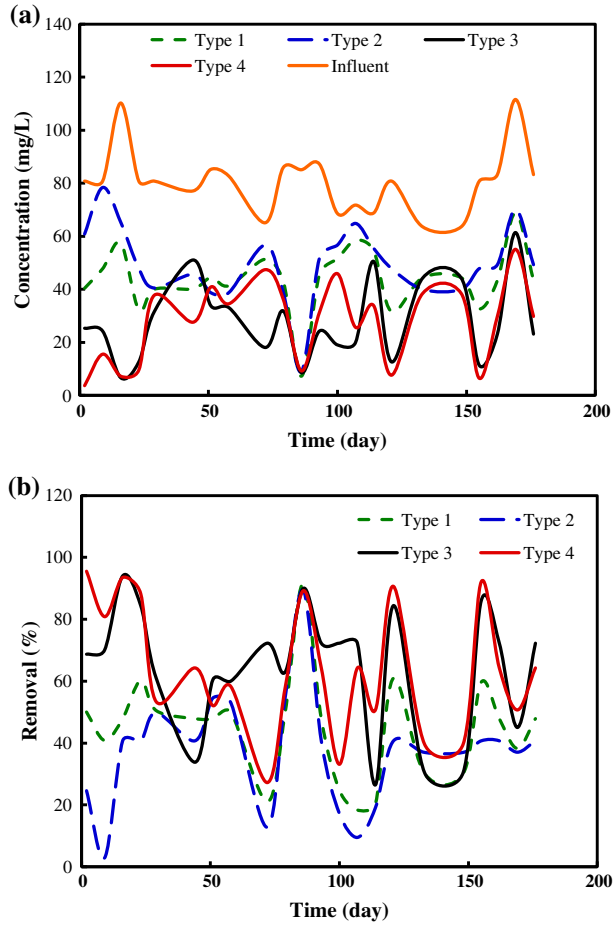

Fig. 3. The variation of concentration (a) and removal efficiency and (b) of BOD_5 in the bioreactor.

3.2. AN removal

In surface water, nitrogen exists in many forms, including organic nitrogen, ammonia nitrogen, nitrite and nitrate nitrogen, with AN being the major form [18]. AN is one of the most important water quality parameters applied to assess a water supply source as it affects the pre-chlorination and disinfection process of the wastewater treatment plants [19]. The time variation of AN concentration and removal efficiency for the different biofilm reactors is plotted in Fig. 5. Although the influent concentrations were extremely low (0.5–2.0 mg/L), the bioreactor could effectively

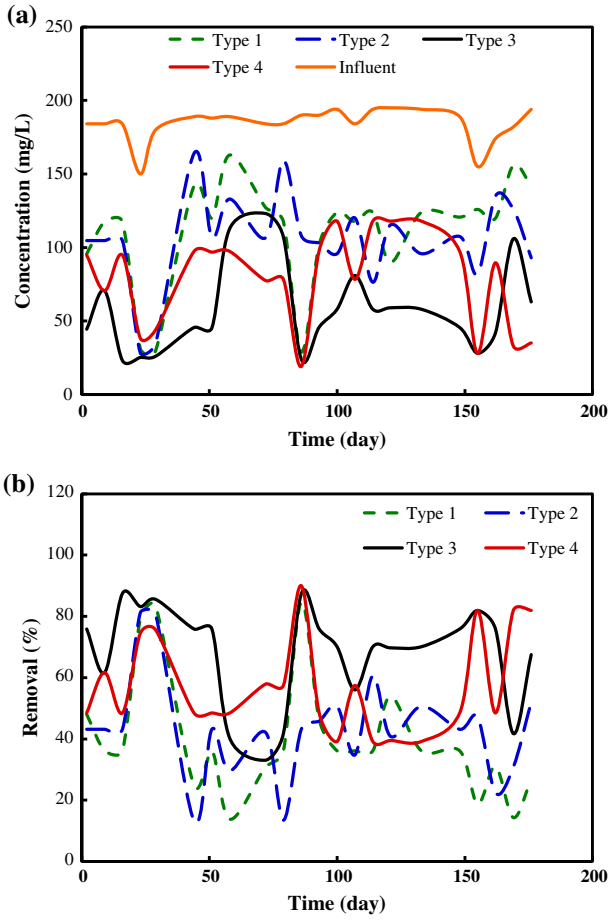

Fig. 4. The variation of concentration (a) and removal efficiency and (b) of COD in the bioreactor.

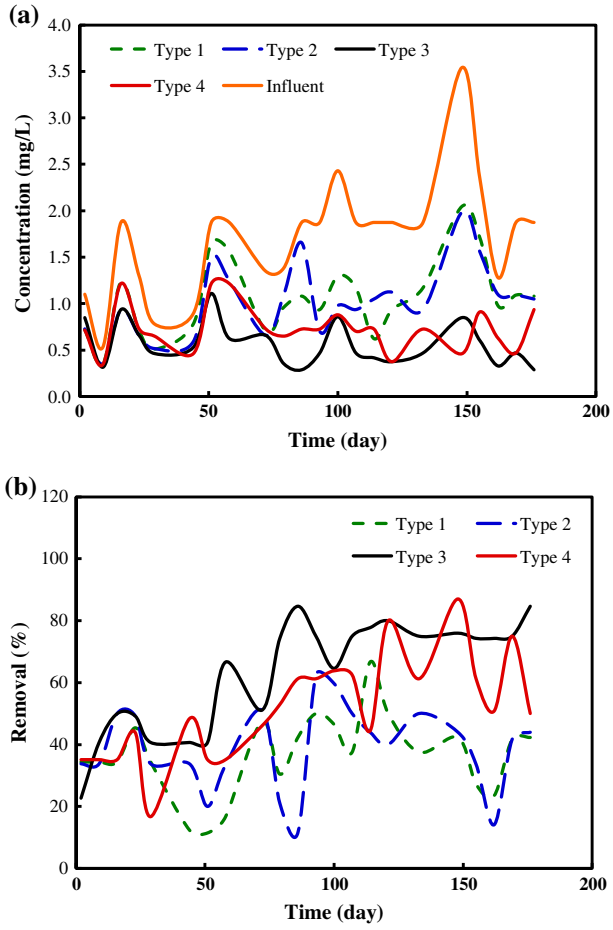

Fig. 5. The variation of concentration (a) and removal efficiency (b) of AN in the bioreactor.

discriminate AN from the systems, with greater than 35% of removal rate.

After the lapse of 50 d, the AN oxidation efficiencies were ranged from 50 to 67%. Although the nitrite concentration was not continuously monitored, random checks illustrated that the nitrite concentrations in the treated effluents were lower than those in influent, which indicated that the biological nitrification could successfully advance without nitrite accumulation. The DO in the aeration tanks was varied from 4 to 9 mg/L. The root oxygen release has been postulated to account for improved purification of AN by stimulating nitrification, aerobic oxidation of AN to nitrate and nitrate, and higher densities and activity of nitrifying bacteria. Moreover, it was demonstrated that the volumetric nitrification rates of the structured biomedia fluctuated with the influent concentration. The mean removal efficiency ranged between 38.84 and 63.33%, and predictably, Type 3 biomedia showed the greatest efficiency and Type 1 media indicated the lowest performance ($F = 13.144$; $\eta p^2 = 0.322$, $p < 0.0001$). Table 2 exhibits a comparison of the performance of different biomedia for the biological treatment of AN and COD. The biomedia applied in this work showed relatively high removal efficiency, as compared to some previous works as reported in the literature [8,17,20–23].

3.3. TSS removal

TSS, an identical measurement on the dry-weight of particles trapped by a filter, is the most visible indicators of water quality. It describes the impurities present in the water body, from soil erosion, runoff, discharges, stirred bottom sediments or algal blooms, and is a direct quantification of sedimentation rates [24]. Excessive suspended sediment could impair water quality for aquatic and human life, impede navigation and increase the flooding risks. The lower TSS

Table 2
A comparison of the performance of different biomedia for the biological treatment of AN and COD

Biomedia	Pollutants	Maximum removal (%)	Refs.
Type 3	Ammonical nitrogen	85	Present study
MB3 media	Ammonical nitrogen	14	[8]
Activated sludge	Ammonical nitrogen	50	[20]
Kaldnes K1 carrier	Ammonical nitrogen	60	[21]
Polyvinyl chloride cylinder	Ammonical nitrogen	70	[22]
Type 3	COD	94	Present study
AnoxKaldnesTM K3 biomass	COD	87	[17]
Polyvinyl chloride cylinder	COD	30	[22]
Bioflow 9 medium	COD	94	[23]

would allow the penetration of light from reaching to the submerged vegetation, to enhance the photosynthetic activities and DO level of the water body, and support a diversity of aquatic life. Some cold water species, such as trout and stoneflies, are especially sensitive to the changes of TSS, DO, and water turbidity [25].

The relation of the TSS concentration and removal efficiency for the biomedia as a function of time is depicted in Fig. 6. Regardless on the variation of influent concentration and the type of biomedia studied, the removal of TSS was generally the highest among other contaminants, with the removal rate of >40%. With the surface area of 500 m/m, the TSS removal of Type 3 biomedia reached to the average removal of 91.36% ($F = 48.466$; $\eta p^2 = 0.637$, $p < 0.0001$). The correlation is in agreement with the research finding by Rodgers et al. [26], who reported that the entrapment of suspended solids in the pretreatment units is always higher at the interface between the distribution zone filled with large stones, and the filtration bed material with a smaller grain size and higher specific surface area. Additionally, the presence of micro-organisms or algae might contribute to TSS removal by aerobic degradation of organic and inorganic compounds and photosynthesis processes. This is the most likely reason for the higher DO saturation in the effluent tanks, which is known to be caused by the high levels of micro-organisms or algal activities in biofilters. As a result, the concentrations of all other water quality parameters, such as COD, BOD_5, and AN would subsequently be reduced.

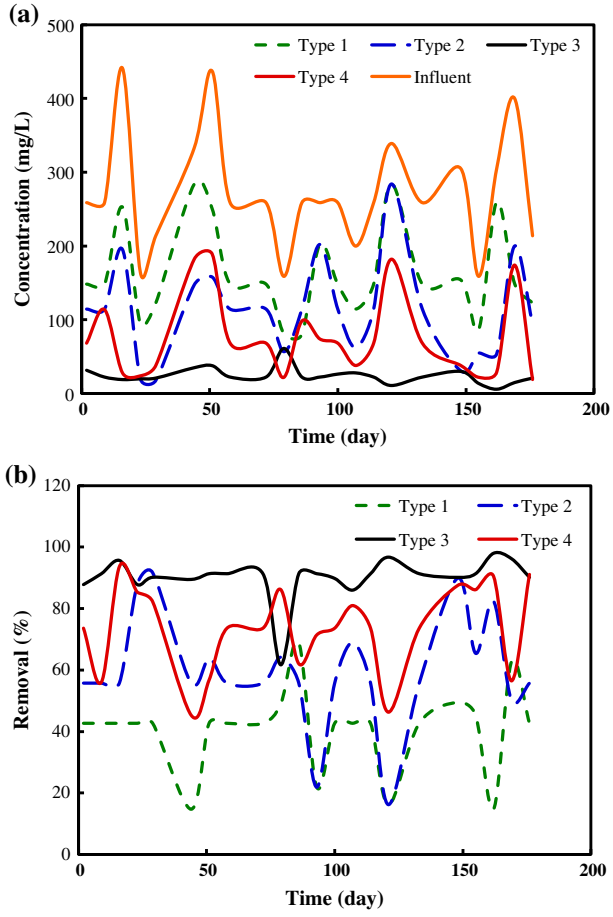

Fig. 6. The variation of concentration (a) and removal efficiency (b) of TSS in the bioreactor.

3.4. WQI improvement

WQI serves as the basis for environmental assessment of a watercourse in relation to pollution load categorization and designation of classes of beneficial uses as provided by the Interim National Water Quality Standards for Malaysia (INWQS). It combines the measurement of several water quality variables in such a way to produce a single score to represent the quality impairments or suitability of use (Table 3).

Table 3
The water quality classification according to WQI

Water Quality Index (WQI)	Class	Condition
>92.7	I	Very good
76.5–92.7	II	Good
51.9–76.5	III	Average
31.0–51.9	IV	Polluted
<31.0	V	Very polluted

WQI is applied to determine the water quality status: clean, slightly polluted, or polluted category (Table 4), and to classify the rivers in Class I, II, III, IV, or V. It was calculated based on the sub-indices (SI) value as stated in Eqs. (1.1(a))–(1.6(d)) [27].

The variation of WQI of the influent river water and treated effluents of different biomedia in the bioreactor during the operation period of 6 months is depicted in Fig. 7. The values of WQI of the influent river water and treated effluent reached to the minimum reading of 27.3 and 31.6–59.7, respectively. This fact indicated the promising capability of the bioreactors in the regulation of BOD_5, COD, TSS, pH, DO, and AN for water quality improvement. According to the Classification of WQI given by INWQS, the value of WQI of the influent river water and treated effluents falls in the intermediate between Class IV (31.0–51.9) and V (<31.0), derived as "polluted" and "very polluted", and Class II (76.5–92.7) and III (51.9–76.5), defined as "good" and "average", respectively. The findings was supported by Viau et al. [28] that showed that approximately 55% of BOD_5, and more than 30% of nutrients were removed to improve the value of WQI reading.

The pollutant removal was due to the natural attenuation processes, biodegradation, adsorption, sedimentation, oxidation, and nitrification that serve for appropriate water purification. High fluctuation of the WQI during the early months of trial operation was due to the new start-up of the bioreactors. In overall, the WQI improvement in the biomedia followed the sequence: Type 3 > Type 4 > Type 2 > Type 1 in a descending order, in accordance to the performance removal of BOD_5, COD, AN and TSS ($F = 4.593$; $\eta p^2 = 0.142$, $p < 0.01$).

3.5. Adsorption of MB

The variation of adsorption capacity (mg/g) of the biomedia for MB at the concentrations 5–20 mg/L was displayed in Fig. 8. Initial concentration provides an essential driving force for alleviating the mass transfer resistance between the aqueous phase and the solid medium [29]. In the present study, the adsorption equilibrium of MB, q_e increased from 0.025–0.037 to 0.224–0.297 mg/g with an increase in the initial concentration from 5 to 20 mg/L. No tremendous difference between the adsorption capacities of MB was observed on different biomedia. According to this data, it could be expected that the variation of COD, BOD_5, and AN removal, and overall WQI improvement throughout the operation of the bioreactors was the net result of the biofilm development of the different carrier supports.

3.6. Morphological study

The morphological changes of the biomedia before and after the operation period of 6 months were visualized using the scanning electron microscopy at the magnification of 1,000× (Fig. 9). The morphological structures of the raw biomedia were light with lower cellular density. After the course of the operation, a dramatic changes of porosity, biomass concentration, particle size, shape, and surface thickness were noted, indication of the development of biofilm. Such differences in the developing structures shed information about the axis of biofilm under different conditions.

Table 4
Classification of water classes and their uses

Class	Uses
Class I	Water supply—practically no treatment necessary Fishery—very sensitive aquatic species
Class IIA	Water supply—conventional treatment required Fishery—sensitive aquatic species
Class IIB	Recreational use with body contact
Class III	Water supply—extensive treatment required. Fishery—common, of economic value and tolerant species; Livestock drinking
Class IV	Irrigation
Class V	None of the above

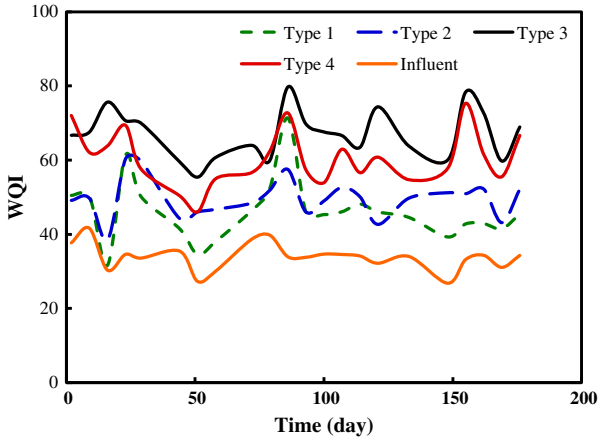

Fig. 7. The variation of WQI of the influent river water and treated effluents of different biomedia in the bioreactor.

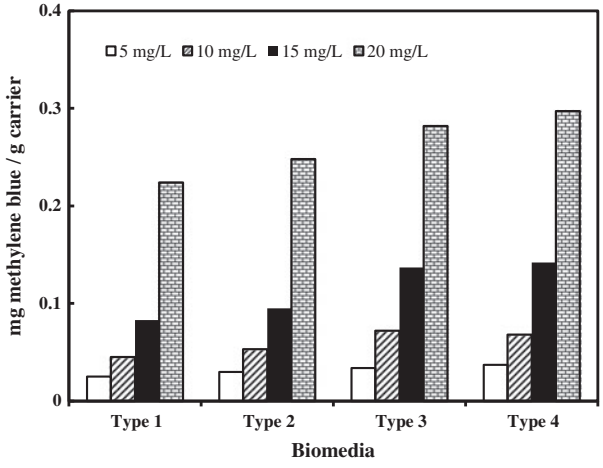

Fig. 8. The variation of adsorption capacity (mg/g) of the biomedia for MB.

According to Zhang et al. [30], the initial biofilm growth was more pronounced from the base in the lateral direction. The lateral axis probably offers the least resistance to growth as the fluid elements at the biomedia are thought to be stationary. Further, the adhesive forces between the biomass and the support also favor growth along this axis. Accordingly, once a thin layer is established along the wall of the biomedia, growth begins to occur towards the direction perpendicular to the carrier supports.

In this work, the differences in apparent biomass densities revealed the existence of different growth rates under different biomedia supports. From Fig. 9(a) and (b), the Type 1 biomedia that manifested as a porous layer had grown into a dense base structure, which is highly porous with a variety of surface

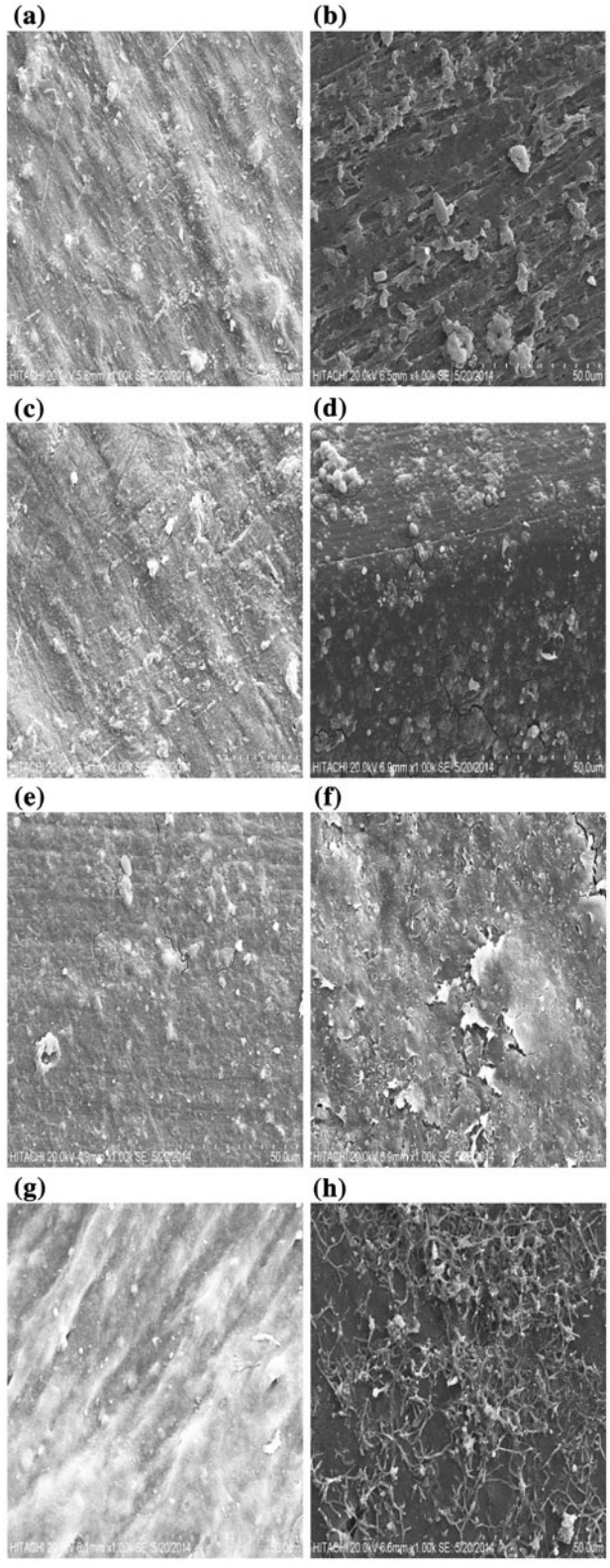

Fig. 9. The morphological changes of the biomedia before and after the operation period of 6 months.

irregularities. Competitive growth was observed between the filamentous and biofilm-formed bacteria along the surface. In contrast, Type 2 biomedia (Fig. 9(d)) demonstrated a medium porous biofilm with a regular surface profile. The biofilm resembled those structures obtained during the initial biofilm formation process, partially covered with high cellular biomass. On the contrary, the microscopic image of Type 3 biomedia (Fig. 9(f)) showed less structural heterogeneity with a remarkable smooth surface profile. It was densely populated by the micro-organisms with no visible pores and thinner structures in evidence. The visual observations of this biofilm structure agreed qualitatively with the predictions by models of van Loosdrecht et al. [31]; Picioreanu et al. [32]; Noguera et al. [33] and Rittmann et al. [34]. Fig. 9(h) photographically shows the formation of biofilm and filamentous bacteria over the Type 4 biomedia. The predominat development of these filamentous micro-organisms after 180 d of operation could behave as a completely mixed aerobic bioreactor for the effective treatment of contaminated river water. However, it was likely that there was still a thin layer of biofilm-forming bacteria remaining on the surface of the particle, which in turn, would serve as a root for filamentous attachment.

3.7. Biofilm development

Fig. 10 presents the evolution of the biofilm development on different biomedia. For all the tested situations, the biofilm accumulation increased rapidly with time, and the shape of bioparticle was becoming more spherical as the biofilm grew. These measurements were corroborated to the accumulation of loaded biomass on different carrier supports as observed by the microscopy (Fig. 9). The accumulation of a biofilm on a support is the net result of two competitive phenomena: the production of biomass by the micro-organisms in the biofilm and the continuous removal of attached biomass due to the biofilm detachment caused by the liquid shear, interactions between the particles and walls, and between the particles themselves [2]. When the growth of the biofilm is higher than the detachment from the surface, the biofilm density around the support would increase as a function of time, as depicted in Fig. 10.

It is possible to conclude that the detachment forces attained in the bioreactor were not enough to remove the biomass that was continuously growing around the supports. Although the collisions between particles could account for the detachment of biofilm from the surfaces, the detachment rate due to such

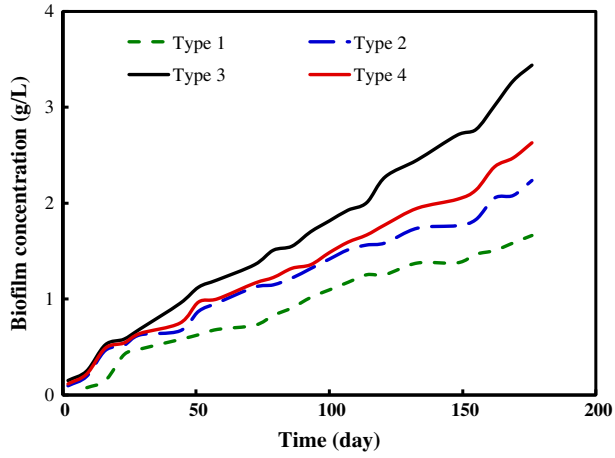

Fig. 10. The evolution of the biofilm development onto different biomedia.

collisions is mainly attributed to contact between biofilm pellets and bare carriers. Hence, in this case, as all the carriers were covered with biofilm, the level of abrasion was probably low. The substrates in a mature biofilm are mainly transported in and out of the biofilm by diffusion [35]. As the thickness of biofilm increases, its interior space becomes isolated from aeration and fresh substrate, to increase the age and adaptation of micro-organisms placed in the interior matrix of the biofilm to anoxic and anaerobic conditions [36]. According to Hibiya et al. [37], a thick biofilm is necessary for successful nitrification because of the distribution of heterotrophic and autotrophic nitrifying micro-organisms in the biofilm, and the presence of oxygen competition between these microbial groups. As a result, the thicker the biofilm, the more likely there are operating conditions where the bacteria may coexist.

The current study illustrated a similar behavior to support the feasibility of these engineered biomedia to provide a unique surface for the appropriate growth of heterotrophic micro-organisms that were involved in the water purification process. Comparison of the results revealed the variation of biofilm densities on the tested biomedia, which could be related, probably, with the different microbial processes occurring inside the biofilms. These findings outlined a strong implication of different biomedia on the bioreactor stability. The operating conditions in the bioreactor are set up according to the key characteristics of the carrier supports. If those characteristics change deeply during the operation, as occurred in this work, it may affect the biofilm formation and growth, for the successful operation of the bioreactor.

4. Conclusion

A laboratory scale bioreactor was investigated for the purification of contaminated river water over the operation period of 6 months. Result showed that the use of geotextile as the support medium would facilitate the rapid formation and growth of biofilm, with high biomass retention capacity. High removal efficiencies of BOD_5, COD, AN, and TSS were obtained throughout the operation period, reaching the maximum removal rate of 94, 88, 85, and 98%, respectively. The growing microstructure visualized using scanning electron microscopy, and verified by the determination of biofilm concentration exemplified the viable role of biofilm development for the water purification process.

Acknowledgment

The authors acknowledge the financial support provided by Ministry of Higher Education Malaysia and Universiti Sains Malaysia under the Long Term Research Grant (LRGS) (Project No. 203/PKT/6720004) and Research University (RUI) Grant (Project No. 1001/PREDAC/814272) schemes

References

[1] K.Y. Foo, B.H. Hameed, An overview of dye removal via activated carbon adsorption process, Desalin. Water Treat. 19 (2010) 255–274.
[2] S.S. Begum, K.V. Radha, Effect of hydrodynamic characteristics on the performance of biofilm for degrading phenol in inverse fluidized bed biofilm reactor, Desalin. Water Treat. 55 (2015) 2023–2033.
[3] Z.Q. Shen, J. Hu, J.L. Wang, Y.X. Zhou, Biological denitrification using starch/polycaprolactone blends as carbon source and biofilm support, Desalin. Water Treat. 54 (2015) 609–615.
[4] S.S. Begum, K.V. Radha, Effect of hydrodynamic characteristics on the performance of biofilm for degrading phenol in inverse fluidized bed biofilm reactor, Desalin. Water Treat. 55 (2015) 2023–2033.
[5] M.A. Baghapour, M.R. Shirdarreh, M. Faramarzian, Amoxicillin removal from aqueous solutions using submerged biological aerated filter, Desalin. Water Treat. 54 (2015) 790–801.
[6] C.F. Alves, L.F. Melo, M.J. Vieira, Influence of medium composition on the characteristics of a denitrifying biofilm formed by Alcaligenes denitrificans in a fluidised bed reactor, Process Biochem. 37 (2002) 837–845.
[7] Q. Yang, Q. He, H.T. Ibrahim, Review on moving bed biofilm processes, Pakistan J. Nutr. 11 (2012) 706–713.
[8] T.J. Pfeiffer, P.S. Wills, Evaluation of three types of structured floating plastic media in moving bed biofilters for total ammonia nitrogen removal in a low salinity hatchery recirculating aquaculture system, Aquacult. Eng. 45 (2011) 51–59.
[9] S. Yang, F. Yang, Z. Fu, T. Wang, R. Lei, Simultaneous nitrogen and phosphorus removal by a novel sequencing batch moving bed membrane bioreactor for wastewater treatment, J. Hazard. Mater. 175 (2010) 551–557.
[10] H. Odegaard, Innovations in wastewater treatment: The moving bed biofilm process, Water Sci. Technol. 53 (2006) 17–33.
[11] A. Valdivia, S.G. Martinez, P.A. Wilderer, Biological nitrogen removal with three different SBBR, Water Sci. Technol. 55 (2007) 245–254.
[12] APHA, AWWA, WPCF, Standard Methods for the Examination of Water and Wastewater, eighteenth ed., American Public Health Association, Washington, United States, 1992.
[13] K.Y. Foo, B.H. Hameed, A rapid regeneration of methylene blue dye-loaded activated carbons with microwave heating, J. Anal. Appl. Pyrolysis 98 (2012) 123–128.
[14] A.G. Lina, A. Al-Refaie, G. Kassab, D. Abu-Ghunmi, N. Bata, Minimizing discrepancies in oxygen demand-based biodegradability (ODB) results using Taguchi method, Desalin. Water Treat. 52 (2014) 4664–4672.
[15] H. Djelal, Y. Lelievre, C. Ricordel, Combination of Electro-Coagulation and biological treatment by bioaugmentation for landfill leachate, Desalin. Water Treat. 54 (2015) 2986–2993.
[16] K.Y. Foo, L.K. Lee, B.H. Hameed, Preparation of tamarind fruit seed activated carbon by microwave heating for the adsorptive treatment of landfill leachate: A laboratory column evaluation, Bioresour. Technol. 133 (2013) 599–605.
[17] L. Dvořak, T. Lederer, V. Jirku, J. Masakc, L. Novak, Removal of aniline, cyanides and diphenylguanidine from industrialwastewater using a full-scale moving bed biofilm reactor, Process Biochem. 49 (2014) 102–109.
[18] K.Y. Foo, L.K. Lee, B.H. Hameed, Preparation of activated carbon from sugarcane bagasse by microwave assisted activation for the remediation of semi-aerobic landfill leachate, Bioresour. Technol. 134 (2013) 166–172.
[19] S. Xie, X. Tang, W. Wu, D. Wen, Z. Wang, Biological pretreatment of Yellow River water, J. Environ. Sci. 17 (2005) 557–561.
[20] T.S. Szilvia, O. József, M. Makó, G. Palkó, K. Barkács, G. Záray, Comparison of different granular solids as biofilm carriers, Microchem. J. 107 (2013) 101–107.
[21] B. Rusten, B. Eikebrokk, Y. Ulgenes, E. Lygren, Design and operations of the Kaldnes moving bed biofilm reactors, Aquacult. Eng. 34 (2006) 322–331.
[22] R.C. Wang, X.H. Wen, Y. Qian, Influence of carrier concentration on the performance and microbial characteristics of a suspended carrier biofilm reactor, Process Biochem. 40 (2005) 2992–3001.
[23] A.K. Thalla, D. Chella, M. Torrijos, Experimental evaluation of activated sludge–biofilm reactor: Influence of composite media, J. Hazard. Toxic Radioactive Waste 16 (2012) 134–141.
[24] S. Memon, M.C. Paule, B.Y. Lee, R. Umer, C. Sukhbaatar, C.H. Lee, Investigation of turbidity and suspended solids behavior in storm water run-off from different land-use sites in South Korea, Desalin. Water Treat. 53 (2015) 3088–3095.

[25] J. Iqbal1, M.W. Mumtaz, H. Mukhtar, T. Iqbal1, S. Mahmood, A. Razaq, Particle size distribution analysis and physicochemical characterization of Chenab River water at Marala headworks, Pak. J. Bot. 42 (2010) 1153–1161.
[26] M. Rodgers, X.M. Zhan, J. Prendergast, Wastewater treatment using a vertically moving biofilm system followed by a sand filter, Process Biochem. 40 (2005) 3132–3136.
[27] M.G. Nabeel, M.K. Yusoff, Z.A. Ahmad, J. Hafizan, M.F. Ramli, Artificial neural network modeling of the water quality index for Kinta River (Malaysia) using water quality variables as predictors, Mar. Pollut. Bull. 64 (2012) 2409–2420.
[28] V.E. Viau, J.M. Ostera, A. Tolivia, E.L.C. Ballester, P.C. Abreu, E.M. Rodríguez, Contribution of biofilm to water quality, survival and growth of juveniles of the freshwater crayfish *Cherax quadricarinatus* (*Decapoda*, *Parastacidae*), Aquaculture 324–325 (2012) 70–78.
[29] K.Y. Foo, B.H. Hameed, Preparation of activated carbon by microwave heating of langsat (*Lansium domesticum*) empty fruit bunch waste, Bioresour. Technol. 116 (2012) 522–525.
[30] T. Zhang, Y. Fu, Competition for substrate and space in biofilms, Water Environ. Res. 67 (1995) 992–1003.
[31] M. van Loosdrecht, D. Eikelboom, A. Gjaltema, A. Mulder, L. Tijhuis, J. Heijnen, Biofilm structures, Water Sci. Technol. 32 (1995) 35–43.
[32] C. Picioreanu, M. van Loosdrecht, J. Heijnen, Mathematical modeling of biofilm structure with a hybrid differential-discrete cellular automaton approach, Biotechnol. Bioeng. 58 (1998) 101–116.
[33] D. Noguera, G. Pizarro, D. Stahl, B. Rittmann, Simulation of multispecies biofilm development in three dimensions, Water Sci. Technol. 39 (1999) 123–130.
[34] B. Rittmann, M. Pettis, H. Reeves, D. Stahl, How biofilm clusters affect substrate flux and ecological selection, Water Sci. Technol. 39 (1999) 99–105.
[35] T. Wik, Trickling filters and biofilm reactor modelling, Rev. Environ. Sci. Biotechnol. 2 (2003) 193–212.
[36] M. Alimahmoodi, L. Yerushalmi, C.N. Mulligan, Development of biofilm on geotextile in a new multizone wastewater treatment system for simultaneous removal of COD, nitrogen and phosphorus, Bioresour. Technol. 107 (2012) 78–86.
[37] K. Hibiya, J. Nagai, S. Tsuneda, A. Hirata, Simple prediction of oxygen penetration depth in biofilms for wastewater treatment, Biochem. Eng. J. 19 (2004) 61–68.