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Pilot-scale comparison of non-coated and activated carbon-coated cosmoball for removal of organic matter and nutrients from municipal wastewater

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ABSTRACT

The performance of activated carbon–coated cosmoball against non-coated cosmoball regarding organic matter and nutrients removal at different loadings in a biofilm process was investigated. The pilot-scale reactor was successfully designed, constructed and installed at the hostel 10 wastewater treatment plant to facilitate the pumping of a continuous flow from the equalisation tank to the reactor. The flow rates examined included 15, 30 and 60 L/h for the pilot scale, in which the pilot-scale reactor had a useful volume of 90 L. Activated carbon-coated cosmoballs as plastic carriers biofilm reactor were developed for this purpose. Following a monitoring period of 92 d for the coated reactor and 123 d for the non-coated reactor, the results showed BOD_5, COD, total suspended solids (TSS), volatile suspended solids (VSS), turbidity, TP and NH_3–N for non-coated media concentration in effluent were 9.98 mg/L, 31.83 mg/L, 8 mg/L, 5.75 mg/L, 4.29 NTU, 2.80 mg/L and 5.59 mg/L, respectively. While the corresponding concentration for coated media were 3 mg/L, 23.50 mg/L, 2.83 mg/L, 2.44 mg/L, 3.10 NTU, 0.51 mg/L and 2.08 mg/L, respectively at the optimum hydraulic retention time (6 h). Improvements in removal efficiency at the flow rate of 15 L/h (HRT = 6 h) were 6%, 14%, 6%, 4%, 2%, 42% and 18.8% for BOD_5, COD, TSS, VSS, turbidity, TP and NH_3–N, respectively, and improvements of 9%, 13%, 9%, 8%, 6%, 52% and 44.4% at a flow rate of 30 L/h (HRT = 3 h) when coated media was applied. Even at a short retention time in the coated cosmoball reactor (1.5 h), the system showed high potential for removal, almost falling under the Malaysian Standard (*A*) when coated media was used. In essence, the results of this study indicate that coated cosmoballs are considered to be favourable media for improving biological treatment performance. Given this enhancement, coated cosmoballs may practically be employed to facilitate compact treatment or modernise weak-performing treatment plants.

Keywords: Activated carbon; Biofilm; Coating; Domestic sewage; Organic matter; Nutrients

1. Introduction

The construction of traditional sewage treatment facilities and operations tends to be quite expensive and require a large open space to operate efficiently. In addressing this challenge, attempts have been made to construct and enhance traditional treatment plants, offering alternate options along with fewer requirements regarding land, operations, and assembly costs.

From a global perspective, water quality continues to attract significant interest since people require water in carrying out activities on a day-to-day basis. However, to sustain this need, water needs to be treated to make it safe

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for human consumption and other living organisms, such as animals and other forms of wildlife. As such, a compact and efficient system in the treatment of wastewater is needed. Moreover, the availability of land and costs in conjunction with the introduction of ancillary treatment requirements and standards has given rise to the demand and establishment of wastewater treatment facilities in producing high-standard effluent while simultaneously fulfilling the requirements for waste minimisation [1]. Increasing the surface area of the carrier media in a biofilm reactor is just one of many options that could help reduce the necessity and capacity needed for this unit in justifying the costs and other outlays.

Over the last few decades, new technologies have emerged in the form of oxidation ponds, aerated lagoons, package systems, and various types of mechanical plants [2]. One of the current treatment methods uses activated carbon (AC) to remove wastewater pollutants. In 1965, for the first time, a comprehensive innovative (tertiary) plant facility to treat wastewater that incorporated granular AC commenced operating in California at South Lake Tahoe. Granular AC embedded has since been used as a unit process in tertiary treatment systems [3]. Granular AC has also been utilised in reusing effluent from civic plant facilities in the treatment of wastewater for various purposes, such as the use of cooling water in manufacturing and engineering plants, watering of parks, and more. In addition, adsorption with AC has effectively been utilised to advance the treatment of civic and wastewater of various industry sectors such as manufacturing and engineering [4–7]. Numerous studies have tested the application and use of AC against inorganic pollutants such as cadmium [8,9], lead, copper [10,11], methylene blue [12,13], dissolved organic carbon [14], and natural contaminants such as phenol and its by-products [15–18]. Numerous kinds of materials have been examined, believed to be appropriate media to enhance nutrients and other organic matter, such as plastic, fibres, ceramic, sponge and AC [19–22].

Accordingly, the application and use of AC as a coating on plastic media such as cosmoballs as a biofilm media can offer an alternative design for compact treatment plants that tend to be more effective than conventional wastewater treatment systems. Cosmoball is a commercial media with relatively low weight, remains buoyant in water, and is easily removed and cleaned as needed. It has also been proven to remove acceptable levels of organic matter and nutrient successfully. The unique characteristics underlying these systems are mainly attributed to the permeability of AC, which is relatively high, and its high surface area of 426 m^2/g.

These properties can increase the efficiency of treatment processes by adsorption of contaminants by AC and increasing the number of bacteria on their surface that can thrive. Although, the prolonged or lengthy time of these bacteria on organic surface areas in the treatment of contaminated wastewater may give rise to economic problems regarding fiscal outlay needed to construct a basin of a sizeable volume as well as the large space required for its construction. Therefore, new, rougher materials are required to enhance the effectiveness of wastewater treatment from an operational perspective by enhancing the retention of solids in various areas and more affordable by reducing large land areas presently required to operate wastewater treatment plants.

Nevertheless, the main reason for choosing AC as a coating material for high-density polyethylene (HDPE) substrate in this research is due to the material's vast surface area in proportion to its capacity [23,24], which could result in the roughness of the surface area when the substrate is coated. Surface roughness is an important factor in determining the adhesion of bacteria since the surface roughness typically contributes to the adhesion of bacteria, thereby increasing the development of biofilm. Several studies have shown that aerobic microorganisms survive mainly on the surface of carbon particles, with relatively few surviving in carbon pores [25–27]. Some researchers have discovered that surface irregularities offer large surface area for the bacterial cells to shelter by stimulating their adhesion [28]. Similarly, several studies have also shown that bacterial adhesion increases with an increase in the roughness of substratum surfaces. Therefore, this study compares AC-coated cosmoballs against non-coated cosmoballs regarding organic matter and nutrient removal at different loadings.

2. Materials and methods

2.1. Materials

2.1.1. Characterisation of granular activated carbon

The coating material used in this study, granular activated carbon (GAC) was produced from the shell of coconuts. The size of the tiniest particle was 100 μm, and the biggest particle was around 800 μm. The size of the majority of particles was around 363 μm. Particle size analyses for D10, D50 and D90 were 253.1, 443.9 and 748.3 μm, respectively.

2.1.2. Characteristics of the wastewater

The study was performed using wastewater collected from the boarding house at the Engineering Faculty of University Putra Malaysia (UPM) as seeding material for the reactor. The hostel provides accommodation for 340 students, along with a large central kitchen. The main characteristics of raw sewage collected are depicted in Table 1.

2.1.3. Carrier for microbes

The cosmoballs sourced from Putra University (Serdang, Malaysia) were hollow and spherical, produced from tough HDPE plastic with a density of 75 kg/m^3, lower than the density of water and immersed in an aeration tank. The cosmoballs were shaped similar to a ball with eight holes; each hole was around 1 cm in diameter, with each ball having a nominal diameter of 10 cm with cross and lengthwise fins both inside and outside the balls. The cosmoball carriers had a particular biofilm shielded surface area with a bulk volume of 160 m^2/m^3 and a 65% filling ratio suggested by the manufacturer (trademarked by Pakar Management Technology/Malaysia). Fig. 1 illustrates the shape of the cosmoball biofilm carrier.

Table 1
Characteristics of raw sewage (average ± standard deviation)

Parameter	Value
Biochemical oxygen demand (BOD), mg/L	150 ± 20
Chemical oxygen demand (COD), mg/L	290 ± 40
Total suspended solid (TSS), mg/L	120 ± 30
Volatile suspended solid (VSS), mg/L	84 ± 20
Turbidity, NTU	120 ± 40
Ammonium (NH_3–N), mg/L	20 ± 3
Total phosphate, mg/L	6 ± 1.5
Temperature, °C	30 ± 3
pH	7 ± 0.2
Nitrite (NO_2), mg/L	0
Nitrate (NO_3), mg/L	0.4–0.9

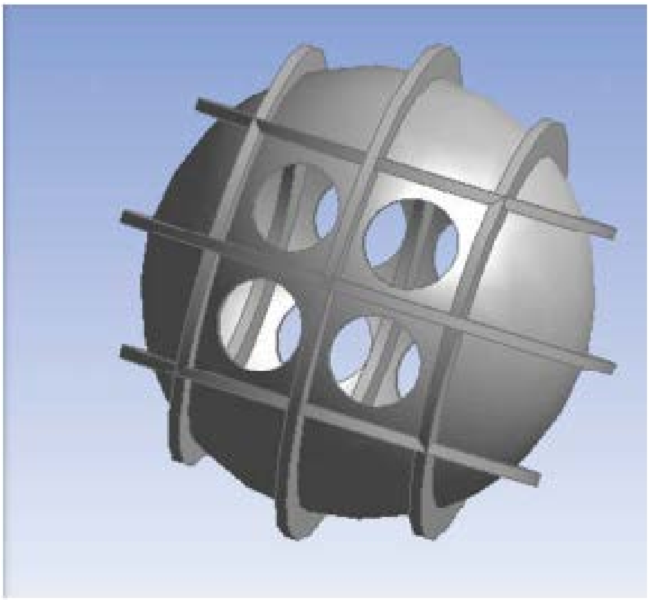

Fig. 1. Cosmoball biofilm carrier.

2.1.4. Laboratory-scale reactor

The laboratory-scale biofilm cosmoball reactor had been installed in the real wastewater treatment plant (WWTP) at the hostel, earlier highlighted, and was produced of translucent PVC, consisting of various units, as shown in Fig. 2.

2.1.4.1. Feeding tank

The feeding tank was a 700-L circular plastic tank fabricated from HDPE, used to receive wastewater from the raw point of the wastewater treatment station before transferring to the reactor. Mixing inside the feeding tank was performed using a mechanical stirrer to produce homogenous sewage.

2.1.4.2. Peristaltic pump

A peristaltic pump (Heidolph Pumpdrive 5206) was utilised in pumping the influent originating out of the feeding tank into the reactor where the inlet was located in the anoxic zone. The pump with the flow rate of 5, 10 and 20 L/h, and a plastic tube of 4 mm in diameter were used to supply the influent. The same type of peristaltic pump was used to recycle the flow from the top of the settling tank to the anoxic zone. The flow rate of this pump was 10, 20 and 40 L/h.

2.1.4.3. Anoxic tank

In order to prevent algae growth, the reactor was wrapped in aluminium foil. The anoxic tank was fabricated from an acrylic sheet. The tank's size and volume had the following dimensions; length, width, and depth of 26, 20 and 50 cm (26 L net capacity), respectively, and a hydraulic retention time (HRT) at 1.5 h. During the denitrification process, which was carried out to achieve an anoxic environment, no oxygen was supplied to this zone.

2.1.4.4. Aerobic reactor

The aeration tank was fabricated using a 70 × 50 × 26 cm acrylic sheet with a working volume of 90 L and operated

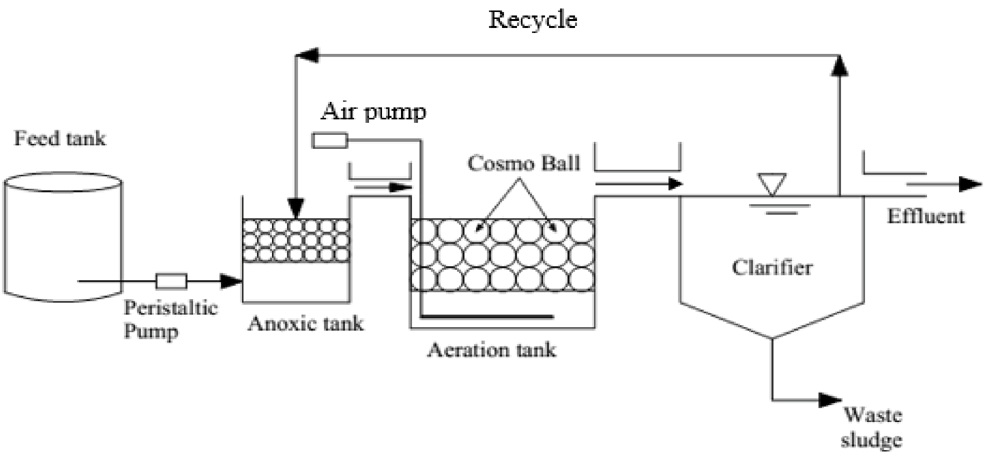

Fig. 2. Illustration of the laboratory-scale cosmoball system.

to follow three retention times of 6, 3 and 1.5 h. The reactor was filled with a 65% standard filling ratio of the cosmoball media for non-coated and coated media. At the bottom of the aeration tank, five air diffusers were installed to supply oxygen for the microorganisms. The dissolved oxygen (DO) concentration was maintained above 2 mg/L inside the aeration tank to conserve the biofilm, thereby maintaining an optimal condition. The reactor used a filtering system with an up-flow system in which influent was pumped to the top from the bottom of the reactor.

2.1.4.5. Settling tank

The settling tank made of plastic was used to collect the treated sewage. The dimensions of this tank varied depending on the flow with an HRT of 1.5 h.

2.2. Methods

2.2.1. Paint-spray-dry method

The cosmoballs were coated with GAC, sized between 100 and 800 μm. Before applying the coating, the AC was thoroughly rinsed with purified water to remove any signs of ash that might obstruct their pores, followed by drying the AC at room temperature for 1 d. The epoxy method was used to synthesise the AC coating, which was performed by brushing the epoxy onto the HDPE as a foundation layer for the AC to adhere to before spraying the AC onto the substrate (cosmoball). It was then left to dry for 3 h at room temperature. At last, a layer of AC having a thickness of 0.76 mm was applied to the surface. Fig. 3 shows the cosmoball before and after coating.

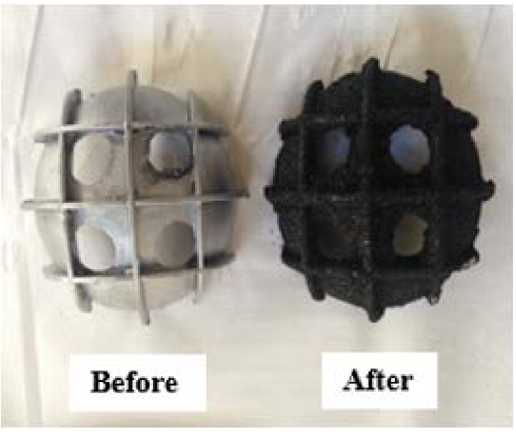

Fig. 3. Cosmoball before and after coating.

2.2.2. Start up of the laboratory scale

The non-coated cosmoballs were positioned in the aeration tank, with the lab-scale operating pump at a flow rate of 5 L/h; the same process for coated cosmoballs. Given that actual civic wastewater was utilised for this experiment, the variability in the wastewater quality was anticipated, although what was not expected was the efficiency of the fixed removal process. Therefore,1 week was given to enable the bacteria the chance to grow. The data collected concerning the performance in running the experiment performance was successfully performed following this period. The steady state was attained approximately after 25 d for the non-coated cosmoballs and 15 d for the coated cosmoballs.

2.2.3. Experimental plan

After the plant (i.e., unit) was stabilised, 2 to 3 experiments each week were successfully conducted. Suja and Donnelly [29] gathered data following 14 days beginning with the flow, which had altered to confirm stabilisation and acclimatisation of the biofilm under its new condition. Pedros et al. [30] for similar reasons, paused for 21 d. Both utilised the same attributes of wastewater. In another study, variable civic wastewater was used by Hameed et al. [31], with a waiting period of 10 d to compensate for any changes that might occur in biofilm behaviour. In this study, the variability of civic wastewater was used, although maintaining the static organic load was not justifiable. As such, the constant or static state condition of biofilm following each alteration of flow was not foreseen. This was similar to work by Hameed et al. [31]. However, despite that, a 7-d waiting period was used.

2.2.4. Analytical methods

The analysis was conducted once the samples arrived at the laboratory. The samples were collected in 2-L plastic containers and immediately analysed for BOD, COD, total suspended solids (TSS), NH_3–N, NO_3, TP, VSS, pH, temperature, and turbidity at three locations, namely influent, anoxic, and effluent, in accordance with the standard method (5210) as articulated by the American Public Health Association (APHA) in determining BOD_5, (5220 C) for COD, (2540 D) for TSS, (2540 B) for VSS (4500–NH–3 C) for ammonia nitrogen, (4500–P C) for the determination of TP following absorption [32]. Nitrate according to 4500 NO_3, and DO concentration and pH, was also used in the determination utilising an O_2 electrode in addition to a pH electrode, respectively. In this experiment, the oxygen level that was dissolved (DO) was kept above 2 mg/L by continuously supplying air to the aeration tank as recommended by several other researchers [33,34]. pH of the wastewater before treatment in the present research remained at approximately 7.2 ± 0.2.

The experiments were conducted to determine the impact of three different HRTs regarding the ability of the non-coated and coated media to remove organic matter and nutrients. The recommended HRT for the experimental setup was 6, 3 and 1.5 h, respectively, with a filling ratio of 65%.

3. Results and discussion

3.1. Removal of organic matter

3.1.1. Effect of HRT on BOD_5 removal by non-coated and coated cosmoballs

The removal of organic matter is typically carried out in a secondary treatment plant and is one of the main targets to achieve domestic effluent treatment [35]. This process is evaluated regarding the reduction of BOD_5 and COD. The wastewater treatment using non-coated and coated cosmoballs was executed continuously for 123 and 92 d, respectively. Three HRTs were evaluated: 6, 3 and 1.5 h with a 65% filling ratio. Fig. 4 displays (a) the BOD_5 concentration for non-coated cosmoball and (b) coated cosmoball.

The initial run (1) was operated for 102 and 46 d for the non-coated and coated balls, respectively, with an HRT of 6 h until steady conditions were attained. The steady-state condition was assumed when the BOD_5 concentration for 7–10 consecutive effluents did not vary by more than 10% [36].

The recorded average values of the BOD_5 concentration for the influent were 118.3 and 134.6 mg/L for non-coated and coated balls, respectively. The average effluent BOD_5 concentration for the non-coated and coated balls with an HRT of 6 h reached 9.9 and 3 mg/L, respectively. The second run (2) was established when the flow was increased to 30 L/h (HRT = 3 h) and was operated for approximately 3 weeks for both non-coated and coated cosmoballs. During this period, the effluent concentration was increased to 19.2 mg/L for the non-coated balls and 8.08 mg/L for the coated balls due to the decrease in HRT (3 h) and 11.88 mg/L at a flow rate of 60 L/h (HRT = 1.5 h) for the coated media, as shown in Fig. 4b. The removal efficiencies for the non-coated and coated cosmoballs were 91.6% and 97.9% at the flow rate of 15 L/h, respectively, with a sufficient HRT of 6 h. Meanwhile, at a flow rate of 30 L/h, the BOD_5 removal was reduced to 84% for non-coated balls and 92.9% for coated balls.

Here, the coated media attained a 91% removal efficiency at the flow rate of 60 L/h (HRT = 1.5 h); the non-coated media was not studied under a flow rate of 60 L/h (HRT = 1.5 h) since the effluent concentration at the flow rate of 30 L/h was almost similar to that of the Malaysian Standard (20 mg/L). Also, significant deterioration was evident given the short HRT of 1.5 h. On the other hand, the enhancement of cosmoball performance was evident when AC coated the media. Here, an improvement of 6.17% and 8.9% at a flow rate of 15 and 30 L/h, respectively, was achieved when coated media were applied in the aeration tank, as depicted in Table 2.

According to Chrispim and Nolasco [37], they used a moving bed biofilm reactor to treat grey water. The operating condition applied an HRT of 4 h, the ratio of filling was 14%, and the biofilm surface area was 490 m^2/m^3. The average BOD_5 effluent concentration of 44.37 mg/L along with the consequent removal efficiency was 59%. Similarly, Valipour et al. [38] conducted a study to treat domestic wastewater using a miniature plastic packing matrix referred to as "Bio-cache", which provides a surface area of 300 m^2/m^3 with 100% filling ratio and at an optimum HRT of 2 h where approximately 88% BOD_5 removal was achieved. However, based on the present study and the research conducted by other researchers, it can be concluded that using coated cosmoballs is a highly efficient system for the removal of BOD_5 in which the removal efficiency between 95% and almost 98% can be achieved for a BOD_5 concentration up to 200 mg/L when the system is operated with an HRT of 6 h, and a removal efficiency up to 93% when the system is operated with an HRT of 3 h. Therefore, the coated cosmoballs justified that the percentage removal of BOD_5 was higher than that achieved by Chrispim and Nolasco [37], and Valipour et al. [38], given the roughness of the surface caused by the AC leading to the higher surface area.

From the discussion above, the removal efficiency fell as the HRT reduced, despite the extremely short time (HRT = 1.5 h) in the case of the flow rate at 60 L/h, the removal efficiency, which was significant, was observed when applying the coated media.

3.1.2. Effect of HRT on COD removal by non-coated and coated cosmoballs

As shown in Figs. 5a and b, the COD behaviour is similar to that of BOD_5 behaviour and displays the plots for COD concentration with the time depicted in the feeding, anoxic and effluent stage for both non-coated and coated balls. COD concentration in the feeding tank was recorded at 263 and 295 mg/L for non-coated and coated balls, respectively. The COD concentrations for the effluent were 31.8 and 23.5 mg/L at a flow rate of 15 L/h (HRT = 6 h) for the non-coated and coated balls, respectively, and at a flow rate of 30 L/h (HRT = 3 h), the effluent concentration was

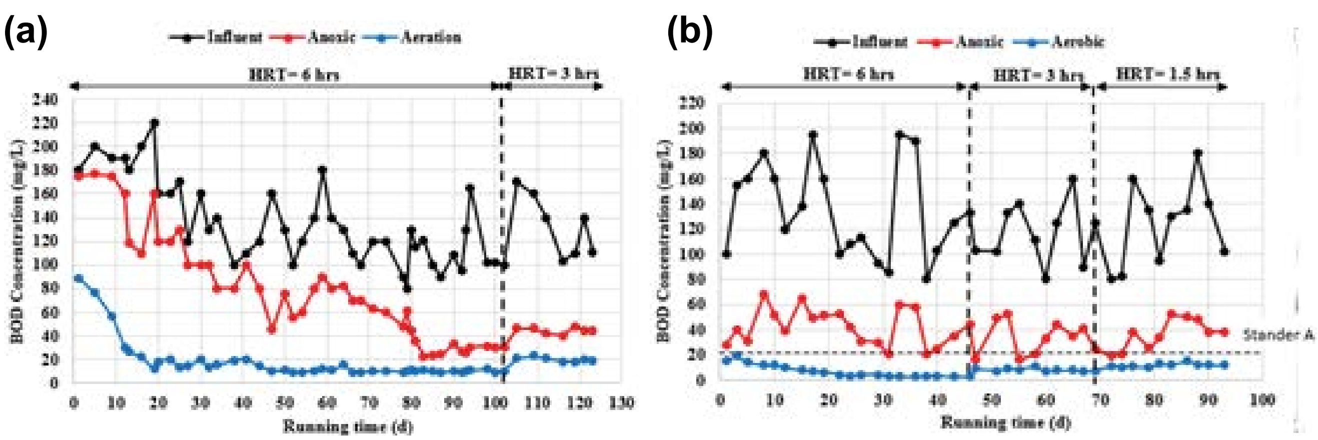

Fig. 4. BOD_5 concentration vs. time for (a) non-coated cosmoball and (b) coated cosmoball.

Table 2
Average BOD_5 effluent and removal efficiency

Hydraulic retention time (h)	Flow (L/h)	BOD_5				
		Non-coated media		Coated media		Improvement (%)
		Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)	
6	15	9.9	91.6	3	97.7	6.17% better
3	30	19.2	84	8.08	92.9	8.9% better
1.5	60	–	–	11.88	91	–

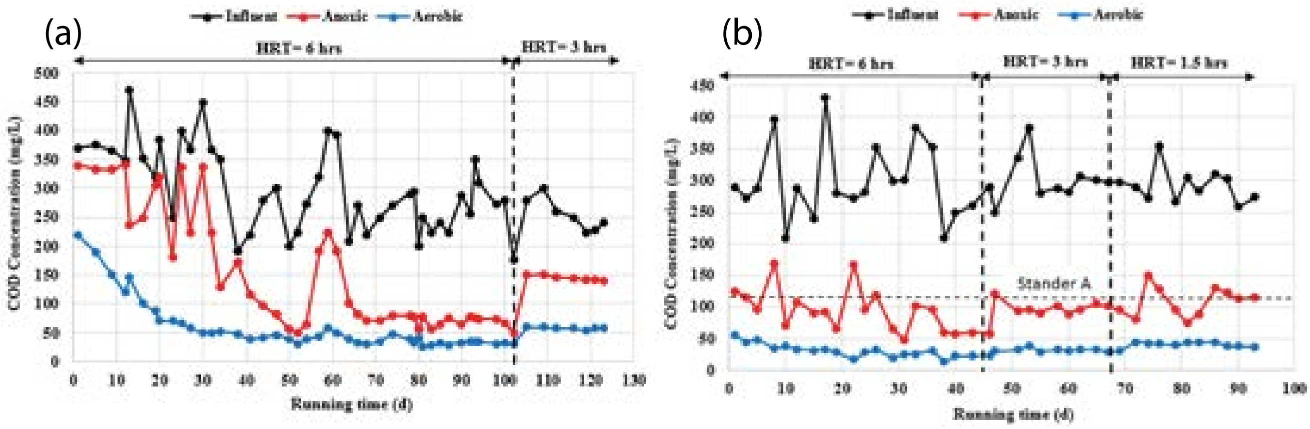

Fig. 5. COD concentration vs. time for (a) non-coated cosmoball and (b) coated cosmoball.

increased to 56.6 mg/L for the non-coated balls and 31 mg/L for the coated balls. At the flow rate of 60 L/h (HRT = 1.5 h), a slight declination of COD concentration was observed for the coated balls, recording 40.9 mg/L, which is still below the Malaysian Standard (A = 120 mg/L).

Table 3 presents the COD removal efficiency for the non-coated and coated cosmoballs. The overall efficiency of removal was established on the final effluent of the reactor. It was found that the average efficiency of COD removal was 88% and 92% for the non-coated and coated balls, respectively, for an HRT of 6 h, while at a flow rate of 30 L/h (HRT = 3), a slight declination was observed for the non-coated balls with the efficiency decreasing to 76%; thus, exceeding the standard level due to the low HRT of 3 h. The high removal efficiency of 89% was observed with the same flow in which 86% removal efficiency was recorded for the coated media at a flow rate of 60 L/h (HRT = 1.5 h), maintained below the Malaysian Standard A.

It was also observed that the removal efficiency was high in the reactor containing coated cosmoballs and stable over 10 d compared with the reactor containing non-coated cosmoballs reported to be stable over 30 d. As such, this suggests that the heterotrophic bacteria responsible for degrading the carbonaceous components were enriched in the coated part of the reactor given the vast area and roughness of the surface [39].

Several studies regarding the removal of COD from civic wastewater using attached media were recently conducted. Zinatizadeh and Ghaytooli [40] examined two types of media, namely, Ring form and Kaldnes–3. The packing media used in the study was similar to the specific surface area of 500 m^2/m^3 with a 50% filling ratio; the experiments were performed with an HRT of 12 h in two parallel reactors. The highest COD removal efficiency was recorded at 85% and 88%, respectively.

Zhang et al. [41] in their study compared natural ventilation trickling filters and a range of carriers, namely, ceramsite, zeolite and sponge, to treat civic wastewater. The filling ratios were 85%, 50% and 65%, with a specific surface area of 1,000; 300 and 700 m^2/m^3, respectively. The effectiveness of COD removal was recorded in the range of sponge > ceramsite > zeolite, associated with the particular surface area of these biofilm carriers. A COD removal efficiency of 90% was achieved when using a suspended carrier biofilm reactor in treating synthetic civic wastewater with an HRT of 4 h [42].

Accordingly, by comparing this study on coated vs. non-coated media and the studies reported by the other researchers, it can be concluded that the reactors with coated media provide an extremely efficient system for removing COD with a removal efficiency of 92% and 89% with an HRT of 6 and 3 h, respectively. Likewise, 4% enhancement in performance was recorded with an HRT of 6 h and an enhancement in performance of 13% with an HRT of 3 h. This was better due to the effect of the coated balls on removing COD. Moreover, despite the extremely short HRT in the case of a flow rate of 60 L/h, the significant removal efficiency of 86% was achieved when coated balls were introduced.

Table 3
Average COD effluent and removal efficiency

Hydraulic retention time (h)	Flow (L/h)	COD				
		Non-coated media		Coated media		Improvement (%)
		Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)	
6	15	31.8	88	23.5	92	4% better
3	30	56.6	76	31	89	13% better
1.5	60	–	–	40.9	86	–

3.1.3. Effect of HRT on TSS and VSS removal by coated and non-coated cosmoballs

Given the sloughing of biofilm in these affixed systems, causing frequent uncertainty or irregularity, the TSS was quantified as indicators of the system's stability. Since TSS and VSS follow a similar trend, and VSS is almost 80% of TSS, the results are combined. The concentration of TSS against the running time is illustrated in Figs. 6a and b for non-coated and coated cosmoballs, respectively. The average influent concentrations of TSS for non-coated and coated media were 121 and 144.5 mg/L, respectively. In contrast, the effluent concentrations of TSS were 8 and 2.83 mg/L with an HRT of 6 h, and 17.4 and 7.21 mg/L with an HRT of 3 h for non-coated and coated media, respectively, and recorded 9.6 mg/L when coated media was used with an HRT of 1.5 h.

As observed in the figures, the results are relatively stable from the first day of the process when the coated media was applied, though taking quite a while for the process when non-coated cosmoballs were used. There is no doubt that the roughness of the surface plays a key role in TSS removal since the TSS adhered more robustly to the coated surface compared with the smooth surface given the roughness of the AC coating.

Table 4 below shows the average TSS effluent and RE for the non-coated and coated cosmoballs, showing 92% and 98%, respectively, with an HRT of 6 h. This indicates an improvement of 6%, resulting in 86% and 95% efficiency, with an HRT of 3 h, 9% better removal. The improvement in TSS removal was due to the application of the AC coating, which can be seen even at an extremely short HRT (1.5 h), recording efficiency of 93%, using an HRT of 6 h in the non-coated media process.

In the biofilm system, biomass was attached to the carrier, where bacteria growing the biofilm expanded in thickness, and consequently, flocs of bacteria began to disengage from the biofilm mainly due to the hydrodynamics. The flocs that had disengaged (VSS) then remained in the secondary clarifier generating secondary sludge.

Figs. 7a and b show VSS concentration, in which the average VSS concentration of influent was 84.2 and 103 mg/L for the non-coated and coated media, respectively. The VSS concentration of effluent for the non-coated and coated media was 5.75 and 2.44 mg/L, respectively; not a significant difference for an HRT of 6 h (flow = 15 L/h). The corresponding concentration for an HRT of 3 h (flow = 30 L/h) was 11.7 and 5.16 mg/L, resulting in a better RE of 8% when coated media was introduced. Table 5 summarises the average VSS effluent and RE of VSS by the non-coated and coated media. As mentioned earlier, 94% and 98% removal was achieved, respectively, with an HRT of 6 h, recording a 4% improvement when the coated media was applied, and 87% and 95% improvement for an HRT of 3 h; achieving an improvement of 8% for the coated media. Even at an extremely low HRT of 1.5 h (flow = 60 L/h), 92% removal could be achieved by the coated media.

According to El-Shafai and Zahid [43], they employed an up-flow biofilm reactor that was submerged comprised

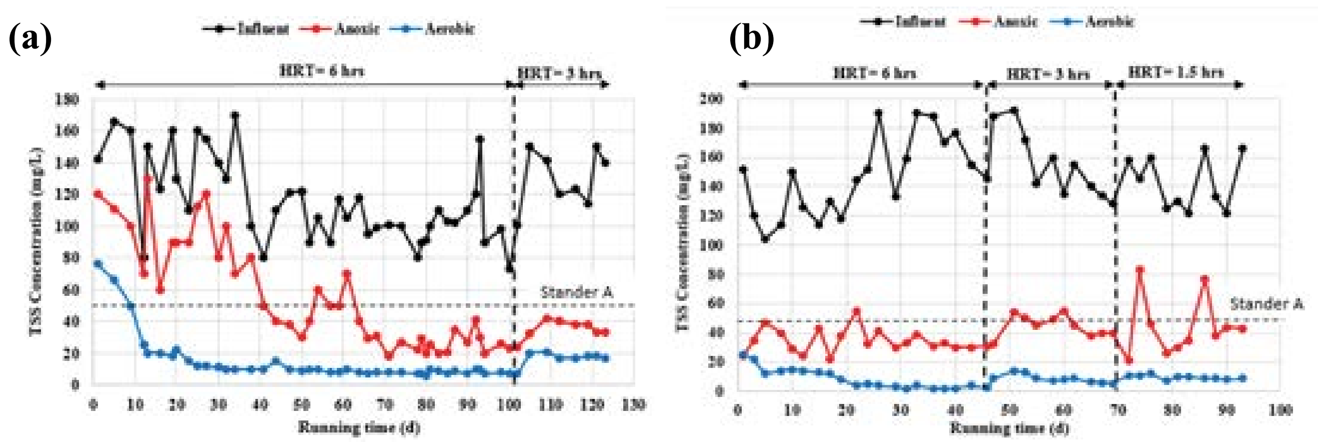

Fig. 6. TSS concentration vs. time for (a) non-coated cosmoball and (b) coated cosmoball.

Table 4
Average TSS effluent and removal efficiency

Hydraulic retention time (h)	Flow (L/h)	TSS				
		Non-coated media		Coated media		Improvement (%)
		Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)	
6	15	8	92	2.8	98	6% better
3	30	17.4	86	7.21	95	9% better
1.5	60	–	–	9.6	93	–

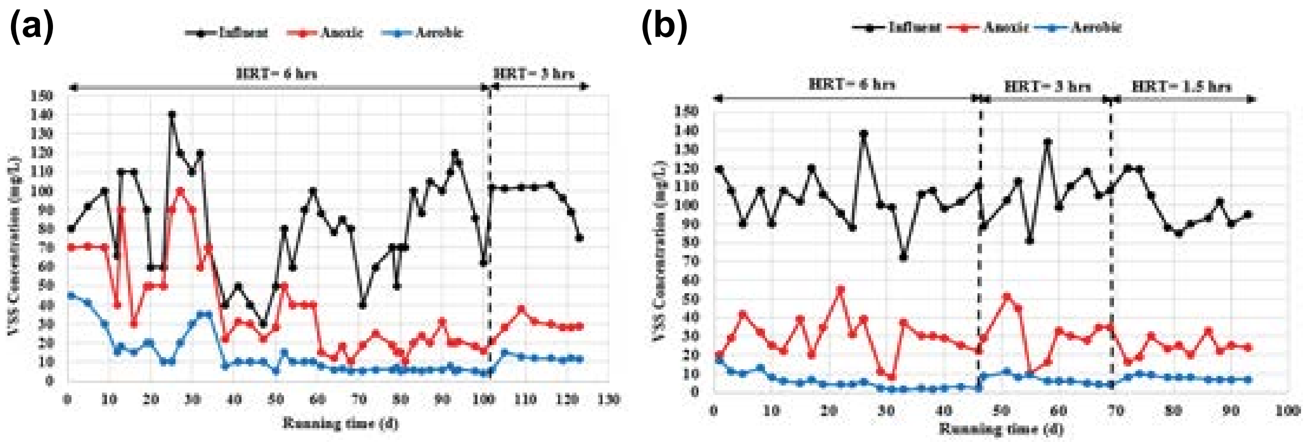

Fig. 7. VSS concentration vs. time for (a) non-coated cosmoball and (b) coated cosmoball.

Table 5
Average VSS effluent and removal efficiency

Hydraulic retention time (h)	Flow (L/h)	VSS				
		Non-coated media		Coated media		Improvement (%)
		Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)	
6	15	5.75	94	2.44	98	4% better
3	30	11.7	87	5.16	95	8% better
1.5	60	–	–	6.83	92	–

of scoria at a 70% filling ratio to treat municipal wastewater. The hydraulic loading rate was varied between 3.5 and 5.2 L/d while the TSS concentration was 175 ± 31 mg/L. The results of their work indicated that the effluent was 9 mg/L with a corresponding RE of 95%. Indeed, this was slightly higher and comparable with the TSS RE of 92% achieved in the current study when using non-coated media, though it was slightly lower than the TSS RE of 98% when coated media was used. In another study, where domestic wastewater was treated in an Moving Bed Biofilm Reactor, a TSS RE of 76.5% was reported by Andreottola et al. [44].

The TSS and VSS removal mechanism when using a coated surface is considered a natural process. In this situation, particles bond or adhere to the coated surface given the high surface roughness compared with the smoother surface of the non-coated surface media.

Nevertheless, based on the results of using media non-coated and coated media, it can be concluded that the TSS and VSS RE from 4% to 9% was better when coated media was used compared with non-coated media and of previous studies cited in the literature. This could be attributed to the high surface area in addition to higher surface roughness.

3.2. Removal of nutrients

3.2.1. Effect of HRT on ammonia removal by coated and non-coated cosmoballs

Concerning nitrogen removal, in this experiment, the influent NH_3–N concentration ranged between 14 and 26 mg/L for both coated and non-coated media, with a mean effluent concentration of 5.6 mg/L and an HRT of 6 h, which dramatically increased with an HRT of 3 h (flow 30 L/h), recording 15.2 mg/L when non-coated media was used (Fig. 8a). However, when coated media was introduced at a flow rate of 15 L/h, the effluent was recorded at 2.1 mg/L with a slight decline observed at a flow rate of 30 L/h (HRT = 3 h), in which the concentration of 5.4 mg/L was observed to be slightly higher than the Malaysian Standard (A = 5 mg/L). However, significant deterioration was observed using a flow rate of 60 L/h, given the extremely brief HRT of 1.5 h, as shown in Fig. 8b.

For non-coated media, during the initial stage, including the following 20 d, the recycle flow from the top of the clarifier tank to the anoxic zone was 50% (half that) of the in-flow rate. However, a surprising reaction then occurred, and the ammonia concentration of the effluent was higher than that in the influent. The removal recorded was less than zero (0), as reflected in Fig. 5a. Following 20 d, the recycle flow increased from 50% to 100% for 25 d, and the RE improved slightly to around 15%, which is considered quite low. The recycle flow was then increased to 200% of the influent, and the improvement in RE resultantly became much higher at 69% with an HRT of 6 h and 23% with an HRT of 3 h, as shown in Fig. 9a.

Indeed, this issue was avoided when coated media was used by making the recycled flow from the top of the clarifier to the anoxic tank 200% of the in-flow rate to achieve the denitrification process. Fig. 9b shows that the RE achieved was much higher compared with non-coated media was used, which recorded 88%, 67% and 36% with an HRT of 6, 3 and 1.5 h, respectively.

As mentioned earlier, regarding Figs. 8a and b, the ammonia concentration in the final treated wastewater in the aerobic zone was shown to be the lowest compared with the concentration in the anoxic effluent. This was due to the nitrification process, which occurred in the aerobic zone. Thus, ammonia nitrogen was oxidised to nitrate over nitrites, and complete nitrification occurred. Here, ammonia and nitrites nitrogen were removed, producing nitrate.

Table 6 summarises the average ammonia effluent and RE. Here, an improvement of 18.8% and 44.4% at 6 and 3 h retention time was achieved when coated media was used. Throughout the experiment, it can be seen that the reactor performed significantly better when using coated media than non-coated media.

Fig. 10 depicts the nitrate concentration for the treatment plant when coated and non-coated media were used. It clearly shows that the nitrate concentration decreased

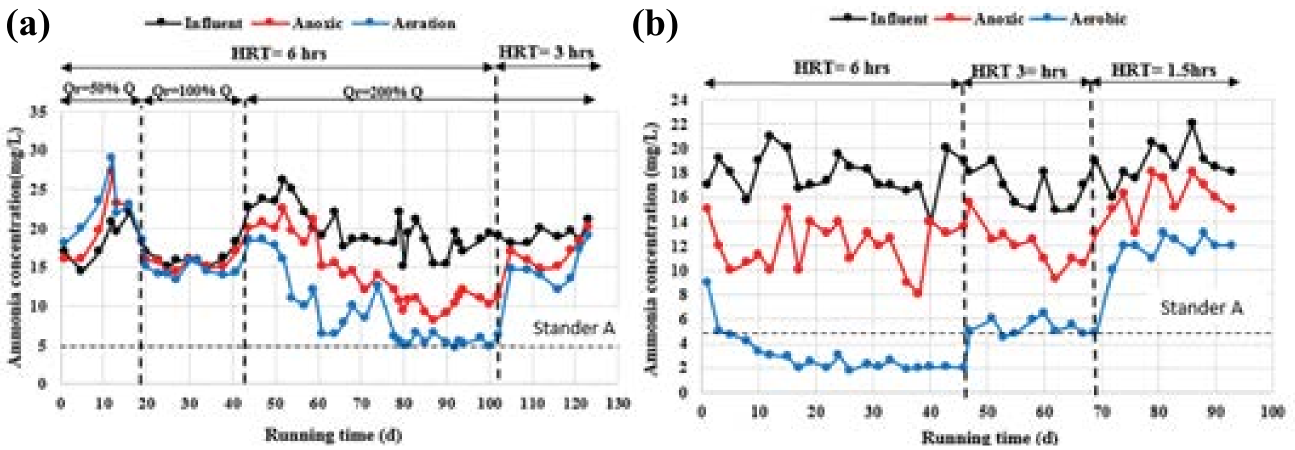

Fig. 8. Ammonia nitrogen concentration vs. time for (a) non-coated cosmoball and (b) for coated cosmoball.

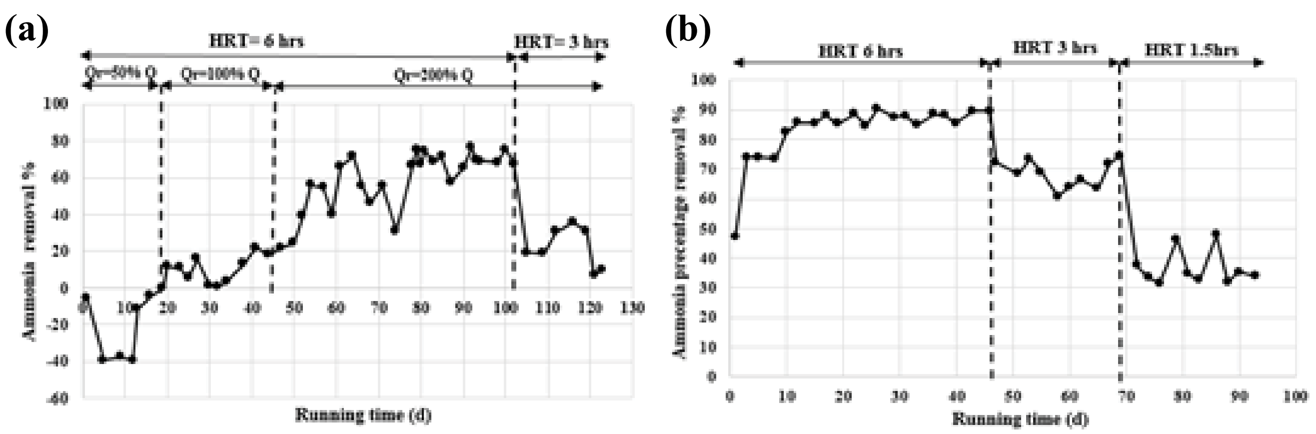

Fig. 9. Ammonia nitrogen removal by (a) non-coated cosmoball and (b) coated cosmoball.

Table 6
Average ammonia effluent and removal efficiency

Hydraulic retention time (h)	Flow (L/h)	Ammonia removal				
		Non-coated media		Coated media		Improvement (%)
		Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal%	
6	15	5.6	69.2%	2.08	88%	18.8% better
3	30	15.1	22.6%	5.43	67%	44.4% better
1.5	60	–	–	12.3	37%	–

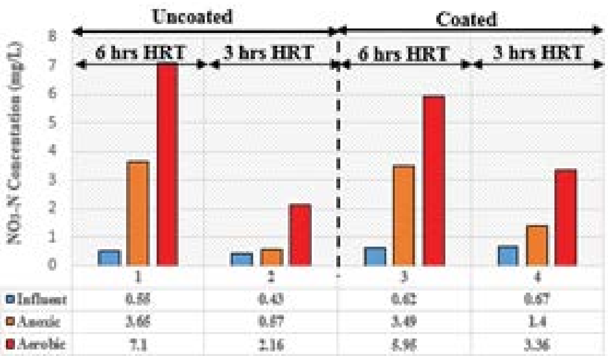

Fig. 10. Nitrate concentration under feeding, anoxic and aerobic conditions when coated and non-coated media were used at HRT of 6 and 3 h.

in the anoxic zone and increased in the aerobic zone. The nitrate concentration was twofold higher in the aerobic zone than in the anoxic zone. This was due to the transformation to nitrate from ammonia in addition to nitrite to nitrate, which occurred during the denitrification process, reducing nitrate to nitrogen gas. Similarly, recirculation played a key part in carrying mixed liquid between the aerobic and anoxic zones. The results show that the highest amount of nitrate in the aerobic zone was due to the production of nitrate in the nitrification process.

Furthermore, with an HRT of 6 h, the concentration of NO_3–N increased from the anoxic to the aerobic zone from 3.65 to 7.1 mg/L and from 3.49 to 5.95 mg/L for the non-coated and coated media, respectively. The percentage of ammonia removal was 67% and 88% for the non-coated and coated media, respectively. For an HRT of 3 h, the nitrate concentration increased from the anoxic to the aerobic zone from 0.57 to 2.16 mg/L and from 1.4 to 3.36 mg/L for non-coated and coated media, respectively. This clearly shows that a decrease in HRT will decrease nitrate concentration given the decrease in ammonia removal. In contrast, 85% and 80% NH_4–N removal were obtained by Ahmed et al. [45] with an HRT of 24 and 18 h when using cosmoballs to treat textile wastewater. They concluded that for any further decrease in the HRT, it would result in a gradual reduction in RE.

Likewise, several other researchers mentioned that nitrification would never reach 100% since the aeration time would be exceedingly short to allow nitrification [45–47]. The reason given may support the result obtained in the current study, in which the highest percentage of nitrification achieved was 69% and 88% for non-coated and coated media, respectively. Therefore, the highest nitrification efficiency achieved with coated media was related to the high HRT, which was conducive to good growth of nitrifying bacteria given the high surface area and high surface roughness.

3.2.2. Effect of HRT on total phosphorus (TP) removal by coated and non-coated cosmoballs

Fig. 11a shows the concentration of phosphorus vs. time for a monitoring period of 4 months when non-coated media was used. Fig. 11b shows the concentration of phosphorus vs. time (92 d) when coated media was used. The average influent concentrations were 5.17 and 5.01 mg/L for non-coated and coated media, respectively. In the anoxic part of the reactor where non-coated media with an HRT of 6 h (flow = 15 L/h) and 3 h (30 L/h) was used: the average TP concentrations for each respective HRT were 3.10 and 3.55, while for coated media it was 1.03 and 0.91 and 1.62 mg/L with an HRT of 1.5 h.

Moreover, the effluent concentrations when non-coated media was used were 2.73 and 3.01 mg/L for an HRT of 6 and 3 h, respectively. However, there was a noticeable drop in these values when coated media was introduced in the aeration tank; the values were 0.52 and 0.59 mg/L, respectively. Therefore, it is evident that AC plays a significant part in improving the reactor's performance, even at a low HRT of 1.5 h (flow = 60 L/h) when the concentration fell below the Malaysian Standard (A = 1 mg/L), achieving 0.92 mg/L.

Table 7 shows the average TP effluent and RE. Here, phosphate removal efficiencies were exceptionally low, at around 47% and 36% at a flow rate of 15 L/h (HRT = 6 h) and 30 L/h (HRT = 3 h), respectively, using non-coated media. This low percentage was anticipated given no chemicals were added to the system, and no alternative methods were used, such as biological treatment for phosphorus removal. However, as suspended solids in wastewater contain phosphates, similar to body waste and food deposits [31], it is anticipated that low removal of phosphate would be obtained by eliminating those solids from the wastewater. Although the removal rate was beyond expectation, 89% and 88% at a flow rate of 15 L/h (HRT = 6 h) and 30 L/h (HRT = 3 h), respectively. Even at a high flow rate of 60 L/h, this removal only slightly decreased to 82%, given the short HRT of 1.5 h when coated media was used without adding any chemicals.

Even though a significant improvement of 42% and 52% can be seen in Table 3 with a HRT of 6 and 3 h due to the coated media application being extremely poor, Boki

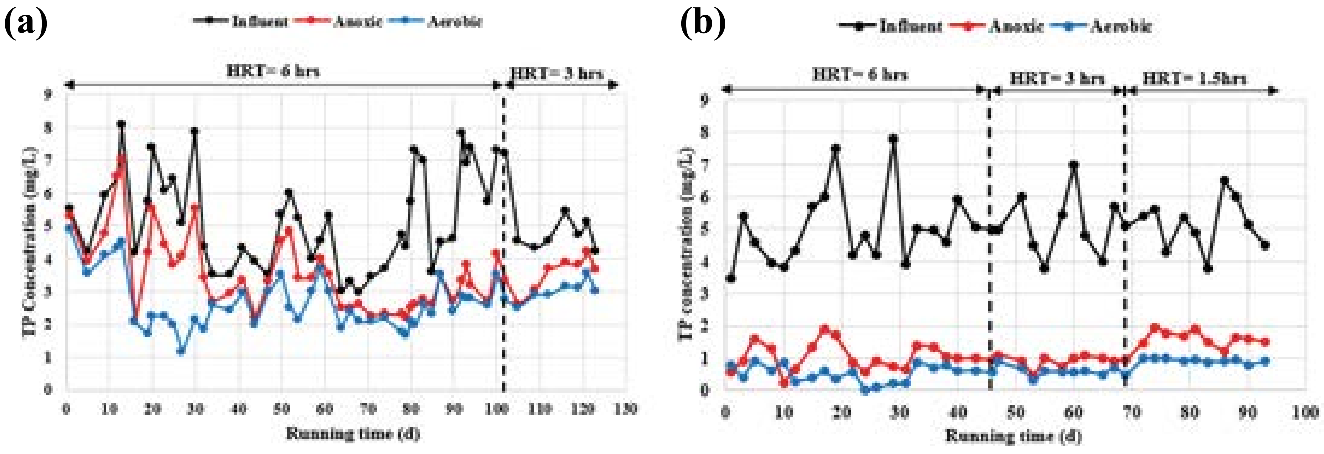

Fig. 11. TP concentration vs. time for (a) non-coated cosmoball and (b) coated cosmoball.

et al. [48] stated that the rate of phosphate adsorption on AC increases with increasing pore volume. There is no doubt that this high removal percentage is due to AC, which serves as an adsorbent via the adsorption process resulting from the higher surface area and pore volume.

3.3. Effect of HRT on turbidity removal by coated and non-coated cosmoballs

The results of the turbidity removal for all experiments are presented in Table 8, showing that the average turbidity concentration for the influent is 114.3 and 126.7 NTU for non-coated and coated media, respectively. On the other hand, the effluent concentration varied depending on the HRT. Here, the turbidity concentration for the effluent is 4.29 and 3.10 NTU for the flow rate of 15 L/h (HRT = 6 h) for non-coated and coated balls, respectively. For the flow rate of 30 L/h (HRT = 3 h), the concentration was recorded at 9.7 and 3.74 NTU for non-coated and coated balls, respectively.

As shown in the table, the intensity of turbidity at the coated media remains better for coated media at an HR of 3 h than 6 h for the non-coated media, thereby confirming that AC can adsorb the cloudy colour in wastewater. For a flow rate of 60 L/h, the turbidity increased from 3.7 to 7.76 NTU for the coated media, given the low HRT of 1.5 h. The overall RE was determined according to the final effluent of the reactor. It was found that the average efficiency of turbidity removal was 96% and 98% for the non-coated and coated balls, respectively, with an HRT of 6 h, while with an HRT of 3 h, the respective efficiency was 91% and 97%. The lowest removal percentage was recorded at a flow rate of 60 L/h given the short HRT of 1.5 h, which was 94% for the coated media. Therefore, an improvement of 2% and 6%, respectively, was shown when coated cosmoballs were introduced. Hameed et al. [31] achieved a 60% RE increasing to a flow rate of 18 L/min when a tannin-based agent was introduced as a coagulation and flocculation process.

3.4. Effect of temperature, pH and DO on water quality

As with all bacterial activities, nitrification and denitrification are profoundly affected by temperature, pH, and dissolved oxygen (DO) concentration. The ambient temperature in this research was set at 30°C ± 3°C. Yan and Hu [49] observed accelerated nitrification at a temperature between 15°C and 35°C, while Shahot et al. [50] observed the quality of effluent of the activated sludge process at two different temperature ranges, 10°C–15°C and 25°C–30°C and found that higher efficiency was recorded during the high-temperature season. Other researchers likewise reported observing an enhanced nitrification process at a higher temperature [36–51].

Sensitive organisms, such as nitrifying bacteria, are exceedingly vulnerable to a broad range of inhibitors. For instance, DO is one of the main factors affecting bacterial

Table 7
Average TP effluent and removal efficiency

Hydraulic retention time (h)	Flow (L/h)	TP				
		Non-coated media		Coated media		Improvement (%)
		Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)	
6	15	2.73	47%	0.52	89.6%	42% better
3	30	3.01	36%	0.59	88%	52% better
1.5	60	–	–	0.92	82%	–

Table 8
Average turbidity concentration and its removal

Hydraulic retention time (h)	Flow (L/h)	Turbidity (NTU)				
		Non-coated media		Coated media		Improvement
		Effluent (NTU)	Removal (%)	Effluent (NTU)	Removal (%)	
6	15	4.29	96	3.10	98	2% better
3	30	9.7	91	3.74	97	6% better
1.5	60	–	–	7.76	94	–

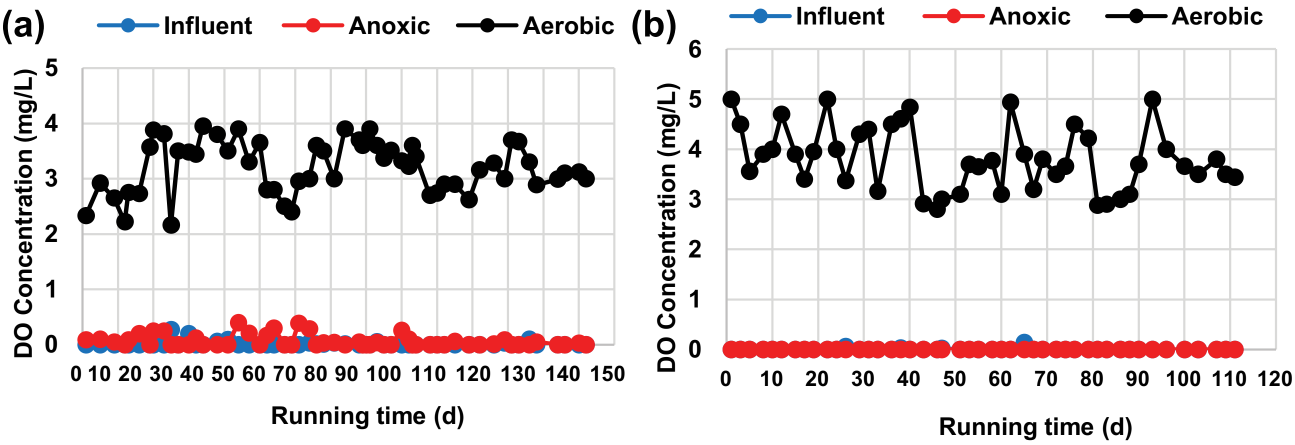

Fig. 12. DO concentration for (a) non-coated and (b) coated media.

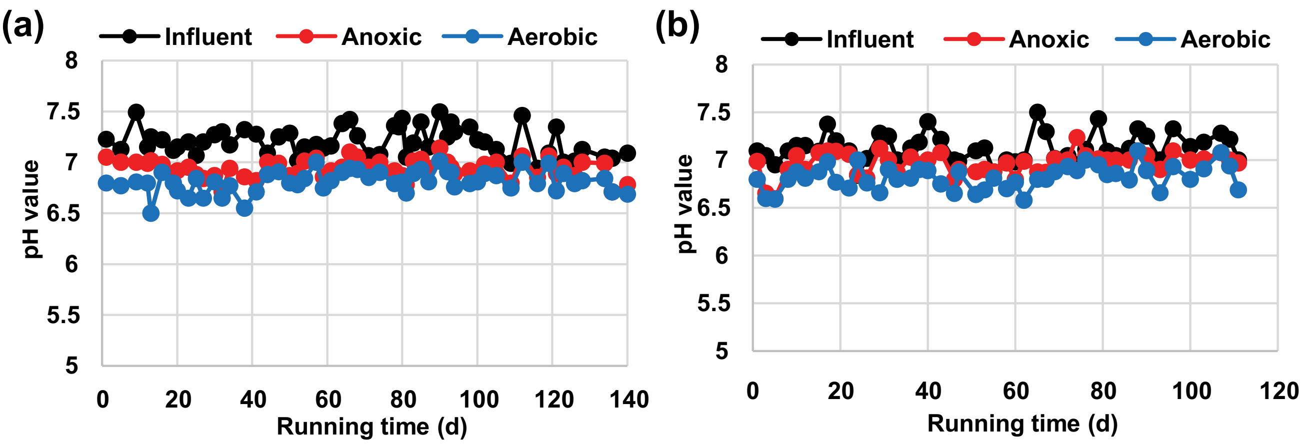

Fig. 13. Variation of pH with time for (a) non-coated and (b) coated media.

activities. The use of non-coated and coated media in the aeration tank resulted in a DO concentration ranging between 2.16 and 4 mg/L for non-coated media and between 2.5 and 5 mg/L for coated media. While in the anoxic zone, the concentration varied from 0 to 0.39 mg/L. The variation in DO in this study is illustrated in Figs. 12a and b for non-coated and coated media, respectively.

Accordingly. based on this study and studies carried out by other researchers [33,34], one can conclude that DO concentration is an important parameter affecting nitrogen removal. For instance, a concentration between 2 and 4 mg/L is required to achieve nitrification and to avoid the possibility of oxygen limitation.

Figs. 13a and b show the pH reading in the feed, anoxic, and aeration tanks of wastewater. The average pH in the influent, anoxic and aerobic tanks when non-coated media was used was 7.20, 6.93 and 6.81, respectively. In contrast, when coated media was used, the average pH was 7.13, 6.96 and 6.82 for influent, anoxic, and aerobic tanks, respectively. It is evident that for both non-coated and coated media, the pH is higher than the feeding tank. However, the net decrease in pH in this study might be due to the removal of acidic compounds.

Nevertheless, as with other biological processes, nitrification is strongly affected by the pH of the system. Numerous studies have shown that the concentration of hydrogen ion is an important factor in nitrification. Nitrification typically decreases as the pH decreases and stops completely when the pH is less than 5. An investigation carried out by Qasim [34] found that the optimum pH for both nitrosomonas and nitrobacter organisms was between 7.2 and 8.5, and nitrification practically stopped when the pH was less than 6.3.

However, the results of this study indicate that the finishing pH of effluent under variable operational conditions was not more than the allowable threshold for standard *A* according to the discharge standards for Malaysian inland waters where the pH value needs to reside between 6 and 9.

4. Conclusion

The improvement of the biofilm reactor due to AC coating on the cosmoballs was evident. The highest removal of TP was achieved with the coated cosmoball reactor achieved over 90% removal, while non-coated cosmoballs only removed 54.6% of TP. For organic removal, the coated cosmoballs achieved 97.6% BOD, 92.2% COD, 98% turbidity and 98.3% TSS compared with non-coated cosmoballs that achieved 91% BOD, 87.8% COD, 96% turbidity and 92.47% TSS. Notably, ammonia removal was found to be significantly higher for coated cosmoballs, 88.1% NH_3–N, in contrast to non-coated cosmoballs, 69.2% at an optimal HRT. However, even at the short retention period of the coated cosmoballs reactor (1.5 h), the system showed a relatively high potential to remove 91% BOD, 86% COD, 93% TSS, 92% VSS, 94% turbidity, 82% TP and only 37% for NH_3–N.

Therefore, in conclusion, the results of this study suggest that coated cosmoballs are promising media to improve the performance of biological treatment. Although given this enhancement, coated cosmoballs could enhance the weak-performance of treatment facilities for wastewater or achieve compact treatment. The performance with an HRT of 3 h when coated media is applied is similar to the performance with an HRT of 6 h when non-coated media is used.

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References

[1] T. Leiknes, H. Ødegaard, Moving bed biofilm membrane reactor (MBB-MR): characteristics and potentials of a hybrid process design for compact wastewater treatment plants, Proc. Eng. Membr., 1 (2001) 52–57.
[2] A.H. Birima, Performance of Membrane Bioreactor in the Treatment of High Strength Municipal Wastewater, Ph.D Thesis, Universiti Putra Malaysia, 2008.
[3] D. Hendricks, Water Treatment Unit Processes: Physical and Chemical, CRC Press, USA, 2006.
[4] A.M. Deegan, B. Shaik, K. Nolan, K. Urell, M. Oelgemöller, J. Tobin, A. Morrissey, Treatment options for wastewater effluents from pharmaceutical companies, Int. J. Environ. Sci. Technol., 8 (2011) 649–666.
[5] N. Areerachakul, S. Vigneswaran, H.H. Ngo, J. Kandasamy, Granular activated carbon (GAC) adsorption-photocatalysis hybrid system in the removal of herbicide from water, Sep. Purif. Technol., 55 (2007) 206–211.
[6] E.A. El-Sharkawy, A.Y. Soliman, K.M. Al-Amer, Comparative study for the removal of methylene blue via adsorption and photocatalytic degradation, J. Colloid Interface Sci., 310 (2007) 498–508.
[7] M.O. Awaleh, Y.D. Soubaneh, Waste water treatment in chemical industries: the concept and current technologies, Hydrol. Curr. Res., 5 (2014) 1–12, doi: 10.4172/2157-7587.1000164.
[8] M. Ajmal, R.A.K. Rao, R. Ahmad, M.A. Khan, Adsorption studies on *Parthenium hysterophorous* weed: removal and recovery of Cd(II) from wastewater, J. Hazard. Mater., 135 (2006) 242–248.
[9] J. Acharya, J.N. Sahu, C.R. Mohanty, B.C. Meikap, Removal of lead(II) from wastewater by activated carbon developed from *Tamarind wood* by zinc chloride activation, Chem. Eng. J., 149 (2009) 249–262.
[10] S. Koutcheiko, C.M. Monreal, H. Kodama, T. McCracken, L. Kotlyar, Preparation and characterization of activated carbon derived from the thermo-chemical conversion of chicken manure, Bioresour. Technol., 98 (2007) 2459–2464.
[11] K. Kadirvelu, K. Thamaraiselvi, C. Namasivayam, Removal of heavy metals from industrial wastewaters by adsorption onto activated carbon prepared from an agricultural solid waste, Bioresour. Technol., 76 (2001) 63–65.
[12] A.F. Hassan, H. Elhadidy, Production of activated carbons from waste carpets and its application in methylene blue adsorption: kinetic and thermodynamic studies, J. Environ. Chem. Eng., 5 (2017) 955–963.
[13] H. Deng, L. Yang, G. Tao, J. Dai, Preparation and characterization of activated carbon from cotton stalk by microwave assisted chemical activation—application in methylene blue adsorption from aqueous solution, J. Hazard. Mater., 166 (2009) 1514–1521.
[14] W. Xing, H.H. Ngo, S.H. Kim, W.S. Guo, P. Hagare, Adsorption and bioadsorption of granular activated carbon (GAC) for dissolved organic carbon (DOC) removal in wastewater, Bioresour. Technol., 99 (2008) 8674–8678.
[15] R.L. Tseng, F.C. Wu, R.S. Juang, Liquid-phase adsorption of dyes and phenols using pinewood-based activated carbons, Carbon, 41 (2003) 487–495.
[16] A. Kumar, S. Kumar, S. Kumar, D.V. Gupta, Adsorption of phenol and 4-nitrophenol on granular activated carbon in basal salt medium: equilibrium and kinetics, J. Hazard. Mater., 147 (2007) 155–166.
[17] S. Nouri, F. Haghseresht, Adsorption of p-nitrophenol in untreated and treated activated carbon, Adsorption, 10 (2004) 79–86.
[18] F.C. Wu, R.L. Tseng, R.S. Juang, Comparisons of porous and adsorption properties of carbons activated by steam and KOH, J. Colloid Interface Sci., 283 (2005) 49–56.
[19] L. Deng, W. Guo, H.H. Ngo, X. Zhang, X.C. Wang, Q. Zhang, R. Chen, New functional biocarriers for enhancing the performance of a hybrid moving bed biofilm reactor–membrane bioreactor system, Bioresour. Technol., 208 (2016) 87–93.
[20] L. Deng, H.H. Ngo, W. Guo, H. Zhang, Pre-coagulation coupled with sponge-membrane filtration for organic matter removal and membrane fouling control during drinking water treatment, Water Res., 157 (2019) 155–166.
[21] P. Peng, H. Huang, H. Ren, H. Ma, Y. Lin, J. Geng, L. Ding, Exogenous N-acyl homoserine lactones facilitate microbial adhesion of high ammonia nitrogen wastewater on biocarrier surfaces, Sci. Total Environ., 624 (2018) 1013–1022.
[22] H.T. Nhut, N.T.Q. Hung, T.C. Sac, N.H.K. Bang, T.Q. Tri, N.T. Hiep, N.H.K. Bang, Removal of nutrients and organic pollutants from domestic wastewater treatment by

sponge-based moving bed biofilm reactor, Environ. Eng. Res., 25 (2019) 652–658.
[23] W. Mook, M. Chakrabarti, M. Aroua, G. Khan, B. Ali, M. Islam, M.A. Hassan, Removal of total ammonia nitrogen (TAN), nitrate and total organic carbon (TOC) from aquaculture wastewater using electrochemical technology: a review, Desalination, 285 (2012) 1–13.
[24] V.M. Monsalvo, A.F. Mohedano, J.J. Rodriguez, Activated carbons from sewage sludge: application to aqueous-phase adsorption of 4-chlorophenol, Desalination, 277 (2011) 377–382.
[25] S.R. Ha, S. Vinitnantharat, H. Ozaki, Bioregeneration by mixed microorganisms of granular activated carbon loaded with a mixture of phenols, Biotechnol. Lett., 22 (2009) 1093–1096.
[26] P. Sutton, P. Mishra, Activated carbon based biological fluidized beds for contaminated water and wastewater treatment: a state-of-the-art review, Water Sci. Technol., 29 (1994) 309–317.
[27] S.D. Joseph, M.C. Arbestain, Y. Lin, P. Munroe, C.H. Chia, J. Hook, J. Lehmann, An investigation into the reactions of biochar in soil, Soil Res., 48 (2010) 501–515.
[28] M. Katsikogianni, Y.F. Missirlis, Concise review of mechanisms of bacterial adhesion to biomaterials and of techniques used in estimating bacteria-material interactions, Eur. Cell. Mater., 8 (2004) 37–57.
[29] F. Suja, T. Donnelly, Effect of full and partial-bed configuration on carbon removal performance of biological aerated filters, Water Sci. Technol., 58 (2008) 977–983.
[30] P. Pedros, J. Wang, H. Metghalchi, Single submerged attached growth bioreactor for simultaneous removal of organics and nitrogen, J. Environ. Eng., 133 (2007) 191–197.
[31] Y.T. Hameed, A. Idris, S.A. Hussain, N. Abdullah, H.C. Man, F. Suja, A tannin–based agent for coagulation and flocculation of municipal wastewater as a pretreatment for biofilm process, J. Cleaner Prod., 182 (2018) 198–205.
[32] D.P. Cassidy, E. Belia, Nitrogen and phosphorus removal from an abattoir wastewater in a SBR with aerobic granular sludge, Water Res., 39 (2005) 4817–4823.
[33] Y. Cao, C. Zhang, H. Rong, G. Zheng, L. Zhao, The effect of dissolved oxygen concentration (DO) on oxygen diffusion and bacterial community structure in moving bed sequencing batch reactor (MBSBR), Water Res., 108 (2017) 86–94.
[34] S.R. Qasim, Wastewater Treatment Plants: Planning, Design, and Operation, CRC Press, 1998.
[35] Metcalf, Eddy, Wastewater Engineering: Treatment and Reuse, 4th ed., New York, 2003.
[36] J. Ha, Nitrogen and Phosphorous Removal in Biological Aerated Filters (BAFs), Ph.D Thesis, Iowa State University, Iowa, 2006.
[37] M.C. Chrispim, M.A. Nolasco, Greywater treatment using a moving bed biofilm reactor at a university campus in Brazil, J. Cleaner Prod., 142 (2017) 290–296.
[38] A. Valipour, S.M. Taghvaei, V.K. Raman, G.B. Gholikandi, S. Jamshidi, N. Hamnabard, An approach on attached growth process for domestic wastewater treatment, Environ. Eng. Manage. J., 13 (2014) 145–152.
[39] Y. Ammar, D. Swailes, B. Bridgens, J. Chen, Influence of surface roughness on the initial formation of biofilm, Surf. Coat. Technol., 284 (2015) 410–416.
[40] A.A.L. Zinatizadeh, E. Ghaytooli, Simultaneous nitrogen and carbon removal from wastewater at different operating conditions in a moving bed biofilm reactor (MBBR): process modeling and optimization, J. Taiwan Inst. Chem. Eng., 53 (2015) 98–111.
[41] X. Zhang, J. Li, Y. Yu, R. Xu, Z. Wu, Biofilm characteristics in natural ventilation trickling filters (NVTFs) for municipal wastewater treatment: comparison of three kinds of biofilm carriers, Biochem. Eng. J., 106 (2016) 87–96.
[42] S. Xia, J. Li, R. Wang, Nitrogen removal performance and microbial community structure dynamics response to carbon nitrogen ratio in a compact suspended carrier biofilm reactor, Ecol. Eng., 32 (2008) 256–262.
[43] S.A.E. Shafai, W.M. Zahid, Performance of aerated submerged biofilm reactor packed with local scoria for carbon and nitrogen removal from municipal wastewater, Bioresour. Technol., 143 (2013) 476–482.
[44] G. Andreottola, P. Foladori, M. Ragazzi, F. Tatàno, Experimental comparison between MBBR and activated sludge system for the treatment of municipal wastewater, Water Sci. Technol., 41 (2008) 375–382.
[45] M. Ahmed, A. Idris, A. Adam, Combined anaerobic-aerobic system for treatment of textile wastewater, J. Eng. Sci. Technol., 2 (2007) 55–69.
[46] M.F. Hamoda, R.A. Bin-Fahad, Nitrogen removal from wastewater in an anoxic–aerobic biofilm reactor, J. Water Reuse Desal., 2 (2012) 165–174.
[47] B. Zhao, M. Tian, Q. An, J. Ye, J.S. Guo, Characteristics of a heterotrophic nitrogen removal bacterium and its potential application on treatment of ammonium-rich wastewater, Bioresour. Technol., 226 (2017) 46–54.
[48] K. Boki, S. Tanada, T. Miyoshi, R. Yamasaki, N. Ohtani, T. Tamura, Phosphate removal by adsorption to activated carbon, Nippon Eiseigaku Zasshi, 42 (1987) 710–720.
[49] J. Yan, Y.Y. Hu, Partial nitrification to nitrite for treating ammonium-rich organic wastewater by immobilized biomass system, Bioresour. Technol., 100 (2009) 2341–2347.
[50] K. Shahot, I. Habib, A. Ekhmaj, Performance of a full-scale activated sludge process for Sakket (Musrata–Libya) municipal wastewater treatment plant, N. Y. Sci. J., 8 (2015) 34–37.
[51] D.J. Kim, D.I. Lee, J. Keller, Effect of temperature and free ammonia on nitrification and nitrite accumulation in landfill leachate and analysis of its nitrifying bacterial community by FISH, Bioresour. Technol., 97 (2006) 459–468.