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Assessment of brewery wastewater treatment by an attached growth bioreactor

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Abstract

Craft beer is a rapidly growing market globally, placing an increased burden on wastewater treatment plants. To avoid discharge fees, new technology is required to make the on-site treatment of brewery wastewater affordable. This study assessed the application of a novel attached growth bioreactor (AGBR) to treat brewery wastewater to a discharge target (1,500 mg sCOD/L). Specifically, the impacts of the single-pass residence time ($HRT_{single-pass}$), organic loading and media height were investigated. A $HRT_{single-pass}$ of 67 min demonstrated the shortest required time to meet the discharge target and the lowest final effluent concentration after 120 hr treatment time. Long $HRT_{single-pass}$ demonstrated slower biomass development, while smaller $HRT_{single-pass}$ caused an earlier rise in dissolved oxygen (DO) which hindered organic removal by heterotrophic bacteria. The sCOD removal rate increased with loading rates, however plateaued at 65 g sCOD/m²/day for loading rates above 300 g sCOD/m²/day. The media became flooded with biomass for feed strengths above 6.0 g sCOD/L. Greater media height provided additional surface area for biomass development, but marginally decreased the sCOD removal rate (g/m²/day) due to an earlier introduction of DO. Power consumption and footprint considerations found the greater media height to be the preferred choice for breweries.

Key words: attached growth treatment, bioreactor, brewery wastewater, hydraulic retention time

INTRODUCTION

In 2017 alone, almost 1000 additional craft brewers came on-line within the United States, bringing the total number of craft breweries operating across the country to 6000 (Brewers Association 2017). The Australian craft beer production industry is expected to grow at 9.7% a year over the next five years with innovative and new fruit brews and hazy varieties coming to market (Business Insider Australia 2017). This growth has placed a spotlight on an important consequence of the brewing process, the generation of large volumes of wastewater rich in organic material. The wastewater disposal method for craft breweries varies by location, with a typical craft brewery disposing of more than 80% of their wastewater to the local municipal wastewater treatment system (Filtration News 2016). Depending on the wastewater treatment facility's capacity, utilities can actively charge high surcharge fees to cover the added burden placed on the system.

Brewery wastewater originates from several sources, including the disposal of manufacturing waste, rinsing of equipment and vessels, cooling water, packaging/labelling and clean in place (CIP) using acidic or basic solutions (Inyang *et al.* 2012). As a general overview, packaging results in a large volume of wastewater that contains only a small percentage of the total organics discharged from

the brewery process. However, the effluents from the fermentation and filtering processes are high in organics and account for 97% of the total biological oxygen demand (BOD) but only 3% of the total wastewater volume (Finkbeiner 2011).

Brewery wastewater is typically high in organic content (measured in chemical oxygen demand (COD) or BOD) due to the presence of sugars, soluble starch, ethanol and volatile fatty acids (VFAs) (Goldammer 2008). The nitrogen and phosphorus levels in the wastewater depend on the handling of the raw material and the quantity of yeast present in the effluent (Driessen & Vereijken 2003; Goldammer 2008). Brewery wastewater typically has a biological oxygen demand (BOD_5) of 1,200–3,600 mg/L, COD of 2,000–6,000 mg/L and total suspended solids (TSS) of 200–1,000 mg/L (Rao *et al.* 2007; Simate *et al.* 2011; Inyang *et al.* 2012; Mielcarek *et al.* 2013). The pH levels can vary between 2 and 12 depending on the source of the wastewater (wash water or filtrate) and hence the presence of cleaning chemicals such as caustic soda, phosphoric acid and nitric acid (Driessen & Vereijken 2003; Goldammer 2008). Typical brewery wastewater temperature can range between 18 and 40 °C depending on its source (brew kettles and CIP cycles typically use hot water while water used for packaging is at room temperature) (Rao *et al.* 2007). The large fluctuations in the parameters demonstrate the variability of beer production as a batch system leading to a highly variable effluent.

To avoid discharge fees, breweries often choose to implement on-site wastewater treatment systems. In this context, attached growth systems (AGS) present an attractive option based on their small footprint, great tolerance to hydraulic and contaminant shock loads, and low operational and maintenance costs (Loupasaki & Diamadopoulos 2012).

In an AGS, micro-organisms form a biofilm on a support media over which wastewater is applied (Davis 2013). A single biofilm can contain aerobic, anaerobic and anoxic sections allowing for simultaneous occurrence of different processes (Water Environment Federation 2010). The ability to maintain a high micro-organism concentration within an AGS results in high removal rates at reasonable hydraulic retention times (HRT) (Loupasaki & Diamadopoulos 2012). Out of many commercially available AGS, such as tricking filters and rotating biological contactors (RBC), a novel attached growth bioreactor (AGBR) from BioGill™ was investigated for its potential application to treat brewery wastewater. In particular, a number of important design and operating parameters identified in the literature to have a significant impact on treatment performance were studied.

AGS typically use recirculation to increase the wastewater contact time with the active biological material, dilute shock loads, increase dissolved oxygen (DO) levels (to aid nitrification), maintain media wetness and control excess biomass (US EPA 2000; Water Environment Federation 2010; Davis 2013). Insufficient recirculation can lead to biological inactivity; while high recirculation can introduce excessive DO resulting in reduced BOD removal by heterotrophic bacteria (Davis 2013). Additionally, excessive recirculation comes with increased operating (energy for pumps) and capital costs (need a higher capacity of each unit). Two parameters have an influence on the recirculation rate within an AGS: the recirculation tank volume and the recirculation flowrate. For the purpose of this study, two separate HRT were used to define the recirculation:

- Single-pass residence time ($HRT_{single-pass}$) – HRT within the recirculation tank (i.e. time taken for one pass through the system).
- Total residence time (HRT_{total}) – Overall HRT within the process (before discharge or transport to next treatment stage).

The number of recirculation passes, or contact time, is heavily dependent on the volume of water to be treated, the influent strength and required concentration of the final effluent. Taylor (2013) identified that a higher number of recirculation passes within an AGS increased overall treatment performance; however, for higher removal (>80%), diminishing returns were observed with each additional recirculation pass.

A high organic loading rate (OLR) promotes rapid biomass growth and hence organic removal (by heterotrophic bacteria); however, increased recirculation and treatment time may be required due to plugging of pores or media flooding should the growth become excessive (Metcalf & Eddy 2003; BioGill™ 2016). The efficiency of the nitrification process is also directly impacted as heterotrophic bacteria dominate over autotrophs under high BOD loads (US EPA 2000).

The AGS assessed within this study was an AGBR, a hybrid system with an aerobic and anaerobic phase. Oxygen was provided from the air side of the media, aiding biomass development and nitrification processes. As the biofilm developed, the oxygen transfer through the biofilm was reduced and hence an almost anaerobic zone was created. DO was introduced into the wastewater from the distribution of the wastewater over the media and plays an important role in the treatment process. Elevated availability of oxygen within the recirculation tank promotes the production of CO_2, a food source for the autotrophs (lower organic removal rates but capable of nitrification). However, insufficient DO within bioreactors can result in the development of anaerobic biofilms, odour generation and can limit ammonia oxidation.

A larger media surface area allows for a larger capacity for biomass growth and hence a greater ability to accomplish the desired nitrification and organic removal (US EPA 2000). Most of the biological removal is expected to occur within the higher sections of the media due to the expected dominance of the heterotopic bacteria within the recirculation tank (low DO). Since heterotrophic bacteria are fast growing (Judd 2006), rapid DO consumption and biomass development is expected immediately after the introduction of DO by the sprinkler. As the water moves down the media, DO is continuously added to the water and therefore it is expected that the autotrophic bacteria will have time to become more prevalent (BioGill™ 2018). Therefore, a greater media height is expected to provide greater overall performance for a single pass, however whether this increase in performance is on a linear scale is unknown. The reduction in required recirculation also could provide energy savings as fewer cycles are required; however, these savings need to be compared with the greater differential pump head.

The aim of this study was therefore to investigate the impact the main design and operating parameters have on the treatment of brewery wastewater by a novel AGBR. In doing so, craft breweries can further consider and potentially incorporate this type of technology into their long-term strategic planning to avoid discharge fees and environment pollution.

MATERIALS AND METHODS

Materials

The AGBR technology used within this research was the BioGill™ bioreactor. This above-ground AGBR contains a series of hydrophilic nano-ceramic supporting media (or membranes) folded over supports such that two distinct sides are created: one in contact with the wastewater and the other in contact with the air (Taylor 2007). Wastewater is pumped to the top of the bioreactor and is dispersed over the media by a sprinkler before re-entering the recirculation tank below. The microbes consume pollutants in the wastewater from the water side and draw oxygen from the air side to grow and colonise into a healthy treating biomass. Natural air convention from the available vents, resulting from the heat generated by the biomass, increases the supply of oxygen (BioGill™ 2018). The direct access to oxygen results in the air side experiencing aerobic conditions while the water side can experience anoxic, anaerobic or aerobic depending on the nutrient loading. As the biofilm develops and thickens, the outer layer becomes substrate limited and eventually dies and sloughs off (BioGill™ 2018).

Two AGBR units were used within this study, each with 28 sheets (equivalent to 25 m² of active membranes surface) suspended over supports with the entire module encased by an opened top
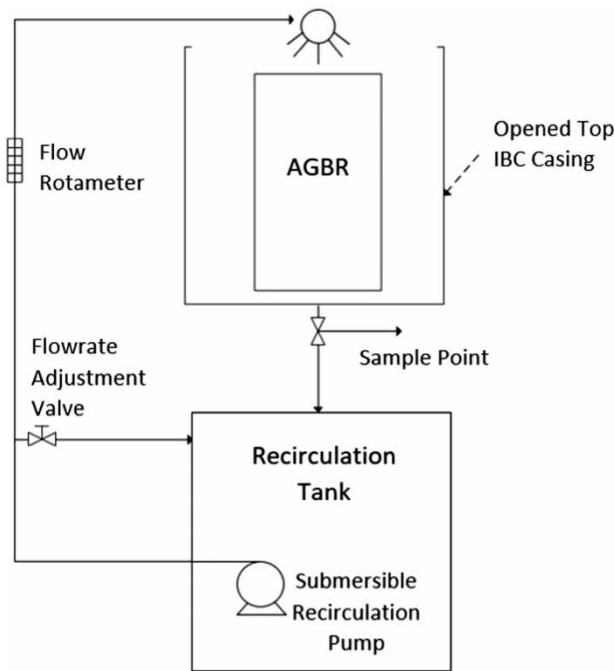
Figure 1 | Process flow diagram for the operation of AGBR.

intermediate bulk container (IBC) as a means of capturing the water spray. The modules were setup as a batch configuration, using a 1,000 L recirculation tank located below the tower and a 350 W Ozito Dirty Water submersible recirculation pump. A third IBC was used to elevate the AGBR above the level of the recirculation tank. On the outlet line of the recirculation pump, a ball valve was attached as a method of varying the recirculation flowrate to the AGBR, when necessary (Figures 1 and 2).

Synthetic brewery wastewater

A standard synthetic wastewater to mimic a typical brewery effluent was created, with the mixture calculated to achieve a C:N:P ratio of 100:4:0.4 to avoid the requirement of nutrient dosing (ratio determined from prior internal trials conducted by BioGill™). Table 1 lists the ingredients used, and quantities, per batch of 1,000 L of wastewater to achieve the following characteristics: 3,000 mg $sBOD_5$/L, 4,400 mg sCOD/L, 60 mg TN/L, 6 mg TP/L and a yeast concentration of 300 mg/L. All dry ingredients were blended to limit the TSS before being added to 1,000 L of water.

Figure 2 | Ariel view of AGBR (left) and side view of entire experimental setup (right).

Table 1 | Standard synthetic brewery wastewater ingredients list per 1,000 L solution

Ingredient	Supplier	Quantity (g)
Blood and bone fertiliser	Richgro	1,250
Refined sugar	Bundaberg	3,000
Urea (46% nitrogen)	Redox	22
Superphosphate (9% phosphorus)	Richgro	39
Yeast	Lowan	300
Sodium bicarbonate	Hy-Clor	450

As a method of controlling pH during the process of acidogenesis, sodium bicarbonate was added throughout the experiments. This effectively counterbalanced the early drop in pH (<5 pH) observed during the first 20 hr of treatment. During this process, soluble organics are taken up by different facultative and obligatory anaerobic bacteria and are degraded into short chain organic acids, alcohols, hydrogen and carbon dioxide (Bajpai 2017) before being consumed by methanogenic bacteria.

Methods

Sample analysis

The sample analysis within this study solely focused on COD rather than BOD due to the ease of measurement procedure. A series of samples (feed and final effluent samples) were sent to an external laboratory for sBOD$_5$ analysis such that a sBOD$_5$/sCOD ratio could be obtained and utilised for later sBOD$_5$ estimates. The ratios were found to be around 0.6 and 0.4 for the feed and effluent samples, respectively. Using a conventional discharge target (to avoid fees) of 600 mg sBOD$_5$/L (BioGill™ 2018), this correlated to a sCOD concentration of 1,500 mg/L for the effluent.

The sCOD values were obtained by first filtering the water samples through Advantec GC-90 glass fibre filter paper before being heated and analysed in an RD125 Thermoreactor and MD600 Photometer, respectively. Ammonia and nitrate concentrations were also analysed using a Lovibond MD600 photometer to assess nitrification and denitrification during the experiments. In terms of monitoring during an experiment, pH and DO were routinely analysed using an Oakton Portable 5+ pH Meter and a Thermo Scientific Orion Start A323 DO Portable Meter, respectively.

The impact of three variables (HRT$_{single-pass}$, organic loading and media height) on the AGBR treatment of brewery wastewater were assessed.

Impact of single-pass residence time (HRT$_{single-pass}$)

In the first series of trials, the HRT$_{single-pass}$ (i.e. time taken for one pass through the system) was varied across the AGBR units, with results compared over a constant (arbitrary) HRT$_{total}$ of 120 hr. During each trial, both recirculation tanks were filled with a standard batch (1,000 L) of synthetic brewery wastewater. The HRT$_{single-pass}$ was varied through the manipulation of the recirculation flowrate (through the flow adjustment valve) and hence subjected the unit to a different hydraulic loading rate. Across six trials, five HRT$_{single-pass}$ values were assessed: 40, 55, 67, 86 and 120 min which equated to a flowrate range of 500–1,500 L/hr.

As a further comparison, the relative difference in power consumption for each HRT$_{single-pass}$ was estimated through the ideal hydraulic pump power equation (Green & Perry 2008).

$$P_H = \frac{Q\rho gh}{3.6 \times 10^6} \tag{1}$$

where P_H is the hydraulic power (kW), Q is the flowrate (m³/hr), ρ is the fluid density (here assumed to be around 1,000 kg/m³), g is gravity (9.81 m/s²) and h is the differential head (m).

Impact of organic loading rates and influent strengths

For this research, OLR is defined as the mass (in kg) of COD applied to the AGBR per day per m² of media surface area. In the second series of trials, the two AGBR units were subjected to four different feed concentrations: 2.5, 4.5, 6.0 and 8.0 g sCOD/L. The feed strength was varied through the addition of a diluted or concentrated percentage of dry ingredients listed in Table 1 (sodium bicarbonate quantity remained constant). These concentrations were assessed over three trials, all of which utilised a HRT$_{single-pass}$ of 67 min. As identified in the Introduction, one of the main criteria for the treatment of brewery wastewater is the ability to handle inconsistent and high BOD feeds, which shock the system. At the conclusion of the second trial (after 160 hr of treatment), the dry ingredients for a standard synthetic wastewater solution (Table 1) were measured, blended and added to each recirculation tank to challenge the robustness of the AGBR.

Impact of media height

The final series of trials involved doubling the media height from 0.9 to 1.8 m to assess the impact on sCOD removal rate (per m² of media area). This assessment was achieved by stacking the two AGBR units on top of each other. The double unit was then subjected to a standard synthetic wastewater solution (Table 1) under a HRT$_{single-pass}$ of 67 min. The trial was then repeated a total of 3 times, with results compared to the 0.9 m case in the HRT$_{single-pass}$ experiment.

RESULTS AND DISCUSSION

Impact of single-pass residence time (HRT$_{single-pass}$)

A series of different HRT$_{single-pass}$ values were assessed through the manipulation of the recirculation flowrate of the AGBR units. The majority of these HRT$_{single-pass}$ (excluding 120 min due to initial poor results and limited project time) were repeated and assessed on both units to ensure accurate results.

By compiling the results from all trials, an overall relationship between sCOD and treatment time was developed for each HRT$_{single-pass}$ (Figure 3).

From Figure 3, varying the HRT$_{single-pass}$ has a significant impact on the microbial activity within the AGBR and hence the treatment of the brewery wastewater. Heterotrophic bacteria are responsible for organic (methanogenesis) and nitrogen removal (denitrification) because they use organic carbon as an energy source and for the synthesis of more cellular material (Judd 2006). Autotrophs, however, derive energy and obtain assimilable material from an inorganic source such as carbon from carbon dioxide or nitrogen from ammonia (Sakairi Yasuda & Matsumura 1996). Both heterotrophic and autotrophic bacteria were assumed to be present within the biomass, however since heterotrophic bacteria are much more efficient and fast growing, they provide faster BOD removal.

As arbitrary performance indicators, two critical values were identified to assess the impact of the HRT$_{single-pass}$, including the time required to meet the discharge target of 1,500 mg sCOD/L and the final sCOD value after a HRT$_{total}$ of 120 hr. Figure 4 shows the relationship between these two values across the various assessed HRT$_{single-pass}$.

As indicated in Figure 4, a HRT$_{single-pass}$ of 67 min was shown to reach the discharge target in the shortest time (59 $\pm$ 3 hr) and displayed the greatest overall removal (final effluent concentration of 332 $\pm$ 104 mg sCOD/L). The larger HRT$_{single-pass}$ (86 and 120 min) demonstrated a much slower
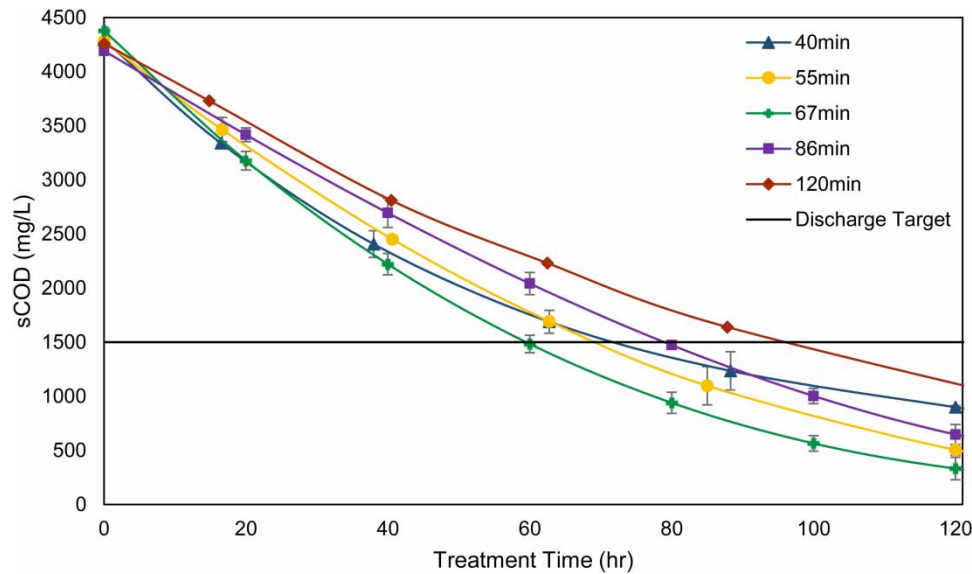
Figure 3 | Reduction in sCOD with treatment time for various $HRT_{single-pass}$.

removal rate, attributed to less contact time with the media and hence the active biological material. The heterotrophic bacteria were therefore not provided with a sufficient energy source resulting in a slower development of the biomass. In contrast, the shorter $HRT_{single-pass}$ (40 and 55 min) demonstrated greater initial removal due to the more frequent recirculation through the media and hence fast biomass development. However, as treatment time progressed, this sCOD removal rate was not maintained. All trials which utilised a $HRT_{single-pass}$ of 40 or 55 min experienced rapid increases in DO after approximately 50–60 hr of treatment. It is important to note that the DO in the recirculation tank for the other three $HRT_{single-pass}$ options remained under 0.4 mg/L for the duration of the 120-hr treatment time (good indication of anaerobic activity). Therefore, the oxygen introduction rate (distribution over the media) was greater than the microbial DO consumption rate in the biomass and recirculation tank, causing a slow accumulation of oxygen within the wastewater. The increased availability of oxygen in the recirculation tank was assumed to then promote for the reproduction of the slower growing autotrophic bacteria. As a result, the heterotroph dominance was reduced, and BOD removal rates decreased. It is important to note that there is a trade-off between organic removal and nitrification rates, based on the DO present. Insufficient DO within bioreactors can result in the development of anaerobic biofilms, odour generation and can limit ammonia oxidation and removal (Parker *et al.*
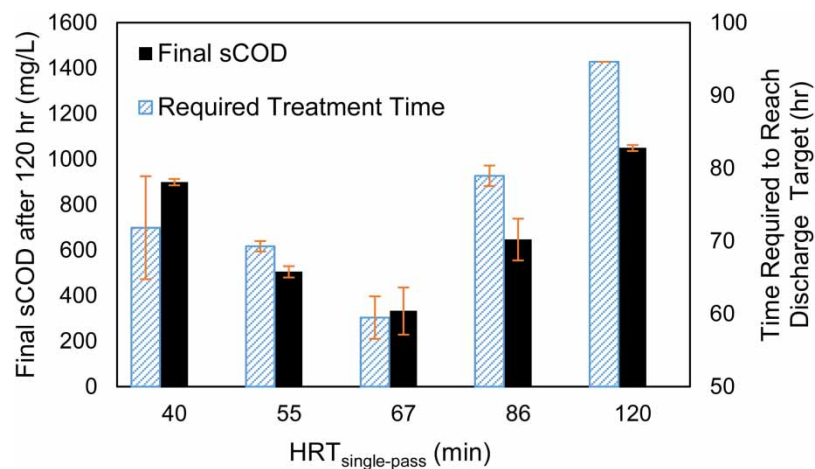
Figure 4 | Impact of $HRT_{single-pass}$ on the required time to reach the discharge target and final sCOD values after a HRT_{total} of 120 hr.

1989). However, since this study is focusing on breweries, organic removal was the main performance indicator. It was also possible that the higher flowrates used within the 40 and 55 min HRT$_{single-pass}$ trials damaged the biomass, limiting the treatment effectiveness.

A HRT$_{single-pass}$ of 67 min was therefore the shortest HRT$_{single-pass}$ (more contact time with the media and biomass) which could maintain a low DO in the recirculation tank for the duration of the experiment. This therefore allowed for a prolonged organic removal performance and microbial activity by heterotrophic bacteria.

Nitrogen removal

Limited nitrification occurred during the initial development of the biomass in all trials due to the expected dominance of heterotrophic bacteria under high BOD loads. However, denitrification was indicated to have occurred immediately in the recirculation tank (rapid nitrate consumption). Once the majority of BOD was consumed, organic removal rates dropped while DO levels in the recirculation tank increased, indicating that the heterotrophic bacteria reproduction had slowed or ceased. Under high DO conditions within the recirculation tank, the reproduction of autotrophic ammonia and nitrite-oxidising bacteria was expected to increase (lighter biomass appearance observed). Figure 5 demonstrates the average TN removal rate over the 120 hr of treatment time across the various HRT$_{single-pass}$.

From Figure 5, the lower HRT$_{single-pass}$ demonstrated greater TN removal due to the expected presence of the autotrophs. Despite the high DO levels within the recirculation tank, denitrification was assumed to still be occurring in the anaerobic sections of the biomass (where the membranes stick together). This combination of nitrification and denitrification enabled the lower HRT$_{single-pass}$ to obtain greater TN removal when compared to the higher HRT$_{single-pass}$, which are assumed to only have had denitrifying bacteria present.
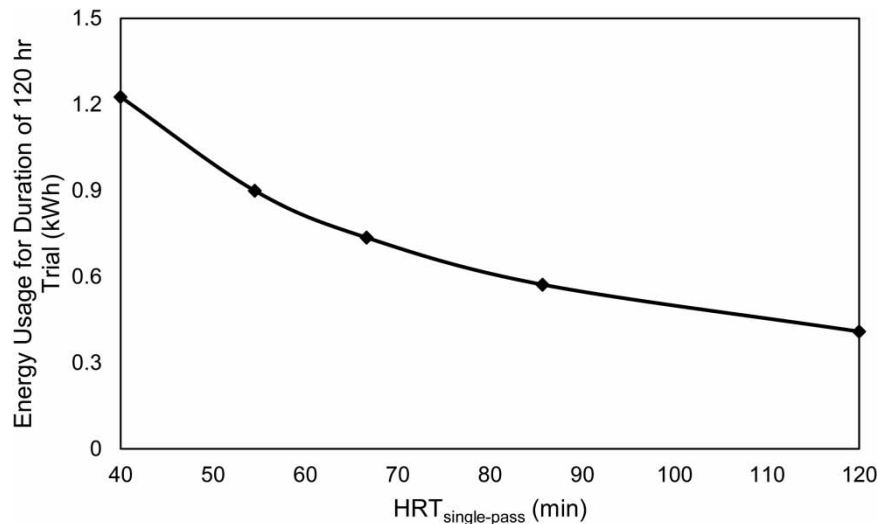
Energy consumption

Relative power consumption across the various HRT$_{single-pass}$ was also calculated as another performance indicator. It was clear that a greater HRT$_{single-pass}$ required less pumping and hence reduced energy costs. Figure 6 depicts the relationship between energy usage and HRT$_{single-pass}$ throughout this study, calculated using Equation (1).
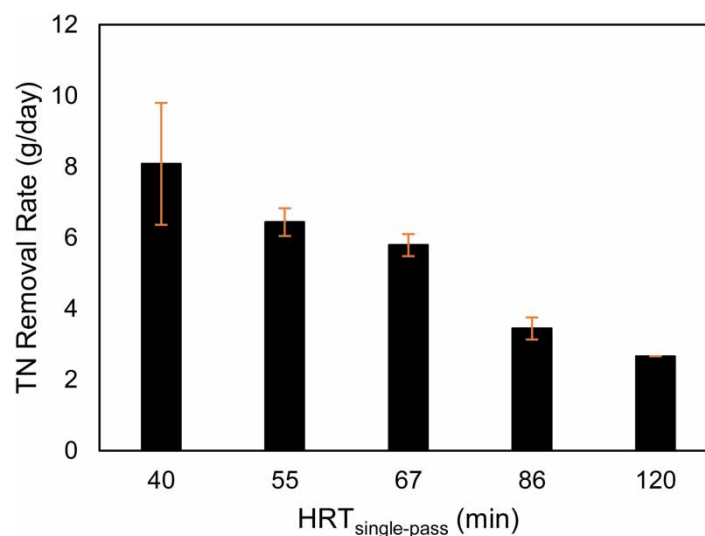
Figure 5 | TN removal rate for various HRT$_{single-pass}$ over the 120 hr treatment time.

Figure 6 | Relationship between $HRT_{single-pass}$ and energy usage for pumping.

This relationship identified that power consumption increased with decreasing $HRT_{single-pass}$ (more pumping). However, the resulting trend was not found to be linear and it can be clearly identified that the power consumption showed a much sharper increase for $HRT_{single-pass}$ below 60–70 min. This further supports the optimal assessed $HRT_{single-pass}$ being 67 min since decreasing it any further (40 or 50 min) would result in a rapid jump in energy costs on top of the reduced performance observed previously. Additionally, increasing the $HRT_{single-pass}$ (86 or 120 min) would result in a lower energy usage, however for the purpose of this study, the increased performance at 67 min clearly outweighs the slight increase in energy requirement.

Impact of organic loading rate

Time required to meet discharge target

The sCOD reduction with treatment time at four different feed strengths can be seen in Figure 7.

When compared to municipal wastewater, brewery wastewater is typically much higher in organics (Goldammer 2008). Therefore, to prove its suitability, the ability of the AGBR to effectively treat high organic feeds must be validated.

It was observed from Table 2 that the removal rate was much smaller for the lower feed strengths due to a reduced food to micro-organism (F/M) ratio. The removal rate grows with increasing strength (and hence F/M ratio), until it reaches the highest feed strength assessed (7.4 g/L) at which time the removal rate begins to decrease again. This indicated that the media has become flooded with biomass growth which limits its further development. Since the greatest removal rate generally occurred within the first 15 hr, increasing the feed strength from 5.9 to 7.4 ± 0.07 g/L provided no additional heterotrophic reproduction during this time. Therefore, since this feed concentration has a higher starting value, the required treatment time increased rapidly. As a result, the removal rate over this extended period of time was lower than the 5.9 g/L case. It can therefore be concluded that no additional time saving or removal performance was obtained by increasing the feed concentration above approximately 5.9 mg/L. 6.0 g COD/L represents the upper bound for a typical brewery effluent (Rao *et al.* 2007), further validating the application of an AGS.

The reduced F/M ratio in the lower feed strengths resulted in an earlier rise in DO. This was due to a reduced biomass production (less carbon for cellular material synthesis) and hence lower levels of heterotrophic bacteria capable of consuming the DO introduced when the wastewater was sprayed over the media. Therefore, since the DO addition rate was much greater than the consumption
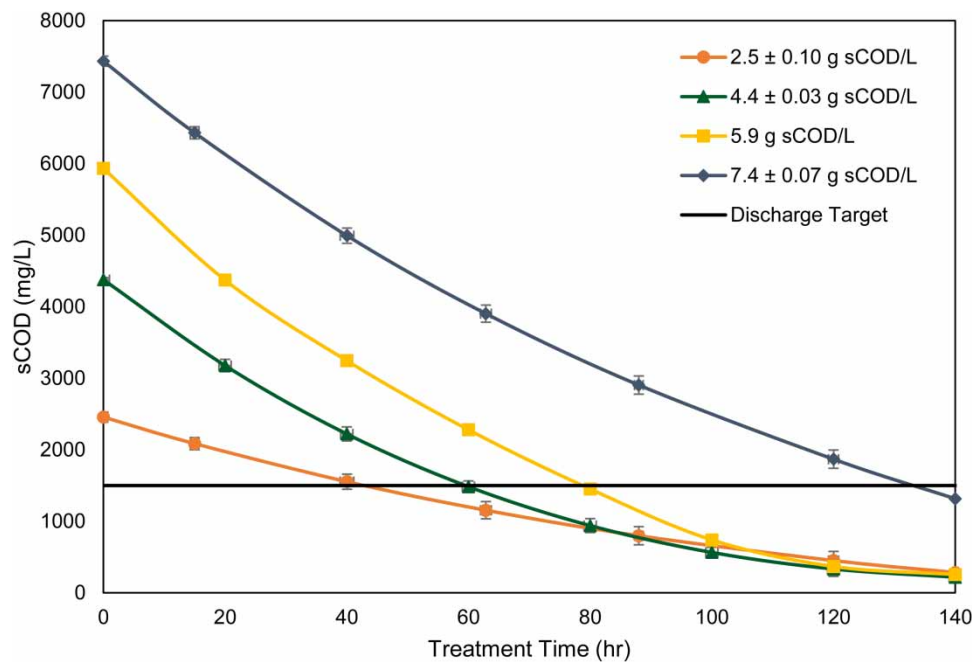
Figure 7 | Reduction in sCOD in recirculation tank with time at various feed strengths.

rate, an accumulation of DO was seen earlier on in the trial. As described in the first experiment, the increase in oxygen availability promoted autotrophic development which hinders the organic removal by heterotrophs. This could be a limiting factor for the effectiveness of the AGBR in low strength influent applications such as domestic sewage. No significant rise in DO was observed for the two highest feed strengths which also aids the removal rate.
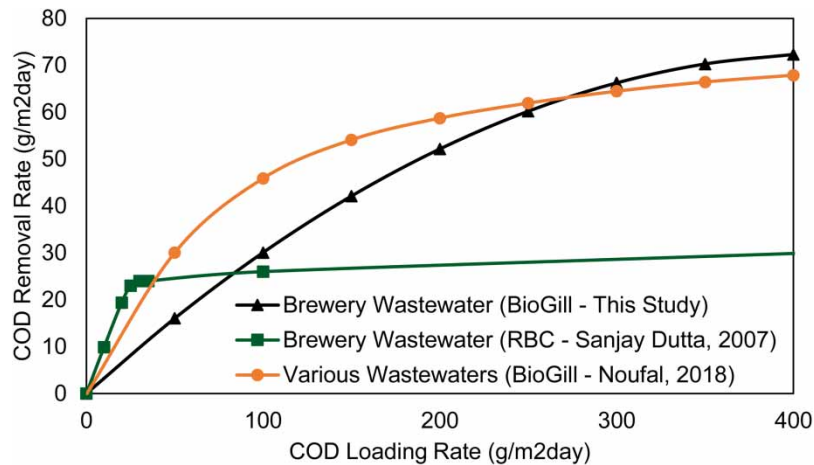
Due to the greater time requirement for the 7.4 g sCOD/L feed to meet the discharge target, a greater amount of energy is used in the process. By dividing the removal rates by the respective amount of energy consumption (Equation (1)), a new removal rate (per kWh) can be obtained, as shown in Table 2. When taking energy into account, the high feed concentration of 7.4 ± 0.07 g/L does not present as a viable option due to the large increase in energy requirements (disproportionally greater treatment time). However, the feed strength of 4.4 ± 0.03 g/L demonstrated the greatest removal rate per kWh energy used, and therefore provides the most cost-effective feed strength. This feed concentration is well within the expected range for a brewery – 2.0–6.0 g/L (Rao *et al.* 2007) and therefore validates the use of the AGBR.

Variation in sCOD removal rate

By conducting the series of experiments with varying feed strengths, a relationship between sCOD loading and removal rates was obtained, as outlined in Figure 8. As a comparison, this relationship has been plotted against previous research using the BioGill™ technology conducted on a variety of wastewater feeds (Noufal 2018) as well as the treatment of brewery wastewater by a RBC (Sanjay Dutta 2007).

Table 2 | Time required to reach discharge target for various feed strengths

Feed strength (g sCOD/L)	sCOD removed to reach discharge target (g/1,000 L batch)	Time to reach discharge target 1,500 mg sCOD/L (hr)	sCOD removal rate (g/m²/day)	sCOD removal rate (g/m²/day/kWh)
2.5 ± 0.10	956	45 ± 7	20	82
4.4 ± 0.03	2,877	59 ± 3	46	127
5.9	4,433	79	54	112
7.4 ± 0.07	5,933	133 ± 8	43	52

Figure 8 | COD removal rate in function of loading rate reported for the present work and compared to previous studies.

The relationship identified within this research demonstrated that the greater sCOD loading rates resulted in a higher removal rate due to the greater F/M ratio present. However, the sharp increase in removal rate does plateau at the very high loading rates (above 300 g/m^2/day) indicating a maximum F/M ratio has been achieved. From the above experimental data, this corresponds to a maximum sCOD removal rate of approximately 65–70 g/m^2/day. A typical brewery wastewater treatment plant can exhibit an influent COD strength of between 2,000 and 6,000 mg/L (Rao *et al.* 2007). For this AGBR module (25 m^2 media area), this feed equates to a sCOD loading rate of 80–240 g/m^2/day. Using the above relationship, the pilot unit can therefore be expected to achieve a sCOD removal rate of 24–54 g/m^2/day, for this particular feed range.

The previous research of the BioGill™ system for other wastewaters demonstrates a similar relationship to that identified in this study but showed greater removal rates for COD loading rates less than 250 g/m^2/day (Figure 8). This difference was attributed to potential differences in temperature since this study was conducted in winter whereas the previous research was performed across several seasons. Additionally, this research reported total COD whereas this study used sCOD, which is typically lower. The removal rates are much closer for higher COD loading rates, which further validates the results obtained in this study.

The treatment of brewery wastewater by RBCs demonstrated high COD removal rates (up to 99%) for low loading rates; however, peaked at a maximum value of approximately 25–30 g/m^2/day. This study showed the AGBR could achieve removal rates up to approximately 65–70 g/m^2/day, more than double what the RBC could achieve when treating brewery wastewater.

Shock load assessment

A shock load condition was assessed when the modules received an initial feed strength of 7.4 and 2.5 g/L, respectively. The minimum and maximum feed strengths used in the previous organic loading trial were chosen as they were expected to show the greatest comparison when subjected to a shock load. After 160 hr of treatment, both modules were subjected to a shock load through the addition of the dry ingredients listed in Table 1 to the recirculation tanks. This was equivalent to an additional loading rate of 160 g/m^2/day – the average brewery wastewater feed (Rao *et al.* 2007).

From Figure 9, it can be seen that before the shock load at 160 hr, the high feed unit (module 1) was still consuming organics within the wastewater at a steady rate, whereas the lower fed unit (module 2) was showing low removal and could be considered substrate limited. During the first 22 hr after the shock load was introduced, both units showed immediate COD removal at a much greater rate (50 and 46 g/m^2/day for modules 1 and 2, respectively) than what was observed before the shock load.
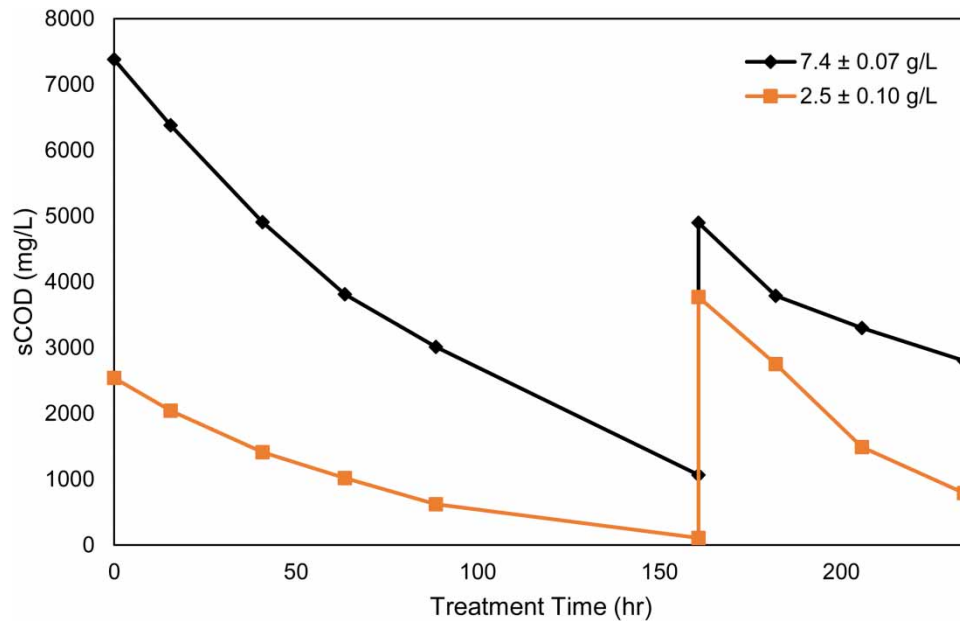
Figure 9 | Change in sCOD with time with shock load after 160 hr of treatment.

The interesting observation was the continuation of this rate by module 2 over the following 24 hr (51 g/m²/day) while the removal in module 1 slowed (20 g/m²/day). This was assumed to be due to rapid biomass development within module 2 as it had not been subjected to a high organic load previously in the trial, unlike module 1. It is assumed that the heterotrophic bacteria were provided a large energy source which could be used for the synthesis of cellular material (biomass).

While module 2 was starved (before shock load), the DO was rising at a steady rate since the oxygen consumption rate by the substrate limited heterotrophic bacteria was smaller than the introduction rate. When the shock load was added, this provided an energy source for the heterotrophic bacteria to reproduce and consume the DO to create an almost anaerobic environment once again (between the media). By the conclusion of the trial, the removal rates had dropped to 17 and 24 g/m²/day for modules 1 and 2, respectively. During lower influent loads, the low DO within the recirculation tank could not be maintained and as previously observed this significantly impacts the removal of organics.

Impact of media height

Two media heights (0.9 m and 1.8 m) were tested under the same operating conditions provided (Figure 10).

The results clearly indicate that the media height of 1.8 m demonstrated a greater initial sCOD removal rate (larger surface area for biomass growth) before becoming substrate limited (starved) after approximately 50 hr of treatment. As observed in the two previous experiments, the reduction in organic loading coincided with an increase in DO. As this DO increases, the presence of auto-trophic bacteria increases while the dominance of the heterotrophic bacteria declines, particularly in the lower sections of the media where the DO is higher. This, combined with a lower F/M ratio, resulted in the COD removal rate decline.

From Table 3, doubling the media height from 0.9 to 1.8 m had very little impact on the sCOD removal rate (g/m²/day) and approximately halved the time required to meet the discharge target. It is important to note that, despite identical wastewater preparation, the identical feed solution could not be achieved for both heights. The mean feed concentrations were $4,378 \pm 29$ and $4,232 \pm 25$ mg sCOD/L for a media height of 0.9 and 1.8 m, respectively. A potential reason for this was the initial feed recirculation (mixing) time of 15 min before the feed sample was taken. During
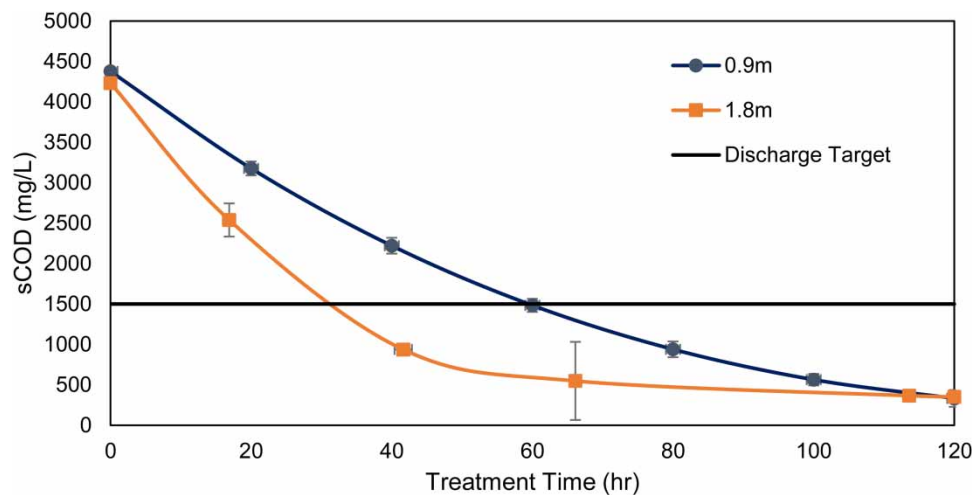
Figure 10 | Reduction in sCOD with treatment time for the two assessed media heights, 0.9 and 1.8 m.

Table 3 | Impact of media height on required time to meet discharge target and subsequent sCOD removal rate

Height (m)	Time to reach discharge target (hr)	sCOD removed in this time (mg/L)	sCOD removal rate (g/m²/day)	sCOD removal rate (g/m²/day/kWh)
0.9	59	2,877	46	127
1.8	30	2,732	44	170

this time, more of the waste materials were absorbed onto the hydrophilic media within the stacked module due to the greater surface area. Therefore the 1.8 m media height had marginally less recorded sCOD to remove in order to reach the discharge target. Nonetheless, this experiment has successfully identified that increasing the media height from 0.9 to 1.8 m has a very marginal impact on the sCOD removal rate.

Increasing the media height gave no additional benefits in terms of reducing the final sCOD after the 120 hr of treatment: 332 ± 104 and 351 ± 40 mg sCOD/L for 0.9 and 1.8 m, respectively. This is not a crucial parameter in the case of breweries which discharge to sewer; however, should much lower sCOD be required, additional media height does not provide additional benefits.

Increasing the media height reduces the operating time of the pumps, an energy saving which outweighs the increase in differential pump height. As indicated in Table 3, the 1.8 m height provided a greater energy normalised removal rate. Therefore, a media height of 1.8 m not only provides benefits in terms of footprint savings but also energy consumption.

CONCLUSION

This study found that an AGBR could achieve sCOD removal rates of 40–50 g/m²/day (more than double reported by a RBC). Furthermore, these removal rates were achieved within the first 15 hr of treatment, verifying an AGBR as an attractive solution capable of rapid and efficient removal of high organic and nutrient loads for brewery wastewater. A HRT$_{single-pass}$ of 67 min was found to be the most effective in terms of removal performance and power consumption. The removal rate of oxidisable organic material to below the discharge target was shown to increase with greater feed strengths up until 6.0 g sCOD/L, which is the top end of the anticipated brewery wastewater strength scale. Doubling the media height from 0.9 to 1.8 m was shown to halve the treatment time in order to reach the discharge target and had negligible impact on the sCOD removal rate per m² of media area. In this case, energy considerations made the doubled height a more cost-effective system.

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