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Domestic wastewater treatment with purple phototrophic bacteria using a novel continuous photo anaerobic membrane bioreactor

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ABSTRACT

A key future challenge of domestic wastewater treatment is nutrient recovery while still achieving acceptable discharge limits. Nutrient partitioning using purple phototrophic bacteria (PPB) has the potential to biologically concentrate nutrients through growth. This study evaluates the use of PPB in a continuous photo-anaerobic membrane bioreactor (PAnMBR) for simultaneous organics and nutrient removal from domestic wastewater. This process could continuously treat domestic wastewater to discharge limits (<50 mgCOD L^{-1}, 5 mgN L^{-1}, 1.0 mgP L^{-1}). Approximately 6.4 ± 1.3 gNH_4-N and 1.1 ± 0.2 gPO_4-P for every 100 gSCOD were removed at a hydraulic retention time of 8–24 h and volumetric loading rates of 0.8–2.5 COD kg m^3 d^{-1}. Thus, a minimum of 200 mg L^{-1} of ethanol (to provide soluble COD) was required to achieve these discharge limits. Microbial community through sequencing indicated dominance of >60% of PPB, though the PPB community was highly variable. The outcomes from the current work demonstrate the potential of PPB for continuous domestic (and possibly industrial) wastewater treatment and nutrient recovery. Technical challenges include the in situ COD supply in a continuous reactor system, as well as efficient light delivery. Addition of external (agricultural or fossil) derived organics is not financially nor environmentally justified, and carbon needs to be sourced internally from the biomass itself to enable this technology. Reduced energy consumption for lighting is technically feasible, and needs to be addressed as a key objective in scaleup.

1. Introduction

Alternative domestic wastewater treatment platforms are emerging that aim to provide the possibility for energy and nutrient recovery, while still achieving acceptable nutrient limits in the effluent (10 mg N L^{-1}, 2 mg P L^{-1}). This has been identified as a key future challenge (Batstone and Virdis, 2014; Verstraete et al., 2009; McCarty et al., 2011), with a need to preserve, rather than dissipate energy, nutrients, and water. Drivers that are particularly emerging are increasing costs of phosphorous, nitrogen, and energy, and the environmental implications of nitrogen dissipation to the terrestrial environment (Bodirsky et al., 2014).

Two platforms have been proposed to achieve these goals. McCarty et al. (2011) proposed low strength anaerobic treatment, followed by direct utilisation of high nitrogen, but otherwise treated wastewater. Batstone and Virdis (2014) has noted that this could be extended to a complete wastewater treatment solution by the use of mainline biological anaerobic nitrogen removal (anammox), and adsorptive phosphorous recovery. Verstraete et al. (2009) proposed the up-concentration of domestic wastewater (by physical or biological methods), followed by anaerobic digestion of organics and reuse of the mineral nutrients. Both concepts incorporate anaerobic treatment as a key carbon removal method instead of conventional activated sludge treatment and hence allow energy positive or neutral wastewater treatment (Batstone and Virdis, 2014). Mainline anaerobic treatment enables carbon and potentially phosphorous recovery, while up-concentration allows carbon, nitrogen, and phosphorous recovery (Batstone and Virdis, 2014).

A key challenge in up-concentration is the partitioning of nutrients from the soluble to the solid phase in order to recover these nutrients in a concentrated side stream. This can be achieved by

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resource intensive physical (van Voorthuizen et al., 2008) and chemical methods (Booker et al., 1999) or by biological means, in which soluble organics, nitrogen, and phosphorous are fixed biologically through accumulation or assimilation. Aerobic partitioning of organics and nutrients can be partly achieved through short sludge retention time (SRT), high rate activated sludge (HRAS), or A-stage process, where heterotrophic growth is used to concentrate organics through growth and adsorption. The hydraulic retention time (HRT), and sludge age are maintained at very low levels in order to minimise oxidation of organics while simultaneously assimilating nutrients into the biomass (Jimenez et al., 2005). However, the extent of assimilation of organics is related to the aerobic biomass yield. Nitrogen and phosphorous assimilation is subsequently limited by the COD:N:P ratio in the resulting biomass (Bloor et al., 1995). This therefore allows maximum assimilation of only 15–20% of nitrogen (Fux and Siegrist, 2004) and 20–30% of phosphorous (Jaffer et al., 2002; Pitman et al., 1991).

Algae and high rate algal ponds (HRAP) are another option to partition nutrients effectively from diluted wastewater (Park et al., 2011), with organics biologically produced from CO_2 and light. However, HRAP application is limited by its large footprint due to typical illuminated surface volume ratios between 4 and 8 m^{-1} (Park et al., 2011; National-Research-Council, 2012).

Another possibility is the partitioning of organics and nutrients using purple phototrophic bacteria (PPB), which uses less light per weight biomass assimilated (since light is used anoxygenically to generate energy for growth) (Basak and Das, 2009). Most previous studies dealing with PPB utilised axenic cultures and defined, sterilized growth media or artificial wastewater in batch tests (Hülsen et al., 2014). However, wastewater cannot be sterilized, and hence mixed culture biotechnology has to be used. It is possible to utilise infra-red (IR) light to enrich specifically for purple phototrophic bacteria. PPB has been applied to mixed culture industrial wastewater treatment (removal of COD, including a laboratory-scale sequencing batch reactor (SBR), a membrane bioreactor (MBR) (Chitapornpan et al., 2012) and a membrane sequencing batch reactor (MSBR) (Kaewsuk et al., 2010).

Batch tests using domestic wastewater as inoculum and growth media showed that (a) infrared could selectively enrich PPB from domestic wastewater alone, and (b) that domestic enriched mixed PPB could remove soluble components from domestic wastewater to current effluent limits by assimilation (Hülsen et al., 2014). However, around 300 mgCOD L^{-1} as acetic acid need to be added to achieve effective nitrogen and phosphorous removal (>90%). PPB cannot utilise the whole spectrum of organics present in the wastewater but are limited to lower molecular substances such as organic acids and alcohols (Inui et al., 1995) and some sugars (Inui et al., 1999). It was noted in Hülsen et al. (2014) that internal recovery of organics would be required to achieve economic wastewater treatment and that this was a key barrier to the process. While batch testing indicates basic capacity to treat domestic wastewater, demonstration and analysis in a continuous process is essential to determine practical feasibility for domestic wastewater treatment. In particular, the degree to which external carbon needs to be added in a continuous process to achieve full nutrient removal needs to be identified.

To address these issues, this study aims to evaluate the application of a mixed culture of PPB for domestic wastewater treatment in a photo anaerobic membrane bioreactor (PAnMBR). The key objectives are; (a) simultaneous removal of COD, TN and TP to below 100 mg L^{-1}, 10 mg L^{-1} and 1 mg L^{-1}; (b) determination of COD, N, P substrate ratios and removal correlation; (c) determination of process parameters such as volumetric loading rate (VLR), sludge retention time (SRT), hydraulic retention time (HRT), sludge loading rate (SLR) and biomass yield. Furthermore, the population development in the reactors over time was determined to identify the major microbial mediator, and to assess whether performance indicators are linked to microbial community.

2. Material and methods

2.1. Raw wastewater

Domestic wastewater was collected at Robertson Park wastewater pump station, Indooroopilly (Brisbane, Australia) (day 1–195 and 245–256) and at Taringa wastewater pump station (Brisbane, Australia) (day 196–244) and stored immediately afterwards in a cold room at 4 °C. The wastewater was allowed to settle in 200 L drums for one day and afterwards used as primary settled wastewater. The composition of the pre-settled wastewater is shown in Table 1. The supernatant was pumped through a heat exchanger to warm up to room temperature (22 °C) and was used as reactor feed.

2.2. Inoculum

The reactor was started with raw domestic wastewater only. No inoculum was added.

2.3. Anaerobic photo-bioreactor (PAnMBR)

2.3.1. PAnMBR configuration

Fig. 1 shows the schematic PAnMBR configuration. A 2 L rectangular acrylic PAnMBR equipped with a submerged flat sheet membrane (1) (values in parentheses refer to elements in the figure) with 0.45 μm pore size and 0.12 m^2 surface area (Kubota, Osaka, Japan) was anaerobically illuminated at 50 W m^{-2} with IR light (IR 96 LED Illuminator for Night Vision Camera (2), St. Louis, MO, USA). Illumination intensity was measured on the outside of the reactor wall with an IR light sensor (PAS Port™, Roseville, CA, USA). The illuminated surface/volume ratio was 30 m^2 m^{-3}. The operating flux of the membrane was at maximum 2.1 L m^{-2} h^{-1}. The width, length and height of the photo-bioreactor were 2, 34 and 40 cm with water height between 28 and 32 cm. The reactor was continuously mixed with an internal gas recycle of 6 L min^{-1} by a vacuum pump (KNF Neuberger Laboport N86KT.18 (3), Trenton, NJ, USA) via a condensate trap (4) through an air stone at the bottom of the reactor (Aqua Nova Aquarium Air Stone 25 cm (5), Geebung, QLD, Australia). The gas recycle also functioned as membrane and inner reactor wall cleaning, to minimise biofilm formation. The reactor was continuously fed (Watson Marlow 120U/DM2 pump (6), Wilmington, MA, USA) with raw domestic wastewater as noted above. A pressure sensor was used as level switch (GE 5000 Series Pressure Transmitter, Fairfield, CO, USA) at the site of the reactor (6) which controlled the effluent pump (WELCO peristaltic pump WPM1-S2AA-BP (8), Tokyo, Japan). Effluent removal was therefore semi-continuous. Transmembrane pressure was measured by a (GE 5000 Series Pressure Transmitter

Table 1
Pre-settled wastewater composition of Indooroopilly and Taringa collection point with standard deviations in parentheses (values in mg L^{-1}, except pH).

Parameter	Indooroopilly (n > 50)	Taringa (n = 19)
TCOD	430 (198)	459 (144)
SCOD	245 (47)	241 (45)
NH_4–N	47 (10)	46 (5.3)
TKN	60 (11)	63 (8.0)
PO_4–P	6.9 (2)	6.5 (0.9)
TP	8.7 (1.6)	8.6 (1.8)
pH	7.4 (0.15)	7.7 (0.3)