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Pursuit of urine nitrifying granular sludge for decentralised nitrite production and sewer gas control

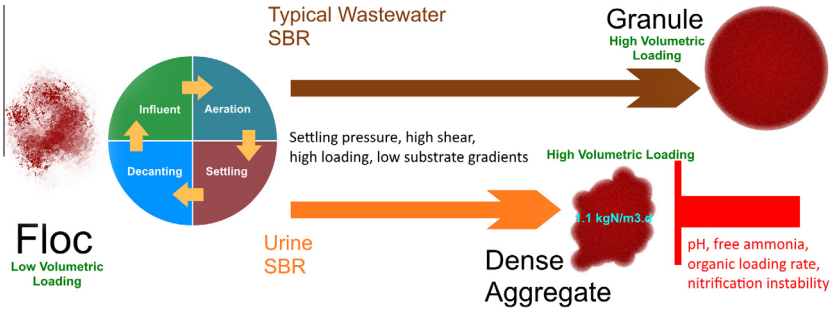
H.R. Mackey [a,b,*], G. Rey Morito [a], T. Hao [a], G.-H. Chen [a,c]

[a] Department of Civil & Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[b] College of Science and Engineering, Hamad Bin Khalifa University, Education City, Doha, Qatar
[c] SYSU-HKUST Joint Research Center for Innovative Environmental Technology, Sun Yat-sen University, Guangzhou, China

HIGHLIGHTS

- Nitrifying SBRs operated for high rate urine oxidation with base addition.
- Granular sludge development explored through various operational parameters.
- Small, compact and strong granule-like aggregates developed.
- Granulation limited by pH/NH_3 and opposing conditions for heterotrophs and nitrifiers.
- High-rate stable nitritation achieved at volumetric conversion rate of 1.1 kg-N/m^3 d.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to develop a high-rate reactor for decentralised urine nitrification using granular sludge, which allows high biomass retention in a small footprint installation. The system incorporated alkalinity dosing to ensure full conversion of ammonia to nitrite for subsequent control of sewer gas production. The key operational parameters for granule formation such as feeding and settling duration were tested as well as environmental conditions including pH. Pulse feeding was found to be instrumental to both the treatment performance and development of well settling granule-like aggregates. These aggregates showed granular characteristics with a compact and well defined shape, excellent settleability and high strength. However, pulse feeding also led to increased pH and free ammonia concentrations which reduced heterotroph activity and aggregate growth. Furthermore, in order to prevent nitrification collapse and high pH and free ammonia associated with such an event the reactor nitrogen loading was limited. Due to the low organic to nitrogen ratio of urine this restrained the organics loading of the dominant heterotrophic community further limiting granule growth. Nevertheless, the development of compact well settling aggregates under pulse feed operation allowed the objective of high-rate nitrification to be achieved with sustained nitritation rates up to 1.1 kg-N/m^3 d at a urine dilution of approximately 25%.

Abbreviations: AOB, ammonia oxidising bacteria; bCOD, biodegradable chemical oxygen demand; BSA, bovine serum albumin; COD, chemical oxygen demand; DO, dissolved oxygen; EPS, extracellular polymeric substances; FISH, fluorescent in situ hybridisation; MLVSS, mixed liquor volatile suspended solids; MLSS, mixed liquor suspended solids; N, nitrogen; NLR, nitrogen loading rate; NOB, nitrite oxidising bacteria; R_{TKN}, removal rate of total Kjeldahl nitrogen (%); SVI, sludge volume index; TAN, total ammoniacal nitrogen; TKN, total Kjeldahl nitrogen; TN, total nitrogen; TNN, Total nitrite nitrogen; TSS, total suspended solids; VSS, volatile suspended solids.

* Corresponding author at: College of Science and Engineering, Hamad Bin Khalifa University, Education City, Doha, Qatar. Tel.: +974 4454 5665.
E-mail address: hmackey@qf.edu.qa (H.R. Mackey).

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1. Introduction

The discharge of nutrients from large urban centres into waterways has historically been one of the main concerns for environmental engineers. To avoid eutrophication of waterways the typical approach is to collect all domestic wastewater for treatment at centralised wastewater treatment plants. However this approach introduces the need for costly sewer networks that are used solely for transport as well as complex and inefficient treatment process configurations for dealing with the mixture of various diluted household waste streams [1].

As urine accounts for approximately 80% of the nitrogen and 50% of the phosphorus of the total nutrient loads present in domestic wastewater [2,3], the decentralised treatment of separated urine could provide an opportunity for efficient nutrient removal and recovery options.

A number of processes already exist for separate urine treatment and nutrient recovery, as detailed in Maurer et al. [3]. The process selection depends heavily on a combination of environmental, social and economic aspects [4]. For instance, in areas with nearby agriculture partial-nitrification and vacuum-compression evaporation can be used for complete nutrient recovery as a fertiliser product [5]. In dense urban areas nutrient removal via struvite precipitation, urine nitrification and in-sewer denitrification is another alterative with the following advantages:

- Phosphorus removal via struvite precipitation using magnesium addition provides an alternative source of fertilisers [6].
- The in situ urine nitrification allows the use of the sewer network as a post-anoxic bioreactor enabling more efficient use of organic carbon in denitrification [7].
- In sewer denitrification allows possible simplification of centralised plants to attain high rate carbon removal [8].

In these and other systems urine nitrification plays the important role of converting ammonia, which is formed through the hydrolysis of urea, to nitrate/nitrite to reduce the bulk pH and prevent odour from ammonia gas release. Additionally, aerobic removal of organics is provided.

For decentralised urine nitrification a high-rate compact bioreactor is highly desirable, which generally requires retention of high biomass concentrations in the system. Biofilm reactors are commonly used for nitrification systems due to their high degree of biomass retention allowing reduced footprint and resilience against cold climate. Nevertheless mass transfer issues generally limit the overall volumetric loading rates that can be achieved [5,9]. Granular sludge, as a self-immobilised and suspended type of biofilm, increases mass transfer of substrate through the biomass while its rapid settling allows excellent liquid–solid separation and high biomass concentrations. In addition the granular structure enhances nitrite oxidising bacteria (NOB) colonisation [10]. As a result granular sludge has already been demonstrated as an ideal system for high rate nitrification [11]. Furthermore, as granular sludge does not require biofilm support it is a more economical alternative for decentralised treatment.

A sequencing batch reactor (SBR) is commonly applied for sludge granulation due to its unique capability in controlling substrate concentrations and sludge settling/decanting flexibility [12]. A few studies have applied granular sludge technology to wastewaters with total ammoniacal nitrogen (TAN) concentrations in excess of 500 mg-N/L [11,13,14], but have significant differences to the current study with regards to higher organic-nitrogen ratios, higher reactor temperatures or use of pre-cultivated granules. A high pH in hydrolysed urine of approximately 9.2, even following significant dilution, may also impact aerobic granulation through either growth inhibition or chemical changes to extracellular polymer structure which holds the granule together [15]. Such a high pH lies outside those previously investigated [13,16,17]. The only previously reported attempt to cultivate granular sludge directly for urine-stabilisation was on strongly diluted urine (200–250 mg-N/L) by Sun et al. [18]. Direct cultivation was not successful although a reactor was successfully operated using pre-cultivated granules for 132 days at a nitrogen loading rate (NLR) of 0.5 g-N/L d [18]. Potential factors preventing granulation in the study of Sun et al. include a low biodegradable organic loading rate of 0.4 g-COD/L d as a result of the low COD:N ratio, nitrifier washout under the short settling time imposed and continuous feeding which would result in low bulk liquid organic concentrations and high concentration gradients within the biomass.

Despite such potential difficulties the present study explores the feasibility of developing urine nitrifying granular sludge, driven both by scientific understanding of previous failure [18] and practical application for decentralised urine nitrification. Therefore, the goal of this study is to explore the feasibility of cultivating urine nitrifying granular sludge by focusing on the key operational parameters of settling time and feeding strategy and other possible influencing factors such as COD:N ratio, loading rate and pH.

2. Materials and methods

2.1. Reactor configuration and operation

In this study, a three-stage experiment was designed. In Stage 1, a urine-nitrifying SBR, named R1, constructed from Plexiglas with an effective volume of 3.2 L (68 mm diameter, 875 mm high) and an exchange ratio of 26% was adopted as the first reactor to explore possible urine nitrifying granular sludge under trial conditions. Fine bubble aeration was provided at 2 L/min, which gave a superficial air upflow velocity of 0.92 cm/s and at the same time maintained the dissolved oxygen (DO) above 4 mg/L. This air upflow velocity was limited by foaming but was deemed sufficient for sludge granulation based on comparisons of the loading rate and substrate composition to similar studies [19,20]. Each operation cycle was set to 6 h. Aerobic conditions were maintained throughout except for the settling phase. The times assigned for feeding and settling were changed over a number of defined periods, as detailed in Table 1. Seed sludge was collected from a secondary sewage treatment plant in Hong Kong with an initial mixed liquor volatile suspended solids (MLVSS) concentration of 2130 mg/L. The reactor was operated at room temperature (22 ± 2 °C). Base (1 mol/L $NaHCO_3$) was dosed to provide sufficient alkalinity for complete nitrification. The pH setpoint for base dosage was 7. Stage 2 coincided with the final period of operation in R1 when the pH controller was replaced by dosing the necessary amount of $NaHCO_3$ (alkalinity) into the influent. This caused the influent pH to rise from around 9.2 to 9.5–9.6 with an increase in influent free ammonia of between 40% and 50% in the influent. This provided the opportunity to study the effects of pH and free ammonia on the sludge properties.

Stage 3 was implemented in order to confirm some of the observations obtained from R1. For this stage sludge was diverted from R1 to two other identical reactors, named R2 and R3, for confirming the effect of feeding pattern and settling time as the two key operational parameters on urine nitrifying granular sludge development. The initial sludge concentration in these two reactors was set at 2550 (±40) mg-MLVSS/L. Both reactors were operated under the same conditions as R1 except that feeding occurred only once per cycle and the exchange volume was reduced slightly to 23%. Feeding in R2 was under a pulse regime and for R3 under a gradual-feed regime to directly compare the role of feeding on