Post-treatment of high-rate activated sludge effluent via zeolite adsorption and recovery of ammonium-nitrogen as alternative fertilising products

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Conventional municipal wastewater (MWW) treatment is highly energy intensive due to the high degree of aeration required to oxidize nitrogen (N) into nitrogen gas (N_2) (Zessner et al., 2010). To address this sustainability issue, N recovery via adsorption is often proposed in literature. The packing material used for adsorption represents a solid waste stream that could potentially be recovered as a fertilising product. However, there is little to no information available regarding the physicochemical characterization of natural packing materials after N removal from MWW and only limited analyses of their marketability (Sheikh et al., 2023; Zhang et al., 2023). On the flipside, large amounts of energy are also funnelled into the Haber-Bosch process to fix N_2 to produce N fertilisers (International Energy Agency, 2021). To address this gap, this study focused on investigating the feasibility to connect nutrient flows between wastewater treatment (WWT) and agriculture by characterising the potential fertilising products obtained via a novel two-stage wastewater treatment system integrating a high rate activated sludge (HRAS) process in contact-stabilization mode (HRAS/CS) with adsorption to recover N from MWW (Figure 1). Integrating these two technologies could reduce energy use and N_2O emissions treatment (Dockx et al., 2022) related to MWW treatment and aid the WWT and agricultural sectors in meeting recent and upcoming European Union (EU) legislation regarding energy use, greenhouse gas emissions and nutrient management.

In the first stage, HRAS/CS was used to biologically oxidize organic matter and remove suspended solids at a high rate with low TN removal. In HRAS/CS, the feeding of MWW is decoupled from aeration to rapidly favour the sorption and storage of substrates and reduce the bio-oxidation of carbon, while in a conventional HRAS system these processes are coupled. HRAS/CS was chosen instead of a conventional HRAS because it has proven to better harness the energy contained in MWW by redirecting a larger fraction of organic matter into sludge with higher biogas conversion potential (Meerburg et al., 2015). In the second stage, N was recovered by an adsorption column packed with natural zeolites, since the N-saturated zeolites could be considered a fertilising product after N adsorption, unlike synthetic materials that cannot be directly applied to soil. The performance of the zeolites column in terms of N recovery and concomitant treatment of HRAS/CS effluent was evaluated and optimized in the laboratory scale by (i) modelling N-breakthrough at different flow rates, (ii) assessing the effect of zeolite regeneration with potassium chloride (KCl) (30 g/L) on N recovery and (iii) enhancing the N content on zeolites by treating HRAS/CS effluent and the liquid fraction of sludge digestate (LFD) with the same column, in series. LFD is a side-stream with a higher N concentration than HRAS/CS effluent and it could be generated from the described system (Figure 1). The N-saturated zeolites were characterised to determine their potential fit in the component material and product function categories (CMCs and PFCs) laid out in the EU's Fertilising Product Regulation (EU 2019/1009) (FPR).

N recovery from HRAS/CS effluent proved to be feasible at flow rates ranging between 5-40 empty bed volumes (BV) per hour, with modelled adsorption and WWT capacities ranging between 2.9-3.7 mg/g and 152-191 BVs (respectively). Adsorption and WWT capacities decreased with an increasing flow rate; however, at the higher flow rates it is possible to treat MWW at a much faster rate (2.5-4 times faster), while the estimated loss of treatment and adsorption capacity is small in comparison (1.1-1.4 times lower). The TN and COD removal efficiencies achieved by the HRAS/CS and adsorption system ranged between 74-82% and 76-89%, respectively, achieving EU discharge standards. The N-saturated zeolites produced after treating HRAS/CS effluent contained 1.4-2.4 mg NH_4^+-N/g fresh weight (FW) and 14-19 mg K^+/g FW. The zeolites' N content was directly proportional to the NH_4^+-N concentration in HRAS/CS, while the potassium (K) content was attributable to K^+ naturally adsorbed on zeolites as well as to K^+ adsorbed during regeneration. KCl regeneration decreased N content in N-saturated zeolites by 0.3 mg/g FW after one cycle. Consecutive N recovery from HRAS/CS effluent and LFD increased N content on zeolites to 8.4 mg/g FW, with a 25% NH_4^+-N removal efficiency from LFD. According to the measured NK content on the N-saturated zeolites, as well their content of regulated metals, the latter could be eligible as fertilising products for PFCs 3-6 in the FPR, which encompass soil improvers, growing medium, nitrification inhibitors and non-microbial plant stimulants. However, the N-saturated zeolites do not fit into an existing CMC. Therefore, if further testing indicates that the produced adsorption outputs have high fertilising product potential, a new CMC encompassing these products, as well as other nutrient-rich products derived from an adsorption process treating wastes, could be proposed.

The use of zeolites as natural packing material can thus successfully treat MWW and potentially mitigate solid waste generation from the proposed 2-stage system, given the exhausted zeolites could potentially be applied as fertilising product. Efforts to optimize the two-stage system in a larger scale should focus on optimization in terms of cost and energy reduction, rather than the final N content on the zeolites, given the maximum reachable N content is far from satisfying the N-fertiliser standards set by PFC 1 (with minimum values set to 100 and 30 g N/kg for straight and compound N fertilisers). Results from this research will be used to test MWW treatment with HRAS/CS and adsorption at a relevant scale to test the N-saturated zeolites' efficacy as fertilising product to confirm whether their life cycle can be extended, as well as to determine the degree of reduction in energy use and N_2O emissions achievable (compared to a conventional system).

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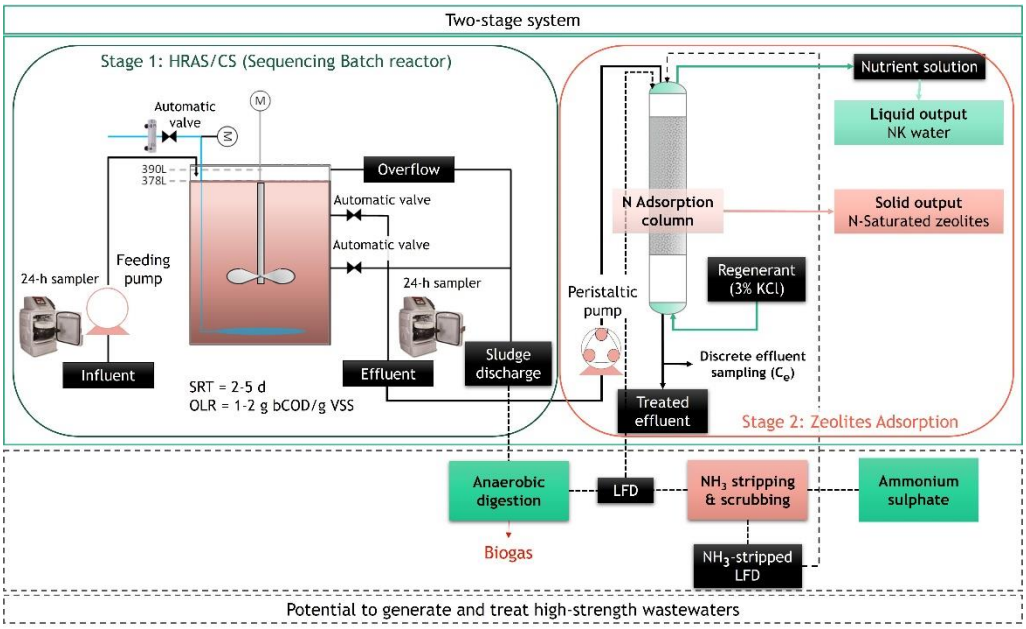

Figure 1. Process flow and outputs of the proposed novel two-stage N recovery and wastewater treatment system. Dashed lines show the additional treatment steps that could generate LFD from HRAS/CS treatment for adsorption. LFD = liquid fraction of sludge digestate, SRT = solids retention time, OLR = organic loading rate, bCOD = biodegradable chemical oxygen demand, VSS = volatile suspended solids

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