Management of microbial community composition, architecture and performance in autotrophic nitrogen removing bioreactors through aeration regimes

Completely autotrophic nitrogen removal from nitrogen-rich wastewaters through the nitritation -plus- anaerobic ammonium oxidation processes can greatly reduce operational energy costs compared to traditional nitrogen removal processes. The footprint can be further reduced by process intensification in single-stage reactors. Single-stage reactors require biofilms or bioaggregates to provide the complementary redox niches for the aerobic and anaerobic bacteria that are required for nitritation and anaerobic ammonium oxidation (anammox), respectively. The nitritation/anammox process might not only reduce aeration and carbon requirements but also reduce emissions of the greenhouse gas nitrous oxide. Successful performance of the intense energy-efficient nitritation/anammox process requires a rather narrow operational window. Outside of this window, disproportionate activities of the involved functional guilds and emergence of undesired guilds can rapidly deteriorate the performance, which will offset the reduced footprint and stability. Hence, robust operational strategies that incorporate microbial process understanding are necessary.

In this work, aeration strategies were systematically evaluated as an approach to manipulate the microbial community structure, to reach efficient nitrogen removal performance, and to reduce nitrous oxide emissions from single-stage nitritation/anammox reactors. First, an iterative protocol was developed to diagnose reactor performance based on process stoichiometry and to propose actions to enhance performance based on discretized aeration parameters, restricted by an overall ratio of oxygen to ammonium loading. The protocol was successfully applied on two bioaggregate-based single-stage sequencing batch reactors during start-up; while recovering from major disturbances such as nitrite accumulation, nitrite oxidizer proliferation, ammonium starvation, and oxygen overloading; and during nitrogen loading increases. Different mitigation methods were validated or falsified ultimately improving the proposed protocol. Differences in performance and, especially, of time resolved nitrogen species dynamics, of the two parallel systems under similar aeration regimes indicated that the aggregate size distribution and microbial community architectures profoundly affected the optimal oxygen to ammonium loadings. Size-segregated aggregates consisting of exclusively aerobic or exclusively anaerobic ammonium oxidizing guilds, could achieve removal efficiencies comparable to stratified aggregates (containing both aerobic and anaerobic ammonium oxidizing guilds), at sufficiently low oxygen to ammonium loadings. However, transient nitrite accumulation and susceptibility of anamorphic ammonium oxidizing bacteria in systems with size-segregated aggregates were considered to weaken the system robustness.

Further assessment of the interaction between aeration regime and architectural evolution of the nitritation/anammox aggregates was carried out on the two systems once they achieved steady state overall performance. With settling time, volumetric exchange ratio, sludge retention time and influent characteristics kept constant, the aeration regime, itself, caused a rapid deterioration of the performance. By increasing aeration frequency, the originally size-segregated community became more redox-stratified with larger aggregates. Increasing the duration of aeration, on the other hand, did not significantly alter the original redox-stratified architecture, but allowed proliferation of unwanted nitrite oxidizing bacteria. The decrease in aeration intensity concomitant with increased duration also decreased the aggregate size. Aggregate morphology and settleability were also altered with aeration regime: increased frequencies led to compact but hollow aggregates that transiently accumulated nitrogen gas. Based on the experimental observations, a conceptual scheme was proposed to describe aggregation and architectural evolution in nitritation/anammox reactors, incorporating the possible influences of intermediates formed with intermittent aeration. Community analysis revealed an abundant fraction of heterotrophic types despite the absence of organic carbon in the feed. The aerobic and anaerobic ammonia oxidizing guilds were dominated by fast-growing Nitrosomonas spp. and Ca. Brocadia spp., while the nitrite oxidizing guild was dominated by high affinity Nitrosospira spp. Emission of nitrous oxide (N2O) was evaluated from both reactors under dynamic aeration regimes. Contrary to the widely held notion that dynamic operation at low dissolved oxygen concentrations would increase nitrous oxide emissions, increasing the aeration frequencies reduced N2O production and emission. N2O production was observed primarily at the onset of aeration after anoxia. Nitric oxide and not free nitrous acid or nitrite correlated to production rates. The measured aerobic ammonia oxidation potential correlated to the nitrous oxide production rates. Shortening the duration of single aerated periods was an efficient way of preventing the exponential increase in N2O production rates. Correspondingly, operating nitritation/anammox reactors under limited aerobic and excess anaerobic ammonia oxidation is recommended to minimize N2O production and emission.

Aeration impacts the nitritation/anammox process in multiple dimensions. This study focused on the different oxygen delivery schemes, and some of the collateral impacts could be isolated, increasing process understanding. It was demonstrated that aeration strategy can be used as a powerful tool to manipulate the microbial community composition, its architecture and reactor performance. We suggest operation via intermittent aeration with short aerated periods to minimize nitrous oxide emission rates and sufficiently long non-aerated periods to suppress nitrite oxidizing bacteria. Under these conditions, redox-stratified aggregates can be established maintaining simultaneously aerobic and anaerobic autotrophic ammonium oxidation in an intensified single-stage reactor. Nitritation/anammox processes have already been successfully applied to treat side stream reject waters, landfill leachates and industrial wastewater streams; now this process is being examined to replace or upgrade conventional treatment trains to treat domestic wastewaters under low temperatures in the presence of residual organic carbon. This work, by examining the interplay between macro- and micro-scale phenomena and processes, contributes to establishment of strategies that can be adopted in practice to operate the single-stage nitritation/anammox systems.