EPSRC DTP (Sandpit) Studentships 2019/20

Newcastle University

Project Title: Harnessing microbially mediated redox processes for sustainable water treatment

Schools: School of Engineering
School of Natural and Environmental Sciences

Supervisory Team	• **Dr Anke Neumann, School of Engineering** https://www.ncl.ac.uk/engineering/staff/profile/ankeneumann • **Dr James Kitson, School of Natural and Environmental Sciences** https://www.ncl.ac.uk/nes/staff/profile/jameskitson

Overview

Providing clean water for all remains one of the main challenges for humanity and thus is one of the UN's Sustainable Development Goals (SDG6). While in most of the western world water and wastewater treatment are implemented comprehensively, our current treatment technologies require immense energy and chemical inputs to deliver high quality (drinking) water, making it unfeasible to directly translate these approaches to developing countries. In this project, we will investigate the potential of a just recently discovered process involving natural sedimentary minerals to sustainably treat water. This process was found to produce highly oxidizing species such as hydroxyl radicals [1], which are also the main reactive species provided by so-called advanced oxidation processes that have been hailed as the water treatment approaches of the future [2]. While reactive species are produced during the reaction of reduced (ferrous) iron in the minerals (clay minerals) with oxygen in the water to be treated, the sustainable use of this process relies on the regeneration of clay mineral ferrous iron by microbes under anoxic, or reducing, conditions. Although oxygenation and microbial iron reduction can be achieved when stimulated in isolation and in the laboratory [3], it is currently unknown whether treatment efficiency can be maintained over several cycles of use and re-generation under realistic environmental conditions. Key factors in the success of this process will be the rate at which microbial communities can move between one redox state and the next and whether this can happen repeatedly without community breakdown. Particularly important aspects that will determine whether this approach can be implemented at scale and operated sustainably include:
(a) Can treatment be achieved over several cycles of treatment and regeneration at mesocosm scale, using only water flow and column saturation for stimulating reducing environments and oxidation?
(b) How will the naturally present microbial communities that drive iron reduction during regeneration periods evolve over several treatment cycles and how does this affect treatment efficiency?
(c) Can a novel, low-cost tool be developed based on ecological indicators and analytical techniques to enable performance monitoring of engineered treatment systems as well as for assessing the natural capital of redox-cycling sediments?
To address these research questions, methods and approaches from a range of disciplines, including environmental engineering, microbiology, mineralogy, analytical chemistry, and ecology, will be combined and applied in a new context.

Methodology

This project will be jointly supervised by Dr A Neumann (AN) and Dr J Kitson (JK), which amongst them provide all technical and thematic expertise for the successful implementation of this interdisciplinary project.
The project will set up model treatment systems in replicated mesocosm (column) experiments, in which

reducing and oxidizing conditions will be induced by modifying water flow and column saturation. Initial experiments will determine the ideal design, experimental setup, and operation conditions. The sediments to be tested include an entirely engineered composition with well-characterized clay minerals; natural sediments amended with the most promising clay mineral(s); and sediments from areas that undergo natural redox cycling. Oxidation of an organic reactive probe molecule will be used to monitor treatment efficiency, and the probe as well as its oxidation product(s) will be quantified using chromatography (HPLC).
The treatment systems will be monitored both spatially and temporally for a range of parameters, employing cutting edge techniques from microbiology, geochemistry, and environmental genetics to gain a comprehensive understanding of the processes and underlying ecology governing the system's efficiency. Pore water will be analysed for its redox potential and oxygen content (micro-sensors), probe compound concentration, and the microbial communities present (both active and inactive using metabarcoding [4]). Minerals and sediments will be characterized before and after the experiments for their composition (XRD, FT-IR), their oxidation state (Mössbauer spectroscopy) and the microbial communities present. Identification of active and inactive microbiota will be achieved by metabarcoding of both DNA and RNA (Illumina MiSeq or HiSeq 2500) and this data will be used to develop an in-depth understanding of the microbial interaction networks active under different redox conditions, their evolution over several redox cycles and their ability to recover following a change in conditions. Additionally, a subset of samples will be tested on the portable Oxford Nanopore MinION using the new Flongle flow cells to test its suitability for developing low-cost field-deployable microbial monitoring for this and other water purification systems.

Impact

This interdisciplinary project will provide the proof of concept that a low energy, low input (waste) water treatment system harnessing microbially mediated redox processes of iron-bearing clay minerals can be operated sustainably and at scale. Because clay minerals are ubiquitous in sedimentary environments, cheap and abundant, this novel and innovative approach could make water and wastewater treatment more cost effective and available in high, middle, and low-income countries alike. For example, remote and sparsely populated areas could be serviced at much lower cost and requiring only minimal monitoring; heavily contaminated waste streams such as hospital effluent could be pre-treated, lowering the ecological burden of pharmaceuticals passing traditional treatment systems; and demonstrating a feasible alternative of providing affordable, low maintenance, and sustainable (waste) water treatment with a small carbon footprint for the developing world.
In addition to the overall proof of concept, the project will also provide detailed understanding of the fundamental processes driving the treatment cycle. These insights are critical for designing, implementing, monitoring, and maintaining future full-scale treatment systems and are key to translating the proof-of-concept to real-world applications. Particularly useful for monitoring and maintenance purposes will be the results on how the observed treatment efficiency is linked to the microbial iron-reducing community present versus active. This relationship will allow for using simple indicators that can be determined based on DNA/RNA analysis, which today can be done cheaply and easily in the field, to assess the performance of the treatment system and if necessary, to suggest interventions to increase the performance, as well as to evaluate the treatment capability of natural redox-cycling sediments, for example for treating pesticides in agricultural runoff.

Timeline

Year 1: Detailed literature review; training in laboratory techniques and analytical methods; design and testing of columns for mesocosm experiments. Outcome: experimental setup and operation conditions finalized.
Year 2: Conduct mesocosm experiments assessing different clay minerals and engineered sediments; monitor treatment efficiency and evolution of microbial communities; destructively sample column sediments and assess changes to mineralogy. Outcome: 1st journal article and conference presentation towards end of year; addressed question (a) and (b) in part.
Year 3: Conduct mesocosm experiments with natural redoximorphic sediments; assess treatment efficiency and microbial communities; laboratory work to be concluded by end of third quarter; begin writing up of thesis. Outcome: 2nd journal article and conference presentation in second half of year; addressed questions (b) and (c).
Year 4: Complete write up of thesis; preparation of journal article(s). Funding ceases after 3.5 years. Outcome: submitted thesis and passed viva.

Training & Skills

During the first three months of the PhD, general and specific training needs will be assessed, involving the PhD student and the supervisory team, and a detailed training plan will be developed. This training plan will cover all laboratory skills, analytical techniques, and microbial ecology approaches required for this project and might also include programming (Python) and statistical analysis courses (R) as well as relevant taught MSc modules. Because the suite of technical skills acquired by the student involves state-of-the-art techniques from across different disciplines which are applied in a non-traditional context, the student will be equipped to use their skills in highly versatile and adaptable manner.
The PhD student will also be encouraged to make use of the broad suite of training opportunities in transferable skills provided at Newcastle University. The supervisory team will build on these skills trainings and consolidate and deepen the student's critical analysis and writing skills, their proficiency in preparing manuscripts for publication in peer-reviewed journals, and their competency at delivering conference presentations. The student will thus acquire the communication skills necessary to follow any chosen career path in either academia, industry, or government.

References & Further Reading

[1] Tong, M.; Yuan, S.; Ma, S.; Jin, M.; Liu, D.; Cheng, D.; Liu, X.; Gan, Y.; Wang, Y., Production of Abundant Hydroxyl Radicals from Oxygenation of Subsurface Sediments. *Environ Sci Technol* **2016,** *50*, (1), 214-221.
[2] von Gunten, U., Oxidation Processes in Water Treatment: Are We on Track? *Environ Sci Technol* **2018,** *52*, (9), 5062-5075.
[3] Zeng, Q.; Dong, H.; Wang, X.; Yu, T.; Cui, W., Degradation of 1, 4-dioxane by hydroxyl radicals produced from clay minerals. *J Hazard Mater* **2017,** *331*, 88-98.
[4] Stoeck, T.; Pan, H.; Dully, V.; Forster, D.; Jung, T., Towards an eDNA metabarcode-based performance indicator for full-scale municipal wastewater treatment plants. *Water Research* **2018**, 144, 322-331.

Further Information

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