UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Phosphorus removal and recovery from sludge centrate by membrane and steel-making slag

by Truong Minh Vu

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of

Professor Duc Long Nghiem
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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Truong Minh Vu, hereby declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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LIST OF ABBREVIATIONS

Symbol	Description
AD	Anaerobic Digestion
AcoD	Anaerobic Codigestion
BET	Brunauer-Emmett-Teller
BOF	Basic Oxygen Furnace
CA	Contact Angle
COD	Chemical Oxygen Demand
CP	Concentration Polarisation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DI	Deionised
DM	Dry Matter
DNA	Deoxyribonucleic Acid
DS	Draw Solution
EAF	Electric Arc Furnace
ED	Electrodialysis
EDS	Energy Dispersive X-ray Spectroscopy
FO	Forward Osmosis
FS	Feed Solution
FTIR	Fourier Transform Infrared
HAP	Hydroxyapatite
HRT	Hydraulic Retention Time
IAP	Ion Activity Product
IC	Inorganic Carbon or Ion Chromatography
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IP	Intra-particle Diffusion
IWA	International Water Association
LMH	$L/m^2.h$

MD	Membrane Distillation
MF	Microfiltration
MPR	Membrane Photo-bioreactor
N	Nitrogen
NF	Nanofiltration
NSW	New South Wales
P	Phosphorus
PA	Polyamide
PRO	Pressure Retarded Osmosis
PZC	Point of Zero Charge
RNA	Ribonucleic Acid
RO	Reverse Osmosis
SEM	Scanning Electron Microscopy
SI	Saturation Index
TAS	Tasmania
TFC	Thin Film Composite
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
UF	Ultrafiltration
US-EPA	United States Environmental Protection Agency
UV	Ultraviolet
WWTP	Wastewater Treatment Plant
XRD	X-ray Powder Diffraction

LIST OF PUBLICATIONS

1. Peer-reviewed journal publications and book chapters related to this thesis work

1. **M.T. Vu,** H.C. Duong, Q. Wang, Z. Cai, N.B. Hoang, N.T.T. Viet, L.D. Nghiem, A low-cost method using steel-making slag to quench the residual phosphorus from wastewater effluent, Environmental Technology & Innovation (2023) 103181 **(Q1)**.
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2. Other peer-reviewed journal publications and book chapters

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ABSTRACT

Phosphorus is an essential element for all lives on earth. It is also a finite resource, derived primarily from phosphorus rock. Given the imminent depletion of minable phosphate rock, phosphorus recovery from nutrient-rich streams is essential for future generations.

Sludge centrate as a by-product from anaerobic digestion of sewage sludge is a phosphorus-rich stream that can be considered as an alternative for renewable phosphorus supply. This study initiated a systematic approach to develop an innovative integrated framework using steel-making slag and membrane-based processes to maximise phosphorus removal and recovery from sludge centrate. The proposed complete framework involved pre-treatment process (i.e. biogas sparging and sand filtration), enrichment process by forward osmosis followed by recovery process using steel-making slag and post treatment of the recovery process effluent by steel-making slag and a membrane photo-bioreactor.

The obtained results demonstrated the proof-of-concept of biogas sparging to control membrane fouling and enhance nutrient enrichment during sludge centrate pre-concentration by forward osmosis. Biogas sparging also resulted in a significant improvement in the enrichment of phosphate ions to close to the theoretical value based on mass balance calculation. In other words, phosphate ions were retained in the concentrated sludge centrate for subsequent recovery.

Results in this study highlighted for the first time the potential of nutrient recovery from sludge centrate using calcium and other alkali metals from steel-making slag. Up to 96% phosphate and 71% ammonia could be recovered from sludge centrate at the optimal conditions. The results also showed that pre-treatment by sand filtration and forward osmosis enrichment was essential to achieve high nutrient recovery. Sand filtration pre-

treatment decreased the total suspended solid of sludge centrate by eightfold, leading to mitigated membrane fouling and reduced nutrient loss during forward osmosis pre-concentration.

In addition, the study demonstrated the feasibility of using steel-making slag to polish the aqueous solution followed by the application of steel-making slag in quenching residual P from the recovery process effluent. At the optimal conditions (i.e. pH 8.5 and steel-making slag dosage of 5 g/L), approximately 98% phosphorus removal could be achieved with the output level of less than 0.1 mg/L.

Furthermore, the study successfully demonstrated the feasibility of using a novel sequencing batch membrane photobioreactor for simultaneous nutrient removal and algal biomass production from sludge centrate. In comparison to the batch mode reactor, the membrane photobioreactor allowed for continuous cultivation of microalgae with 40% higher biomass content.

Keywords: Phosphorus recovery; sludge centrate; membrane filtration; steel-making slag; biogas sparging; microalgae cultivation.