



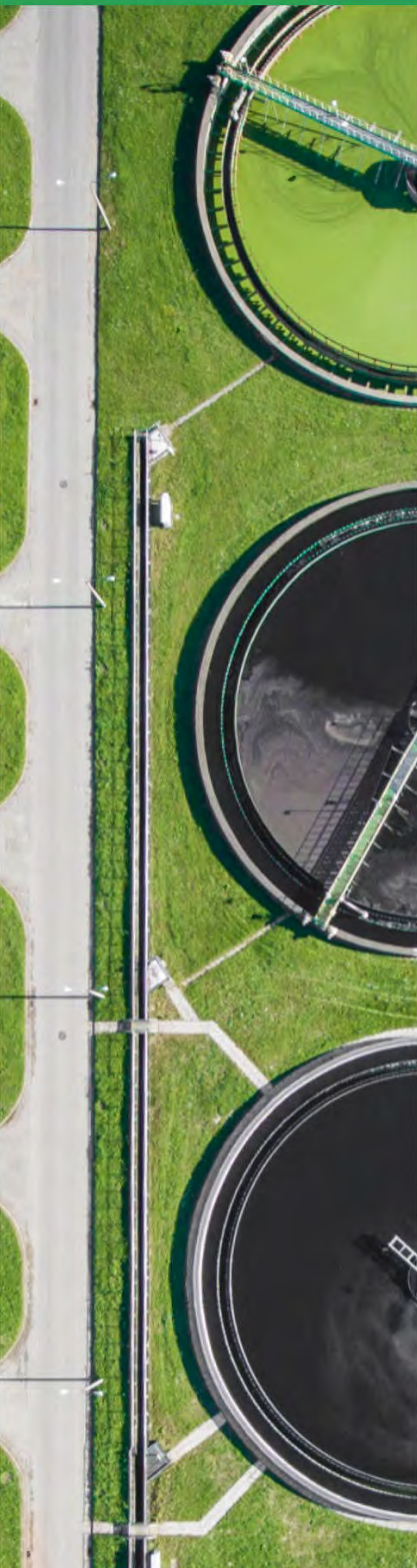
Transforming
Biosolids

Transforming Waste to Resource: Hydrothermal Treatment of Sewage Sludge in Water Recycling Plants

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The ARC Training Centre for the Transformation of Australia's Biosolids Resource has a primary goal of delivering world-class and innovative technological solutions and knowledge, to train the next generation of biosolids practitioners in cutting-edge, transformational approaches, and to guide best practice in the biosolids sector.

A key project delivered by the Centre through this project is to comprehensive investigation of hydrothermal treatment of sewage sludge and its integration with existing or new wastewater treatment plants highlights its potential and limitations.

For further information visit: www.transformingbiosolids.com.au

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Executive summary

This report is part of a broader initiative under the ARC Training Centre for the Transformation of Australia's Biosolids Resource. Project 1B aims to evaluate and benchmark thermal and hydrothermal treatment options namely pyrolysis, gasification, and hydrothermal treatment to support water utilities in transforming biosolids into valuable products while reducing costs, volume, and environmental impact. A comprehensive study of hydrothermal treatment of sewage sludge considering its product yield and properties with a focus on contaminants mitigation and further integration with anaerobic digestion is a critical part of this industry report.

This report outlines the progress and key outcomes of the project titled “**Transforming Waste to Resource: Hydrothermal Treatment of Sewage Sludge in Water Recycling Plants**” conducted under the ARC Training Centre for the Transformation of Australia's Biosolids Resource. The research involved investigation of an integrated hydrothermal treatment (HT) process for sludge management aimed to answer four key questions (i) how will different types of sewage sludge (primary sludge, waste-activated sludge, and digested sludge) behave during HT processing? (ii) what will be the fate of inherent contaminants such as heavy metals and PFAS in sewage sludge during hydrothermal processing? (iii) how will the co-processing of sewage sludge with additives such as lime, alum sludge, and food and garden organics (FOGO) enhance the conversion efficiency and product quality? and (iv) what will be the most promising integration options of HT with existing sewage sludge treatment process, particularly anaerobic digestion (AD)?

To answer these questions, a systematic approach was taken. First, the hydrothermal process was conducted across a temperature range of 180–270 °C, covering the range of operating conditions spanning both hydrothermal carbonisation (HTC) and hydrothermal liquefaction (HTL) conditions. Under these conditions, physicochemical transformations of different sludge types, namely primary sludge (PS), thickened waste-activated sludge (TWAS), and anaerobically digested sludge (DS) were investigated. This study clearly highlighted differences in sludge types and their behaviour during HT. Primary sludge yielded better solid product (hydrochar) quality in terms of carbon content, calorific value and porosity when compared with TWAS and DS. Subsequently, the co-hydrothermal processing of PS was conducted at 270 °C using two co-feeds (i) alum sludge (AIS), and (ii) food and garden organics (FOGO) which were added separately to PS at different mass proportions (25-75 mass%). Due to the catalytic activity of AIS, the hydrochar and bio-oil product showed significant improvement in yield by 52% and 40% respectively. In addition, the total heavy metal concentration in the hydrochar product was reduced by 27-91 %, mainly due to the dilution effects of adding AIS to PS. The co-processing of PS with FOGO had limited impact on product distribution and product properties largely due to similar physicochemical and biochemical properties. Therefore, AIS was identified as an effective co-feedstock to enhance PS processing under the studied HT conditions.

Thereafter, the viability of catalytic HT of PS using lime and co-HT with AIS were benchmarked regarding product enhancement and contaminant partitioning, mainly focusing on heavy metals (HMs) and PFAS. Catalytic HT and co-HT enhanced bio-oil yields by 10% and 15%, respectively, while exhibiting contrasting effects on hydrochar yield. Co-HT increased hydrochar production to 51.3%, while catalytic HT reduced hydrochar yield to 21% compared to sole HT of SS. Both processes improved hydrochar porosity, enhancing its potential as an adsorbent. Heavy metals followed distinct pathways, including precipitation, adsorption, co-precipitation, and complexation. PFAS degradation varied: > 99% of PFOA was removed, whereas PFOS degradation was limited (maximum 41%).

Results from these studies provided quantitative insights into the production of value-added products and their potential applications. Finally, multiple options were assessed to offset the energy demands of HT and identify the most efficient HT-AD integration strategy. Among the integration pathways, AD of PS with the liquid phase from hydrothermally treated TWAS (210 °C) yielded the highest methane production (184.1 ± 15.7 mL/g VS) and biodegradability (> 90%), albeit with an initial lag phase due to high NH_4^+ concentrations. The resulting digestate showed improved nutrient content and reduced HMs levels.

The research advances understanding of how HT parameters, sludge types, and co-processing strategies affect product quality and contaminant distribution/degradation. This comprehensive research aimed to establish an optimised, scalable, and environmentally responsible sludge management process.

Introduction

Wastewater treatment plants across the globe and Australia face increasing challenges in managing the large volumes of sewage sludge generated during the wastewater treatment processes. Sewage sludge is rich in organic matter and nutrients and is recognized as a potential resource for value-added processing aligning with the principles of the circular economy [1]. However, sewage sludge can also contain contaminants such as HMs, PFAS, microplastics, pathogens, etc. As regulatory pressures and environmental concerns grow, the water sector is urgently seeking sustainable, efficient, and integrated solutions to sludge management.

Hydrothermal treatment is a thermochemical process that operates in a water-rich environment under elevated temperature and pressure conditions. It has emerged as an efficient thermal treatment technique for managing wet organic wastes such as sewage sludge, food waste, and other high-moisture residuals. Hydrothermal technologies, particularly hydrothermal carbonization and hydrothermal liquefaction enable the direct conversion of wet sludge into valuable products such as hydrochar, bio-oil, and an aqueous phase without the need for pre-drying treatment [2,3]. These processes not only reduce the overall sludge volume but also help to immobilize heavy metals and degrade organic contaminants such as PFAS [4].

Despite promising developments, existing work has largely overlooked the influence of sludge physicochemical properties on the efficiency of hydrothermal processing. Wastewater treatment plants generate a variety of sludge types such as primary sludge, thickened waste activated sludge, and digested sludge each with distinct structural and chemical characteristics that significantly affect treatment behavior and product quality. Moreover, the potential to enhance resource recovery through co-processing with other problematic wet wastes such as alum sludge and FOGO remains underexplored. Equally important is the understanding of how contaminants behave and potential migrate into the product streams during hydrothermal treatment, and how additives or co-feeds can be used to reduce toxicity while improving output quality. The challenges of hydrothermal processing of sewage sludge and critical knowledge gaps that need to be addressed were illustrated in the Figure 1.

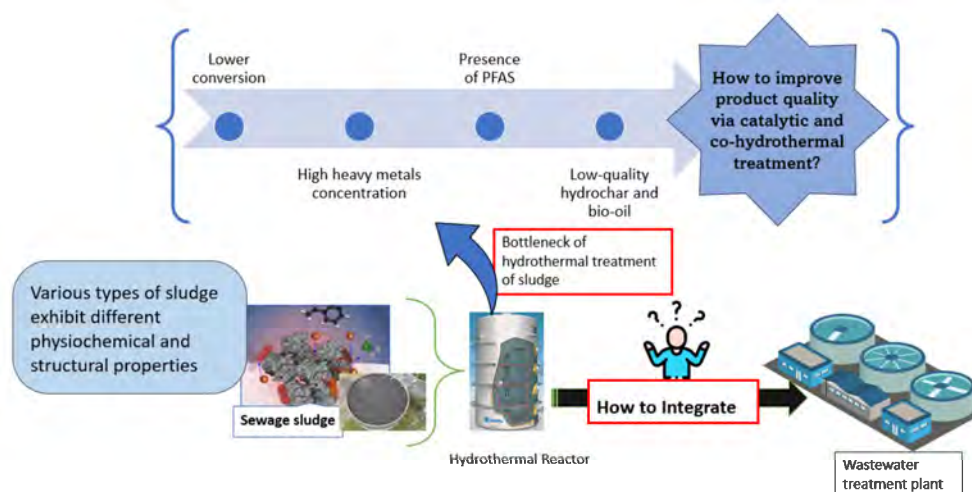


Figure 1. Current bottleneck of hydrothermal treatment of sludge

This report summarises the outcome of a three-year PhD project on hydrothermal treatment of sewage sludge conducted as part of Project 1B of the ARC Training Centre for the Transformation of Australia’s Biosolids Resource. This study mainly focused on characterizing the behavior and transformation of various sludge types under hydrothermal carbonization and hydrothermal liquefaction conditions, and assessing the impact of co-treatment strategies on product yield, composition, and contaminant dynamics. Particular attention was given to HMs and PFAS behaviour during hydrothermal processing and the mitigating effects of strategic co-feeding.

A key part of the project was the investigation of integration pathways for hydrothermal treatment within existing WWTPs, particularly through its alignment with downstream anaerobic digestion. This integration offers a promising route to maximize energy recovery, reduce biosolids volume, and advance the sustainability and circularity of water recycling operations [5].

Purpose of this project

The primary aim of this project is to investigate the application of hydrothermal treatment to various types of sewage sludge and assess its integration with anaerobic digestion within WWTPs. The focus is on understanding the physicochemical transformations, exploring synergistic co-feed interactions, evaluating contaminant degradation pathways, and maximizing the resource recovery potential of the treated sludge. This research addresses critical knowledge gaps and aims to establish robust, scalable strategies for implementing hydrothermal technologies in real-world WWTPs settings.

The study is structured around the following specific research objectives.

Objective 1: Evaluate the transformation of different sewage sludge types under various HT conditions to understand yield and product characteristics

Objective 2: Investigate the co-processing of SS with AIS and FOGO to analyse their synergistic effects

Objective 3: Understand the quality of hydrochar and the fate of contaminants, particularly HMs and PFAS, under sole HT, catalytic HT, and co-HT conditions.

Objective 4: Identify potential pathways for integrating HT with AD to offset HT energy requirements while improving bioenergy production and resource recovery.

Our approach

This project was structured around four core experimental objectives, each aligned with key knowledge gaps to advance the understanding and application of hydrothermal treatment of sewage sludge and its integration into WWTPs. Figure 2 illustrates the overall experimental design.

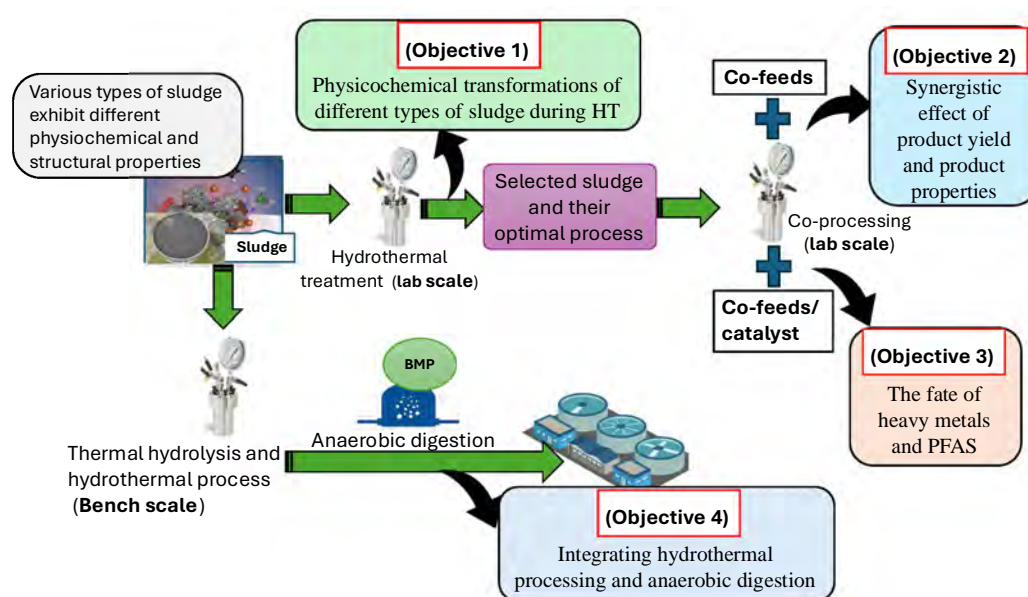


Figure 2. Summary of research methodology on the hydrothermal treatment of sewage sludge

The methodologies applied under each objective are outlined below.

Objective 1: Physicochemical Transformation of Sludge During Hydrothermal Treatment

Sludge Sampling & Characterization:

Various sludge types primary sludge, thickened waste activated sludge, and anaerobically digested sludge were collected from South East Water's Mount Martha Water Recycling Plant, Melbourne, Australia and extensively characterized for their physicochemical and biochemical properties.

Hydrothermal Processing:

Sewage sludge samples were subjected to hydrothermal treatment across a temperature range of 180–270°C, spanning both hydrothermal carbonization and hydrothermal liquefaction conditions.

Solid Product Analysis:

To understand the composition and key properties of hydrochar such as proximate and ultimate analysis, calorific value, heavy metals concentration, surface functional groups and surface morphology (surface area, pore structure) were analysed by using Thermogravimetric Analysis (TGA), CHNS/O elemental analysis, Inductively Coupled Plasma Mass Spectrometry (ICP-MS), X-ray Diffraction (XRD), Fourier-Transform Infrared Spectroscopy (FTIR), Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS) and Brunauer–Emmett–Teller (BET) surface area analysis.

Liquid Phase Analysis:

The chemical compositions of the bio-oil samples and aqueous phase organic residues were examined using Gas Chromatography–Mass Spectrometry (GC-MS). The nutrient content and heavy metals concentration of the aqueous phase product were also quantified.

Objective 2: Co-Hydrothermal Treatment with Alum Sludge and FOGO

Material Collection:

Alum sludge was sourced from Central Highlands Water’s North Ballarat Plant, and FOGO samples were collected from Geelong Council compost Facility, both located in Victoria, Australia.

Experimental Design:

Primary sludge was co-processed with alum sludge and FOGO at varying mass ratios (3:1, 1:1, 1:3).

Product Evaluation:

Resulting hydrochar were characterized to evaluate the changes fuel properties, surface functionality, porosity and surface area. Whereas, the chemical composition of bio-oil samples were determined by GC-MS analysis.

Synergy Assessment:

The synergistic effects of co-processing primary sludge with alum sludge or FOGO were analyzed for product yield and properties to determine improvements in treatment efficiency.

Objective 3: Fate of Contaminants During Catalytic and Co-Hydrothermal Treatment

Catalytic and co-processing of primary sludge:

Catalytic hydrothermal treatment of primary sludge using lime as an additive, along with co-hydrothermal processing of primary sludge with alum sludge was performed

Contaminant (PFAS) Spiking:

To determine the degradation or mineralisation efficiency of PFAS during hydrothermal treatment, primary sludge samples were spiked with known concentration of PFOS and PFOA since the concentrations of inherent PFAS in the primary sludge were low and evade analytical detection.

Fate of heavy metals and PFAS:

Heavy metals concentration were quantified in all product streams (hydrochar, bio-oil (both light and heavy fractions), and aqueous phase) and mass balance closure to ascertain heavy metal flow during the process was conducted.

PFAS distribution and mass balances were determined across all hydrothermal products using LC/TQ analysis in ALS lab.

Objective 4: Integration of Hydrothermal Treatment with Anaerobic Digestion

Experimental Setup:

Various upstream and downstream integration options of hydrothermal treatment and anaerobic digestion using two sludge stream (PS and TWAS) were explored.

Integration Performance Insights:

Key parameters such as biomethane yields as a function of digestion time, biodegradability, as well as kinetics and microbial community dynamics were determined.

Key Research findings

This project successfully addressed several critical knowledge gaps surrounding the hydrothermal treatment of sewage sludge and its integration into WWTPs. The key findings are summarized below, grouped according to the major research questions:

1. How Do Different Types of Sludge Transform During Hydrothermal Treatment?

Feedstock-Specific Behavior:

Product yield and quality were significantly influenced by sludge type and hydrothermal process temperature. A transitional temperature of 270 °C, at the interface between hydrothermal carbonization and hydrothermal liquefaction, proved optimal for producing high bio-oil yields and carbon-rich hydrochar with reduced heavy metal content.

Sludge's Performance:

Hydrochar derived from primary sludge exhibited superior solid fuel properties and lower concentrations of heavy metals compared to hydrochar produced from thickened waste activated sludge and anaerobically digested sludge.

Nutrient Potential of Aqueous Phase:

The aqueous phase obtained from hydrothermal treatment of thickened and digested sludge was rich in nitrogen (N), phosphorus (P), and potassium (K), indicating potential use as a liquid fertilizer in agricultural or land reclamation applications.

2. What Are the Synergistic Effects of Alum Sludge and FOGO During Co-Hydrothermal Treatment with Primary Sludge?

Enhanced Yield and Quality:

Figure 3 summarises the result of co-processing of primary sludge with either alum sludge or FOGO on enhancing the product properties. Notably, it was found that co-hydrothermal treatment enhances both product yield and product quality compared to the treatment of primary sludge alone.

Addition of Alum Sludge:

Co-hydrothermal treatment of primary sludge with alum sludge not only improved hydrochar and bio-oil yields but also introduced unique characteristics to the hydrochar, resembling nano-boehmite, a high-value aluminium compound. This resulted in high surface area and distinct morphological structures (Figure 3), increasing the hydrochar's potential use in adsorbent applications or advanced material development.

Addition of FOGO:

Co-processing of primary sludge with FOGO enhanced the fuel value and soil conditioning properties of hydrochar. Additionally, both co-treatment routes produced bio-oils of higher quality than those generated from the hydrothermal treatment of primary sludge alone.

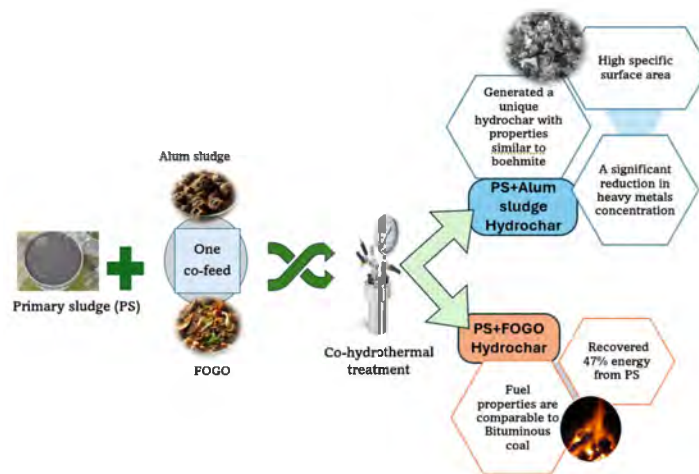


Figure 3. Co-hydrothermal treatment of Primary sludge with Alum sludge and FOGO

3. Can Catalytic and Co-Hydrothermal Treatment Reduce Heavy Metals and PFAS in Sewage Sludge?

Process Comparison:

Figure 4 summarises the fate of heavy metals and PFAS during catalytic and co-hydrothermal processing of primary sludge. Both catalytic hydrothermal treatment (with lime addition) and co-hydrothermal treatment with alum sludge improved bio-oil yields compared to sole hydrothermal treatment of primary sludge. However, catalytic hydrothermal treatment slightly reduced hydrochar yield, while significantly enhancing its porosity, making it more suitable as a functional adsorbent.

Heavy Metal Dynamics:

Heavy metals followed complex mechanisms such as precipitation, co-precipitation, adsorption, and complexation.

- Under alkaline conditions, catalytic hydrothermal treatment concentrated heavy metals in hydrochar.
- Co-hydrothermal treatment, in contrast, diluted the total heavy metal concentrations in the products.

PFAS Behavior:

PFAS degradation varies by chemical structure (Figure 4).

- >99% of PFOA was degraded under all studied hydrothermal treatment conditions.
- PFOS degradation was more resistant, with a maximum observed degradation of 41%.

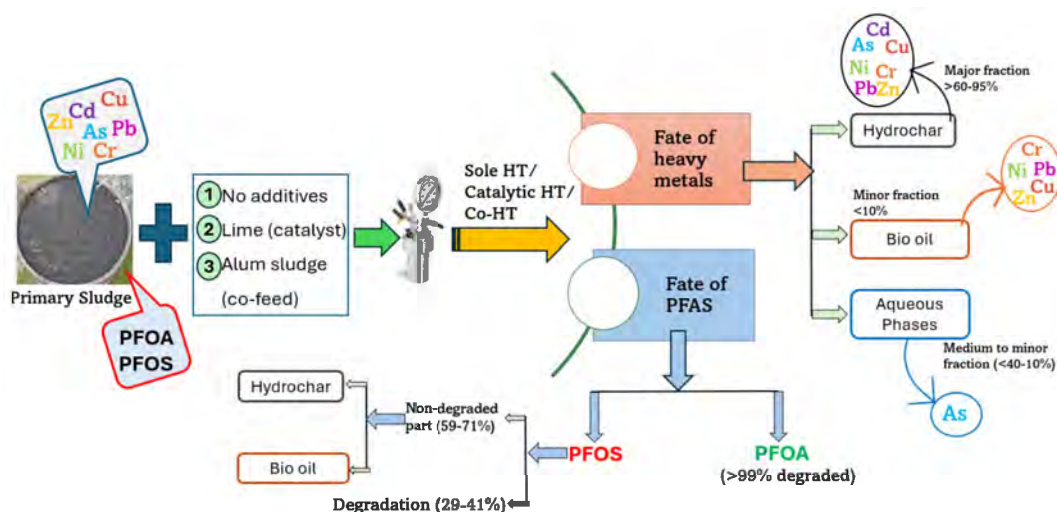


Figure 4. Fate of heavy metals and PFAS during sole, catalytic and co-hydrothermal treatment

4. What is the Most Efficient Process Configuration for Integrating Hydrothermal Treatment in WWTPs?

Integration Pathway Insights:

Among the various integration options investigated, the highest biomethane production yield were achieved from the anaerobic digestion of primary sludge with the liquid phase of hydrothermally treated thickened waste activated sludge.

Digestate Quality:

The digestate residue from the optimum integration option had higher nutrient concentrations and lower heavy metal concentrations.

Contributions and Impact

This project delivers a comprehensive framework for integrating hydrothermal treatment into WWTPs via following contributions:

- Understanding of hydrothermal treatment of sewage sludge, practical innovation and challenges.
- Demonstrated enhanced sludge valorisation through co-treatment and catalytic treatment.
- Understanding the behaviour and fate of contaminants in sewage sludge such as PFAS and heavy metals during hydrothermal processing.
- Proposed pathways for integrating hydrothermal treatment with new or existing anaerobic digestion infrastructure.

Future Recommendations

This project 1B has sparked several new insights, creating opportunities for further exploration. To expand on the current findings, the following recommendations are proposed for future research.

- Explore the advanced application of hydrochar obtained from the co-processing of primary sludge and alum sludge.
- Demonstrate hydrothermal treatment and anaerobic digestion integration at pilot-scale under relevant environment
- Explore the most promising market applications of the product streams from the hydrothermal process.
- Techno-economic and life cycle assessments to guide further development and potential implementation.

Achievements

Awards:

- Finalist of **Victoria Student Award 2025**
- RMIT WETT centre **HDR Publication Award 2025**
- **Conference Grant** – ICOSSE 2025
- **Travel Grant** – Health & Environment Seminar, Cannes 2024

Publications:

The outcome of this project has been published in five peer review articles in Q1 journals.

1. Nahar, K., Thulasiraman, A. V., Vuppaladadiyam, A. K., Hakeem, I. G., & Shah, K. (2024). Current understanding on the fate of contaminants during hydrothermal treatment of sewage sludge. *Current Opinion in Green and Sustainable Chemistry*, 100960. <https://doi.org/10.1016/j.cogsc.2024.100960>
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Conference Presentations:

Several aspects of this project were presented at various national and international conferences and symposia as highlighted below:

- Oral presentation at the NextWater Conference, 20-21 October 2025 (**Melbourne, Australia**)
- Poster and snapshot presentation at the 13th International Congress on Sustainability Science & Engineering (ICOSSE), 20-22 February 2025. (**Auckland, New Zealand**)
- Oral presentation at RMIT WETT Centre Symposium, November 2024 (**Melbourne, Australia**).
- Snapshot presentation in WiOW 2024 Symposium (**Canberra, Australia**)
- Oral presentation at the 4th Annual Symposium of the ARC Training Centre for the Transformation of Australia's Biosolids Resource, September 2024 (**Perth, Australia**).
- Oral presentation at the Health and Environment Seminar, June 2024 (**Cannes, France**)
- Oral presentation at RMIT WETT Centre Symposium, November 2023 (**Melbourne, Australia**).
- Oral presentation at 3rd Annual Symposium of the ARC Training Centre for the Transformation of Australia's Biosolids Resource, September 2023 (**Brisbane, Australia**).
- Poster presentation at Next Water Conference- February 2023 (**Sydney, Australia**).
- Poster presentation at the 2nd Annual Symposium of the ARC Training Centre for the Transformation of Australia's Biosolids Resource, September 2022 (**Sydney, Australia**).

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