Nutrient Recovery and Biogas Production: Advancing Sustainable Wastewater Management with Hydrothermal Treatment – A Life Cycle Assessment

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Abstract**—**This study explores a novel approach to wastewater treatment using hydrothermal treatment (HT) and anaerobic digestion to enhance nutrient recovery and bioenergy production, supporting sustainable wastewater management. A life cycle assessment of four waste-activated sludge (WAS) valorisation scenarios was conducted, assessing impacts such as global warming potential (GWP), eutrophication, and toxicity. The optimal process, combining HT with struvite precipitation and magnetic biochar adsorption, reduced GWP by 26.6%, saved 5,817 m^3 of water annually and achieved 70.6% phosphorus recovery, mitigating freshwater and marine eutrophication by 28.7% and 22.9%, respectively. Magnetic biochar reduced toxicity by 37.9% in phenolic compounds, while energy recovery was critical, enhancing GWP reduction by 17.7%. This research highlights the potential of advanced resource recovery to transform wastewater treatment plants into sustainable resource hubs, advocating for supportive policies in Sub-Saharan Africa and globally to foster a circular economy.

Keywords**—** Biogas Production, Hydrothermal Treatment, Life Cycle Assessment, Nutrient Recovery, Wastewater Management.

I. INTRODUCTION

The exponential growth of the global population [1, 2] has led to a proportional increase in waste material and wastewater generation, placing significant strain on waste management facilities and efforts to mitigate their environmental impact. In regions like Sub-Saharan Africa (SSA), recurrent droughts have compounded this issue, particularly in agriculture-dependent economies, by exacerbating water shortages and increasing the demand for effective water and wastewater treatment solutions [3]. Treating wastewater not only mitigates water scarcity by augmenting available freshwater resources but also presents an opportunity to recover valuable resources and energy, thereby enhancing the economic viability of wastewater treatment plants (WWTPs). Whereas in Sub-Saharan Africa, water scarcity and agriculture are closely related, nutrient recovery is not only a solution to waste management but also food security and environmental protection in line with the SDGs.

The shift towards sustainable wastewater management practices has gained significant traction among scientists, engineers, and industrialists, particularly in the context of waste-to-energy initiatives that alleviate pressure on natural resources and fossil fuels. This study focuses on the treatment of waste-activated sludge (WAS) through hydrothermal treatment (HT) to harness energy via anaerobic digestion (AD) and recover nutrients in the form of struvite, a slow-releasing phosphorus-based fertiliser. The precipitation of struvite is especially pertinent given the depletion of natural phosphate rock reserves [4]. WWTPs are recognised as substantial sinks for phosphorus in various forms, presenting a compelling case for phosphorus recovery to mitigate eutrophication and other ecological issues caused by phosphorus leakage into the environment.

HT facilitates the hydrolysis of complex heterogeneous molecules into simpler compounds, enhancing the efficiency and yield of subsequent anaerobic digestion by making these molecules more accessible for microbial digestion.

However, during the hydrolysis of WAS, undesirable substances such as heavy metals and phenolic compounds are released into the aqueous phase, becoming more reactive and posing toxicity risks to aquatic and terrestrial ecosystems. This study recommends employing adsorption techniques utilising locally produced magnetic biochar from sugarcane bagasse to reduce these pollutants effectively.

Various factors, including environmental, economic, and social variables, through the triple-bottom-line approach, play a significant role in determining the most suitable municipal solid waste management system [5-7].

Several studies have dealt with HT or nutrient recovery independently; however, a few have delved into a combination of HT, nutrient recovery and biogas production with a comprehensive Life Cycle Assessment (LCA) in the evaluation of environmental impacts caused by these processes at system-wide level [8], LCA brings considerable value to foresaid processes by estimating emissions, energy demand, and general sustainability of the process bringing in a holistic approach that is generally deficient in many studies. LCA enables decision-

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makers to make informed choices based on accurate information [9].

To the best of our knowledge, most prior studies on HT and nutrient recovery are not explicitly regional in focus. Sub-Saharan African nations require tailored solutions as they are heavily affected by environmental challenges like droughts and the reliance on agricultural activities [10]. Thus, this study provides an answer to this issue by using LCA in the field in which phosphorus recovery and biogas production from wastewater can address regional demands, offering solutions which contribute to the circular economy. The region's reliance on fertilisers for crop cultivation and the objective to gradually eradicate phosphate fertiliser imports are also significant factors [11, 12].

II. Materials and Methods

A. Life Cycle Assessment Framework

An LCA study was performed to assess the environmental impact of phosphorus recovery using hydrothermal treatment and pyrolysis technology and to select the phosphorous recovery method with the least environmental impact. The assessment procedure was conducted using SimaPro (SimaPro 9.6.0. PRé Consultants, Amersfoort, Netherlands) and is outlined in the standard ISO 14040 [13] and 14044 [14], with detailed explanations and analysis provided in Khoshnevisan, et al. [15], Paes, et al. [16], Rebello, et al. [17] as follows:

a) The definition of goal and
b) Life cycle inventory (LCI)
c) Life cycle impact assessment (LCIA)
d) Life cycle interpretation

B. Goal and scope definition of LCA

1) Functional unit and system boundaries

This study suggested 1 ton as the functional unit based on the cradle-to-grave approach (generation of WAS to disposal). The composition of the waste-activated sludge and respective derivatives, as described by various scenarios (section xx), are shown in Table 1.

TABLE I: ULTIMATE AND PROXIMATE ANALYSIS

Property	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Ultimate				
C (%)	35.7	34.79	37.74	35.27
H (%)	6.53	5.03	5.27	5.38
N (%)	5.88	7.01	4.45	4.18
S (%)	2.70	2.04	2.27	2.11
O (%)	30.98	29.51	16.98	19.43
Proximate				
Ash (%)	21.61±0.002	28.00±3.911	35.08±0.012	35.24±0.239
VS (mg//L)	3233±39	3077±456	7760±269	8653±423

After adsorption, the biochar was separated from the sludge pending desorption of the toxins; however, this was beyond the scope of this study. The hydrochar was yielded as the solid residue, used for heating purposes in the plant, and the excess was sold. The ash produced after heating was proposed to be diverted for alternative uses in construction.

The flow of material and energy used to quantify unit operations in the system is depicted by the system boundary in Figure 1. The system boundary encloses the pumping, resource recovery facilities (RRF), anaerobic digestion and irrigation. Irrigation to the agricultural fields is the activity that completes the boundary.

Each unit process in the system has been quantified in terms of mass and energy input and output flows as well as emission.

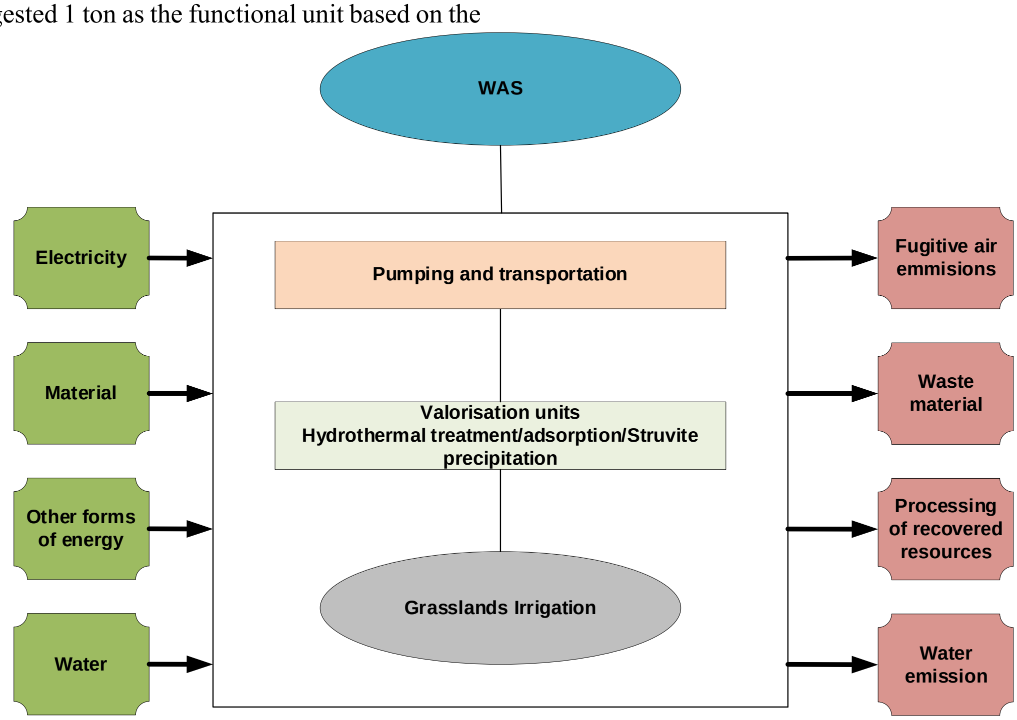

Fig 1 System boundary of the base case scenario

2) Scenario Description

Scenario 1: AD of WAS without HT, where the generated biogas is used for the plant's energy requirements.

Scenario 2: AD of sludge subjected to HT; no resources are recovered at this stage.

Scenario 3: AD of HT-treated sludge following the adsorption process for toxin removal, considering the reuse of biochar. Hydrochar is recovered before the precipitation stage, and it serves as fuel.

Scenario 4: AD of HT-treated sludge post adsorption and precipitation processes, incorporating the recovery of struvite fertiliser/nutrients, heat, and hydrochar.

Figure 2 delineates the material flow for the 4 different scenarios, which were used for comparison in this study, and Figure S2 (in Supplementary data) shows network diagrams for the scenarios presented in Simapro software.

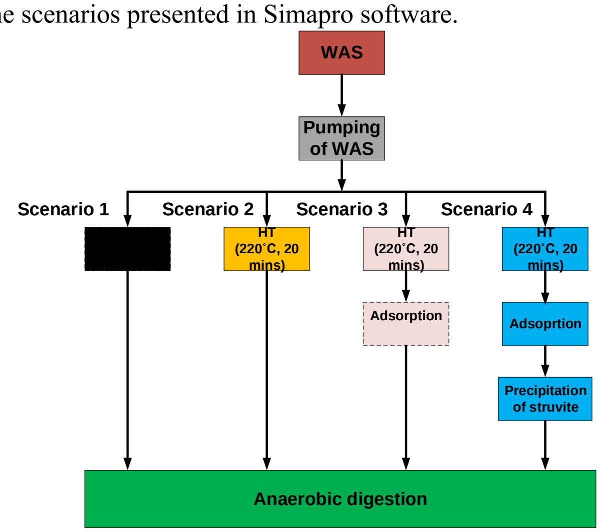

Fig. 2 Configuration of Scenarios

C. Life cycle inventory data collection

The LCI data was sourced from waste characterisation, experimental procedures (extrapolation under scaled-up operations), emissions reports from the wastewater treatment plant (WWTP), relevant literature, and the background data related to the production and processing of materials, chemicals, and energy carriers were sourced from the ReCipe 2016 (Midpoint - H) methodology in SimaPro software database. ReCiPe Midpoint (H) aligns with the research's aim to analyse specific environmental burdens that are relevant to sustainable wastewater management and resource recovery, and it also allows for replicability [18].

All inventory data were normalised to a per-tonne basis of waste. The WWTP in focus processes 100 ML of wastewater daily.

Figure 3 (a-d) Illustrates the material and energy flows of the 4 scenarios. Elemental analysis was utilised to determine the chemical composition of WAS following HT, adsorption, and precipitation stages, represented as CHNS/O.

In this study, capital equipment such as construction materials and machinery were excluded from the inventory analysis [15].

1) Source of the sludge and characterisation

Samples of WAS were sourced from a local WWTP and kept at 4°C. A thorough characterisation was performed to determine key parameters, including soluble chemical oxygen demand (SCOD), volatile solids (VS), nutrient content, and total organic carbon (TOC), according to APHA [20]. The chemical oxygen demand (COD) was quantified using a DR 3900 Spectrophotometer (Hach, Loveland, CO, USA). The pH level was measured with a calibrated pH meter (Lovibond SensoDirect 150, Germany).

2) Hydrothermal Treatment Process and Experimental Setup

The HT process was optimised by varying the input parameters, specifically temperature (ranging from 150 to 230 °C) and residence time (spanning 20 to 70 mins), with SCOD) as the main response variable. Optimisation was conducted using a central composite design (CCD) within the framework of response surface methodology (RSM), facilitated by Design Expert software. The optimisation was carried out in duplicate using a 100 mL bench-scale hydrothermal reactor (HTR) operating in batch mode. For each run, 80 mL of the waste-activated sludge (WAS) stream was introduced into a 100 mL stainless steel HTR, which was then purged with nitrogen gas for 5 min.

3) Toxin Removal via Adsorption

After HT, the effluent was detoxified through adsorption using magnetic biochar (MBC) produced locally from sugarcane bagasse. This adsorption process was conducted at a pH of 6.57, with an adsorbent dosage of 5 g/L and a contact time of 35 mins, conditions identified as optimal in previous research. The effectiveness of the process was assessed by measuring the percentage reduction of phenolic compounds, phosphate (PO_4^{3-}), ammonium (NH_4^+), arsenic, manganese, and nickel concentrations.

After adsorption, the MBC was separated using an electromagnet, and any remaining solids were filtered to isolate the hydrochar. The hydrochar was then characterised for its higher heating value (HHV) (in MJ/kg). The filtrate was further processed to recover phosphorus and nitrogen through precipitation. Elemental analysis (CHNS) was performed. The oxygen content was determined by subtracting the sum of the carbon, hydrogen, nitrogen, sulphur, and ash percentages from 100% [21].

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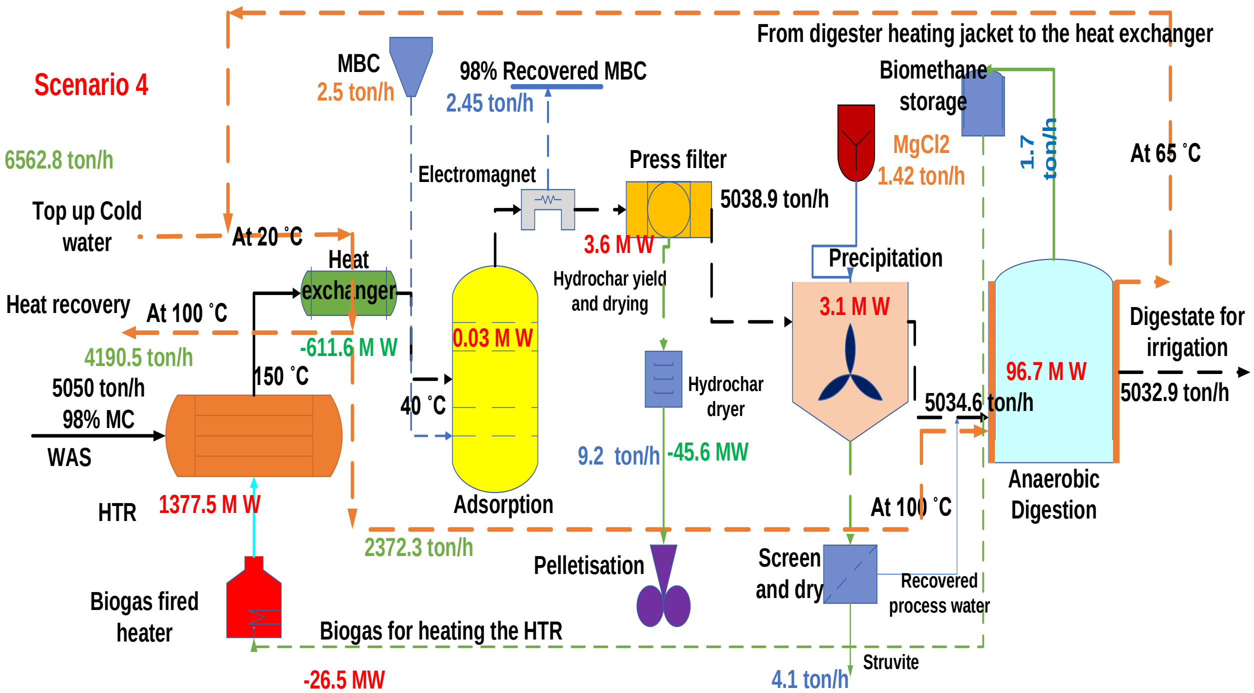

Fig. 3 Energy and material balances for various scenarios

The HHV of spent MBC and residue hydrochar were estimated using the following empirical equation (1) (Moreira et al. 2022):

The HHV and LHV can be estimated using the following empirical equation (1) [22]:

$$HHV = 0.3491 \times C + 1.1783 \times H + 0.1005 \times S - 0.1034 \times O - 0.0151 \times N \quad (1)$$

Where C, H, S, O and N are the weight percentages of carbon, hydrogen, sulphur, oxygen and nitrogen, respectively.

4) *Precipitation of Struvite*

The optimisation of struvite precipitation was conducted using a CCD, with pH and the concentration of external Mg sources as the primary variables set within a range of 7 to 11 [23]. The solution was continuously stirred at 150 rpm on a magnetic stirrer and adjusted to the target pH using either 3 mol/L NaOH or 2 mol/L HCl solutions. A Mg source solution was prepared by dissolving 20 g of $MgCl_2 \cdot 6H_2O$ in 1 L of deionised water, and the volume added to the reaction vessel varied from 1.0 mL to 2.5 mL, in accordance with the stoichiometric balance between NH_4^+ and PO_4^{3-} [24, 25]. The precipitation experiments were conducted at ambient temperature. After a settling period of 2 h, the precipitates were filtered using 20-micron filter paper and subsequently dried at 35°C for 48 hours for further analysis. The filtrate was analysed for phosphate and ammonium concentrations using a Gallery Automated Photometric Analyser, while Mg. Na, Ca and Fe were quantified using inductively coupled plasma optical emission spectrometry. The dried residue was dissolved in concentrated hydrochloric acid (HCl: distilled water at a ratio of 1:9), followed by the appropriate dilutions, and subjected to the same analyses as the filtrate. Mass balances were calculated for each component. X-ray diffraction (XRD) analyses for the crystalline phases were performed within a 2Θ range from 3° to 90°, with a step width of 0.01° and a scanning speed of 30.00 °/min, at a time speed of 0.2 s/step using PXRD (MiniFlex600, Rigaku, Tokyo, Japan). Scanning electron microscopy coupled with energy-dispersive spectroscopy (SEM-EDS) (Zeiss Ultra Plus FEG SEM, Germany) was also employed. Equation 2 illustrates the reaction for pure struvite precipitation in the wastewater stream, following a Mg:P:N molar ratio of 1:1:1 [26, 27].

$$Mg^{2+} + NH_4^{+} + PO_4^{3-} \rightarrow MgNH_4PO_4.6H_2O \quad (2)$$

A. *Sequential Extraction Analysis*

Sequential extraction analysis was conducted to achieve detailed phosphorus (P) speciation, following a modified protocol based on Chang, et al. [28]. The fractionation procedure involved subjecting 1 g of dried sample to sequential extraction using progressively stronger reagents. Each extraction was carried out in a 50 mL polypropylene centrifuge tube with 20 mL of reagent. All procedures were conducted in duplicate. A spectrophotometer at 880 nm wavelength was used through a modified molybdovanadate method [29]

5) *Anaerobic Digestion*

In the final stage, following the precipitation of struvite, the effluent was introduced into a bench-scale anaerobic digester, utilising 1 L Schott bottles in batch mode. The treated mixture was used as the substrate and inoculated with anaerobic digestion sludge obtained from the same WWTP, with the pH adjusted to 7±0.5. The reactors were operated in duplicate, maintaining a 1:1 volumetric ratio of precipitation effluent to inoculum for 21 days. This stream was compared with WAS', HT sludge, and sludge following adsorption. The temperature of the biodigester was maintained at 37±1 °C. Biogas production was quantified using a water displacement system. Biogas output was analysed using gas chromatography with a thermal conductivity detector (GC-TCD). The injector, column, and detector temperatures were set to 120°C, 40°C, and 250°C, respectively (Shimadzu 2014, Japan), with helium serving as the carrier gas at a flow rate of 8 mL/min. Figure 3 provides an overview of the unit operations undertaken in this study for scenario 4 (scenarios 1, 2 and 3 are shown in S2). It is crucial to highlight that all processes were carried out in batch mode, although the schematic may represent a continuous system for illustrative purposes.

6) Life Cycle Impact Assessment Methodology

The categories evaluated include global warming potential and water consumption. These categories were selected due to their relevance and significance to the WWTP under study. The characterisation of these impact categories was conducted based on the LCI results, employing appropriate characterisation factors to ensure accurate environmental evaluation.

D. Limitations

Key limitations include:

- The data used were derived from bench-scale laboratory experiments, which may not fully capture the hydrodynamic complexities present in larger-scale operations. Consequently, this could introduce discrepancies in the estimations provided.

The data collection spanned one year, during which wastewater characteristics and the operational dynamics of the wastewater treatment plant (WWTP) were monitored. However, these variables are subject to change over extended periods, potentially affecting the environmental predictions made in this assessment.

III. Results and Discussion

A. Hydrothermal Treatment Outcomes

The HT process was conducted under a range of operational conditions, with the optimal parameters identified as 220°C and a reaction time of 20 mins, as illustrated in Figure 4. The data indicate that the HT process led to a notable increase in soluble SCOD polyphosphate and ammonium concentrations, with respective values of 3 035 ± 84 mg/L, 173 ± 9 mg/L, and 152 ± 14 mg/L. Upon scaling up to a plant capacity of 100 ML/day, the facility is projected to process approximately 100 400 tons of WAS' per day (sg ~1.004).

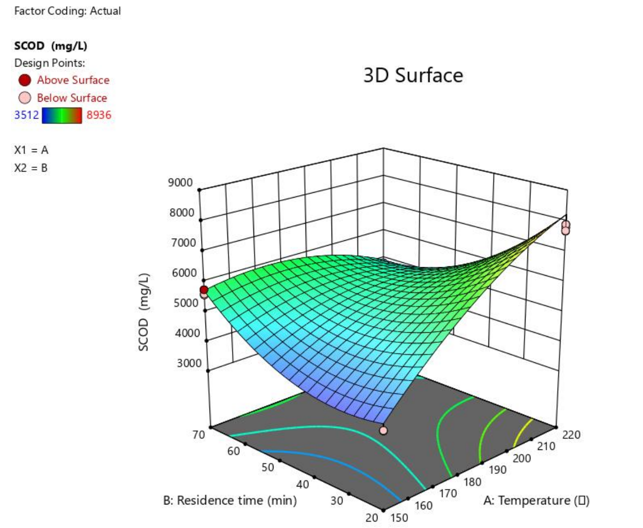

Fig.4 Optimisation of the hydrothermal treatment process

B. Toxin Removal Efficiency

In this study, 98% of the magnetic biochar (MBC) was successfully recovered, while the remaining 2% that escaped the electromagnet is likely to be associated with the hydrochar fraction. The optimal input parameters for the adsorption unit were determined, yielding a desirability factor of 0.907 with an input pH of 6.57 and an MBC dosage of 5 g/L, as illustrated in Figure 5. Adsorption of phenolic compounds (PCs) achieved a removal efficiency of 37.9%, corresponding to an adsorption capacity of 13.4 mg/g for PCs. This indicates that more than 60% of the phenolic compounds evade the adsorption process, potentially leading to considerable environmental risks in subsequent processing stages. The possibility of secondary pollution arises due to the desorption of PCs and heavy metals. Desorption processes are not fully efficient, with reported rates ranging between 20% and 70%, necessitating further treatment to mitigate the risks of secondary pollution [30, 31].

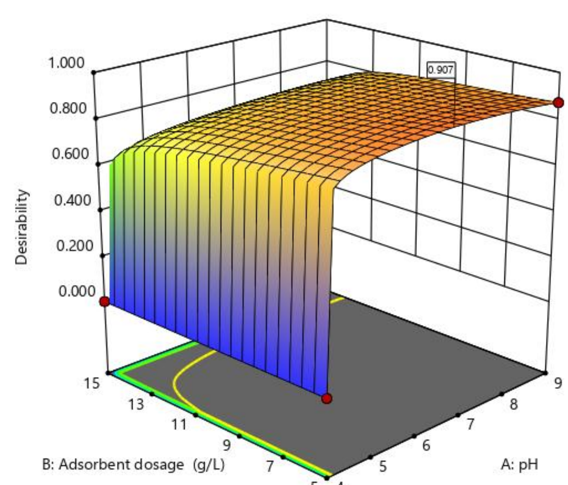

Fig. 5 Optimum conditions for the adsorption unit.

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C. Struvite Precipitation

The optimum conditions were identified as 14.2 mL of Mg(aq)/L-sludge at a pH of 9.24. These conditions facilitated efficient nutrient recovery. Table 2 presents a comparison of the predicted and actual nutrient concentrations after validation under these optimal settings.

TABLE II PREDICTED VALUES OF NUTRIENTS IN STRUVITE AGAINST THE VALIDATED VALUES AT OPTIMUM CONDITIONS.

	Predicted	**Validation**
Phosphate in struvite (mg/L)	72.9	75.3±2.1
Ammonium in struvite (mg/L)	25.7	28.2±1.7
Phosphate extraction (%)	72.9	70.6
Ammonium extraction (%)	35..7	36.8

These Phosphorus (P) fractionation analyses provide crucial insights into the bioavailability and mobility of P species over time, which are essential for accurately modelling environmental impacts within the SimaPro framework.

As presented in Table 3, the phosphorus content in struvite is predominantly soluble in HCl, with over 40 wt% classified as acid-soluble P, while approximately 25 wt% remains as residual phosphorus. The substantial proportion of soluble P highlights the potential for long-term environmental risks, particularly in terms of its gradual release and subsequent bioavailability. If not appropriately managed, this could contribute to freshwater eutrophication, posing a significant ecological challenge due to the enrichment of aquatic systems with nutrients. Therefore, understanding the behaviour of these P fractions is critical for both nutrient recovery strategies and mitigating environmental impacts.

TABLE III: P FRACTIONATION OF THE STRUVITE FERTILISER.

Sequence	**Concentration mg-P/g**
H_2O - P	0.490±0.016
$NaHCO_3$ - P	7.085±0.277
NaOH - P	2.696±0.055
HCl - P	17.186±0.315
P-Residue	14.234±0.225

D. Biogas Production

In this study, the methane yields varied across the different scenarios, as illustrated in Figure 6. Only methane (CH_4) and carbon dioxide (CO_2) were detected within measurable limits; consequently, the LCA focused exclusively on these two biogas components. For Scenarios 1, 2, 3, and 4, the maximum methane yields were recorded as 0.66, 16.15, 12.85, and 7.92 mL-CH_4/g-VS, respectively, while the highest methane concentrations were 10.42%, 81.16%, 69.20%, and 32.05%, respectively. The energy requirements for the anaerobic digester were entirely met through heat exchange, with hot water recirculated from the heat exchanger.

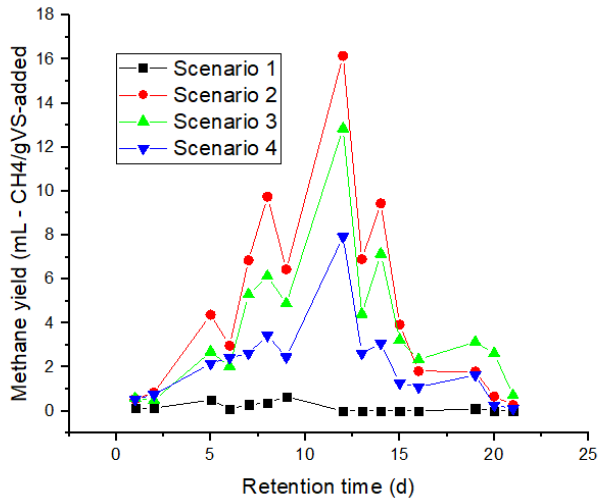

Fig. 6 Methane yields for the four scenarios

E. Life Cycle Assessment Results

This study examines waste management techniques across four distinct scenarios, focusing on the treatment of waste-activated sludge using traditional and advanced integrated approaches. The initial preparation of input data for the Simapro software involved organising raw primary data in Excel 365, as illustrated in Table S1 (supplementary data). This data includes a range of parameters, including the quantities of waste generated, avoided burdens and inputs to the Technosphere.

1) Global Warming Potential (GWP)

Addressing the GWP is paramount when considering biogas production, hydrochar combustion, and energy recovery, as these processes inherently involve greenhouse gas (GHG) emissions. GWP serves as a critical metric for quantifying emissions, including CO_2, CH_4, and N_2O, and provides a comprehensive understanding of the climate impact across various scenarios.

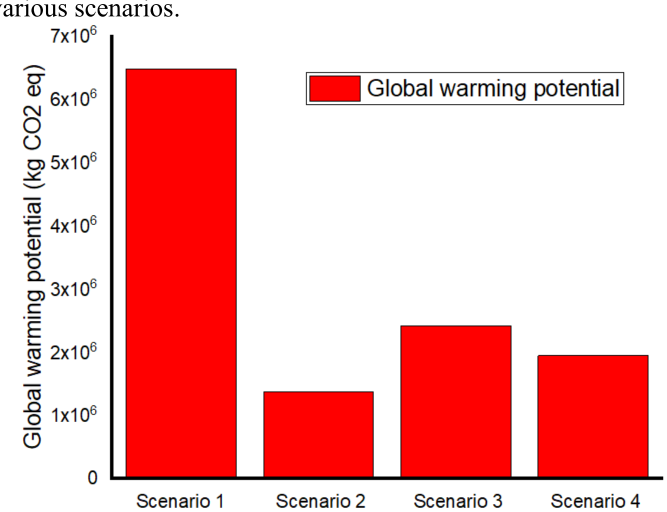

Fig. 7 Global warming

As depicted in Figure 7, Scenario 1 exhibited the highest GWP, with a value of 6 473 658.88 kg CO_2-eq per functional unit (FU), followed by Scenarios 3, 4, and 2, which contributed 37.4%, 26.6%, and 21.3% of the base case (Scenario 1), respectively. Key contributors to GWP included fossil fuel-derived CO_2, dinitrogen monoxide (N_2O) generated from microbial processes such as denitrification, and thermal degradation of nitrogenous organic matter, as well as biogenic methane (CH_4) emissions. It is well-established that N_2O is an exceptionally potent greenhouse gas, with a global warming potential approximately 298 times greater than that of CO_2 over a 100-year time horizon [33, 34].

Notably, scenarios 2, 3, and 4 demonstrated negative GWP values of -17.7%, -13.1%, and -8.53%, respectively, attributed to the heat recovered through heat integration. This underscores the importance of heat recovery systems in processing plants, as they not only reduce energy consumption but also significantly mitigate the impact of global warming through avoided burdens.

Across all scenarios, digestate emerged as a substantial contributor to GWP, accounting for 62.1%, 38.4%, 31%, and 20.2% in Scenarios 1, 2, 3, and 4, respectively. This phenomenon may be attributed to ongoing microbial activity post-anaerobic digestion, during which residual organic matter continues to decompose, releasing GHGs over time [35, 36]. Furthermore, not all organic material is fully mineralised during the anaerobic digestion process, resulting in the progressive breakdown of biodegradable matter and subsequent emissions of GHGs.

The observations made in this study indicate that HT with subsequent AD enhances biogas yield and reduces the overall carbon footprint by utilising organic-rich sludge as a result of HT, which also aligns with a study done by Ogunleye, et al. [37]. This synergy is critical in regions trying towards circular economy practices as it maximises resource efficiency.

2) Water Consumption

Water consumption or depletion refers to the consumption of freshwater resources, either through direct usage or pollution, relative to the renewability rate of these resources. The water scarcity footprint is a tool used to evaluate human contributions to regional water scarcity, taking into account both on-site and remote impacts across global supply chains [50]. It highlights the pressure human activities place on freshwater resources and ecosystems.

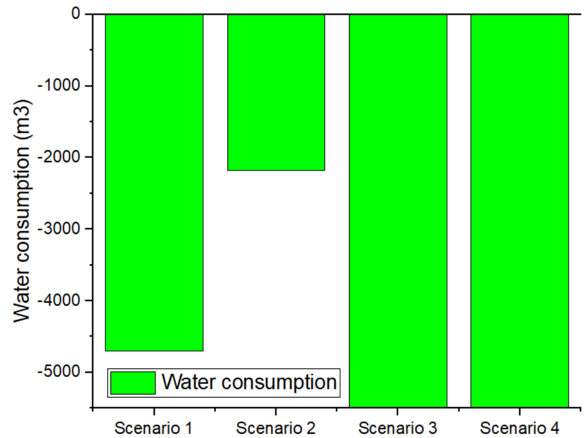

Fig. 8 Water consumption

In this study, the water depletion metric shows negative values across all scenarios, as illustrated in Figure 14. These negative values indicate water savings, which primarily result from reduced water usage due to heat recovery from the upstream hydrothermal treatment (HT) process. Scenarios 3 and 4, with -5,624 and -5,817 m³ respectively, exhibit the most substantial water savings. This is attributed to the residual heat from HT, which minimises the need for external water to maintain the anaerobic digester's temperature, improving overall process efficiency (Müller et al., 2020).

The anomaly observed in Scenarios 1 and 2, with lower water savings, could be due to the absence of heat recovery in Scenario 1 and inefficiencies in Scenario 2, where no resource recovery is implemented. While evaporation may contribute slightly, the main driver of water savings is the efficient heat integration from HT, which reduces freshwater consumption relative to its renewability rate. This efficiency underscores the value of integrating resource recovery processes for sustainable wastewater treatment.

F. Sensitivity Analysis

Sensitivity analysis is essential in LCAs to test the resilience of findings against changes in key variables, such as energy recovery rates or sludge composition. In this study, the sensitivity analysis was concentrated on Scenario 4, as it represents the most comprehensive valorisation effort, integrating nutrient recovery, heat recovery, and biogas production. Sensitivity analysis is an essential tool in LCA because it evaluates the reliability of the results and helps identify the variables that have the most significant influence on environmental impacts [51, 52]. In this case, the analysis examined global warming potential and water consumption, chosen as representative impact categories, by varying key operational parameters by ±10% from their baseline values. These parameters were heating efficiency during hydrothermal treatment and the flow rate of the waste-activated sludge.

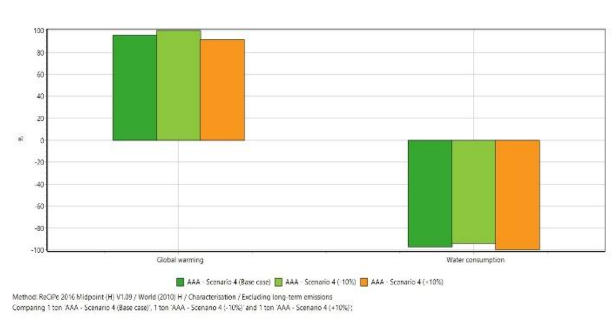

Fig. 9 Heating efficiency alteration in sensitivity analysis

As illustrated in Figure 15, a 10% reduction in the heating efficiency of the hydrothermal reactor (HTR) notably impacts the GWP, resulting in a 4.6% increase from the base case GWP of 1,945,219.75 kg CO_2-eq. Correspondingly, this reduction led to a 3.1% decrease in overall water consumption (base case: -5,816.79 m³). Conversely, a 10% increase in heating efficiency in the HTR led to a 3.8% reduction in GWP and a 2.5% reduction in water consumption (Supplementary Table S4 shows major contributors of emissions to GWP).

The results show that moderate variations in the heating efficiency of the HTR can cause a shift in the impact categories, as represented by GWP and water consumption, as they are strongly dependent on changes in the thermal input. Of interest is that enhanced heating efficiency lowers environmental effects, which is consistent with sustainable design objectives in wastewater treatment systems, where energy efficiency and reduced resource utilisation are of paramount importance [53]. Improving the efficacy of thermal processes reduces GHG emissions, which aligns with carbon neutrality objectives in the wastewater treatment industry [53].

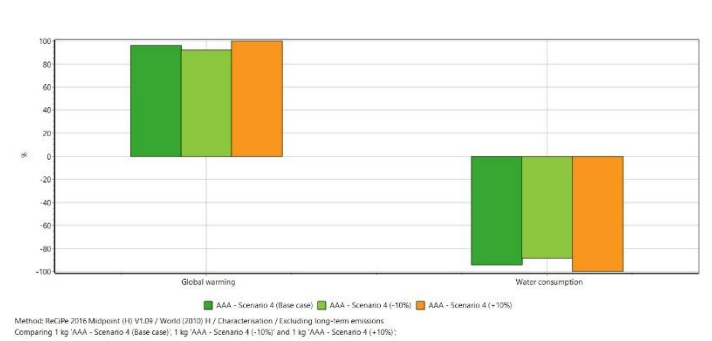

Fig. 8 Waste-activated sludge flow rate alteration in sensitivity analysis.

It is well documented that the amount of influent waste-activated sludge depends on seasonal and operational factors and, therefore, affects the environmental impacts. Figure 16 demonstrates that the reduction of 10% of the sludge flow rate resulted in a 3.9% reduction in GWP along with a 5.7% reduction in water consumption, which can be considered considerable resource savings. Conversely, a 10% increase in the flow rate led to an overall increase of 4% in the GWP and a 5.6% increase in water consumption.

Such results affirm the high sensitivity of the system performance and environmental impacts, including GWP and water use, to sludge flow rates. Seasonal flow variability is therefore identified as a fundamental factor that should be considered in waste management [54, 55]. Regulating flow rates in the form of reservoir lagoons with respect to operational capacity can optimise all unit operations and their performance in terms of environmental and economic performance [56].

IV. Conclusion

HT-AD configurations significantly improve energy efficiency and biodegradability of sludge, which is critical for achieving the energy-neutral or energy-positive operation of WWTPs aligning with SDGs such as clean water and sustainable cities. It is evident that Scenario 4, which incorporates HT, adsorption for toxin removal, and nutrient recovery, offers the most sustainable outcome. This integrated approach can reduce GHGs and fossil resource dependence, as HT aids in the breakdown of complex organic molecules, allowing for higher energy yields and minimising methane and CO_2 emissions from residual waste, significantly reducing GWP (by up to 26.6 %). The process facilitates the recovery of phosphorus as struvite, which addresses both the need for sustainable fertiliser production and the mitigation of eutrophication risks. Furthermore, the enhanced biogas production, reaching methane yields as high as 16.15 mL-CH_4/g-VS, provides a renewable energy source that contributes to the plant’s energy self-sufficiency. The water savings observed, particularly in scenarios integrating heat recovery, underscore the broader environmental benefits of optimising energy and resource use in wastewater treatment.

While the study highlights the environmental advantages, there remain areas for optimisation. The sensitivity analysis indicates that minor inefficiencies in heat recovery or biogas capture can significantly affect the system’s overall environmental performance, emphasising the need for technological improvements, especially in energy management.

This study reveals that operational parameters such as energy recovery efficiency, SCOD inflows, and heat transfer efficiency significantly influence the system's environmental performance. A decrease in these parameters by 10% led to a substantial increase in GWP, showing the critical need for optimisation in upstream processes to reduce the overall environmental footprint. The sensitivity analysis further highlights the importance of energy efficiency in both hydrothermal and anaerobic digestion processes to minimise fossil CO_2 emissions and biogenic methane emissions.

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