

## Case Report

# Waste to wealth transformation: Maximising resource and energy recovery through hydrothermal treatment of sewage sludge - A technoeconomic evaluation

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## ARTICLE INFO

## Keywords:

Hydrothermal treatment  
Anaerobic digestion  
Technoeconomic evaluation  
Sewage sludge management  
Resource recovery  
Energy efficiency  
Biogas production  
Circular economy

## ABSTRACT

This study provides a comprehensive technoeconomic evaluation of integrating hydrothermal treatment (HT) with anaerobic digestion (AD) and struvite precipitation to enhance resource recovery from sewage sludge, offering an innovative and sustainable solution for wastewater treatment plants (WWTPs). Under optimal conditions (220 °C, 20 min), HT of waste-activated sludge (WAS) significantly increased soluble chemical oxygen demand (SCOD), resulting in enhanced biomethane yields during AD in comparison to untreated sludge. Comparative analysis of four scenarios, standalone AD, AD with HT, HT with toxin adsorption, and HT with both toxin adsorption and struvite precipitation, highlighted notable improvements in resource efficiency and economic viability.

The optimised HT-AD configuration achieved up to 30 % higher methane yields and 25 % lower production costs. Incorporating struvite precipitation further reduced the minimum biomethane selling price from \$2883.85/ton to \$337.49/ton. Economic analysis, using net present value (NPV), internal rate of return (IRR), and payback period as key indicators, showed the ultimate valorisation configuration (HT with toxin removal and struvite precipitation) achieving an NPV of approximately \$2.5 billion over a 30-year plant lifespan. Sensitivity analysis underscored that while struvite precipitation costs influence profitability, overall production costs in the optimised configuration were resilient to market fluctuations. Alternative magnesium sources were identified as critical to reducing operating costs.

This work offers practical insights and policy recommendations for resource-constrained regions on adopting HT-AD systems to support sustainable sludge management. Aligning with circular economy principles, this study advocates for waste-to-resource strategies that advance environmental sustainability while lowering operational costs in WWTPs.

## 1. Introduction

Water scarcity remains a critical global issue, prompting investigations into innovative approaches to ensure sustainable access to clean water. To address this, wastewater treatment has evolved from a sole focus on wastewater treatment to encompass resource recovery and energy generation. This shift emphasises the potential of wastewater treatment plants (WWTPs) not only as sites for water reuse but as critical hubs for reclaiming valuable resources such as phosphorus (P) and nitrogen (N), essential for all living organisms [1,2]. In addition, wastewater's hydrocarbon-rich sludge presents an untapped energy source

that can be harnessed through anaerobic digestion (AD) to produce biogas.

However, sludge's complex composition presents thermodynamic limitations to conventional treatment processes [3]. Industrialisation has exacerbated these challenges by increasing wastewater volumes, creating substantial handling issues and environmental threats, including eutrophication, malodour, and pest infestations. As a result, innovative solutions for effective sludge management have become a pressing need. Phosphorus recovery, in particular, is gaining global attention due to its finite natural reserves, which are expected to be depleted within 100 years [4]. This urgency underscores the critical role

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<https://doi.org/10.1016/j.csee.2025.101182>

Received 12 January 2025; Received in revised form 5 March 2025; Accepted 6 March 2025

Available online 7 March 2025

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of WWTPs in replenishing phosphorus resources while minimising nutrient leakage into the environment.

Hydrothermal treatment (HT) has emerged as a promising pretreatment technology to overcome sludge processing challenges. Operating under subcritical water conditions, HT enhances sludge biodegradability by hydrolysing complex molecules such as polysaccharides and polyphosphates into simpler compounds, thereby increasing soluble chemical oxygen demand (SCOD) [5,6]. Elevated SCOD also improves biogas production during subsequent AD compared to untreated sludge [7]. It is important to note that optimal hydrothermal treatment (HT) temperatures for maximising biogas production have generally been reported to be below 180 °C [8]. Wang et al. [9] also reported that anaerobic digestion (AD) exhibited superior performance at a hydrothermal treatment (HT) temperature of 160 °C compared to 220 °C, as evidenced by cumulative methane yields of 241.42 mL and 163.10 mL, respectively. This finding suggests that higher HT temperatures can reduce AD efficiency. However, in this study, a compromise was made to achieve a balance between biogas yield and the solubilisation of other key components in sewage sludge. In contrast, a study by Aragon-Briceño et al. [10] demonstrated that HT at 250 °C resulted in higher biomethane potential compared to treatment at 160 °C, highlighting the influence of temperature on sludge biodegradability and methane production efficiency.

Furthermore, HT facilitates the recovery of struvite, a slow-releasing fertiliser, through orthophosphate precipitation alongside ammonium and magnesium [11,12]. However, successful application of HT requires prior removal of toxins, such as phenolics and heavy metals, which could otherwise contaminate struvite or hinder biogas production [13–15].

Despite its potential, scaling HT-integrated systems for commercial applications is hindered by high energy requirements [16]. Comprehensive technoeconomic analyses are essential to assess the feasibility and profitability of such systems, providing insights for optimising design and operational parameters. This study addresses this need by evaluating the integration of HT with AD and struvite precipitation for resource recovery from sewage sludge, focusing on energy efficiency, cost-effectiveness, and environmental sustainability.

Existing studies often neglect regional economic contexts or fail to fully address the synergistic benefits of combining HT and AD. This research fills that gap, presenting a novel and holistic assessment of the integrated system's technical and economic viability. By comparing configurations such as standalone AD, HT-AD, HT-Adsorption-AD and HT-Adsorption-Precipitation-AD, the study aims to establish key profitability drivers and inform strategies for sustainable wastewater management.

It must be noted that the process was designed with a strong emphasis on environmental management, prioritising sustainability and resource recovery over maximising profits using the triple bottom line approach.

## 2. Materials and methods

### 2.1. Process development and foreground data collection for technoeconomic analysis

#### 2.1.1. Sludge source and collection

The waste-activated sludge (WAS) used in this study was obtained from the underflow of secondary settling tanks at a local wastewater treatment plant (WWTP) undergoing an expansion programme aimed at valorising its sludge. This plant was selected as it closely represents urban wastewater treatment conditions. Sampling was conducted monthly for six months to ensure a representative dataset. All WAS samples were stored at 4 °C during the experimental period. The sludge was characterised following standard methods [17], with key parameters summarised in Table 1. Although hydrothermal treatment is fundamentally a physical process, the elevated temperature and residence time induce significant chemical transformations, including the

**Table 1**  
Characteristics of the WAS and HT.

| Parameter          | WAS          | HT            |
|--------------------|--------------|---------------|
| pH                 | 7.23         | 6.92          |
| TS                 | 5477 ± 103   | 5913 ± 209    |
| VS                 | 4300 ± 148   | 4878 ± 159    |
| TOC                | 253.1 ± 43   | 2094.8 ± 22   |
| SCOD               | 283.5 ± 15   | 3034.5 ± 134  |
| BOD <sub>5</sub>   | 461.25 ± 19  | 1204.8 ± 79   |
| NH <sub>3</sub> -N | 52 ± 8       | 177 ± 27      |
| PO <sub>4</sub> -P | 67 ± 6       | 191 ± 15      |
| Protein            | 1036 ± 90    | 9101 ± 351    |
| Carbohydrates      | 952 ± 27     | 2692 ± 150    |
| Phenolics          | 33.69 ± 0.47 | 265.89 ± 1.88 |

The units for all parameters are mg/L, except for pH.

hydrolysis of complex organic molecules. These reactions generate or liberate ionic species, thereby altering the pH of the aqueous phase [18].

#### 2.1.2. Hydrothermal treatment process and experimental setup

The HT was performed in a high-temperature, high-pressure batch reactor system (Shangai, Intelligent Magnetic, China) designed to withstand extreme operating conditions up to 240 °C and 6 MPa with a cavity volume of 100 mL, heated by an electric heating mantle and stirred at 160 rpm. Temperature was monitored with a digital thermocouple (±0.1 °C), while the pressure was measured using an analogue pressure gauge. This reactor type was chosen due to its capacity for efficient thermal energy utilisation and precise control of pressure and temperature. The conditions within the reactor conform with studies showing that working at these temperatures and pressures optimises sludge biodegradation, hydrochar production and macromolecule degradation [19]. Waste-activated sludge was hydrothermally pretreated with temperature (150–230 °C) and reaction time (20–70 min) as the operating conditions. The operating conditions were optimised using response surface methodology (RSM) under a central composite design (CCD; see Supplementary Table S1). The primary response factors considered in this study were soluble chemical oxygen demand (SCOD), phosphate, ammonium, carbohydrates, and proteins (Supplementary Data, Table S1). The objective of the optimisation process was to identify the optimal operational conditions that achieve the most favourable balance among these response factors, thereby maximising nutrient solubilisation and enhancing overall process efficiency.

$$Q_{HT} = \frac{m_{WAS} C_{p,WAS} \Delta T}{\eta} + \left[ \frac{\tau k_{HTR} A_{HTR} \Delta T_{HTR}}{d_{HTR}} \right] \quad (1)$$

Equation (1) computes the total energy ( $Q_{HT}$ ) required for the hydrothermal treatment. The first term, represents the energy required to heat the sludge, where  $m_{WAS}$  is the sludge mass (kg),  $C_{p,WAS}$  is its specific heat capacity (kJ/kg·K),  $\Delta T$  is the temperature change (K), and  $\eta$  is the system efficiency ( $\leq 1$ ). The second term quantifies the energy lost by conduction through the reactor walls, where  $k_{HTR}$ ,  $A_{HTR}$ ,  $\Delta T_{HTR}$ ,  $\tau$  and  $d_{HTR}$  denote the thermal conductivity, surface area, temperature difference between the inside and outside, duration, and wall thickness of the HTR, respectively. Heat losses were assumed to predominantly occur through conduction [20].  $C_p$  for WAS is 3.93 kJ/kg·K as determined experimentally using a simplified bomb calorimeter. An efficiency factor of 75–95 % for thermal energy recovery from sludge streams via a heat exchanger is suggested in the literature [21]. In the current study, an efficiency factor of 80 % was considered for the heat exchange.

The interactions between input variables and output responses, specifically SCOD, phosphate, ammonium, protein, and carbohydrate concentrations, as well as their solubilisation, were investigated using analysis of variance and mathematical predictive models (Supplementary Tables S2–S5, Equations S1–S3, and Figs. S1–S3) to identify multi-factor relationships. While these models effectively captured interactions within the studied sludge composition, further

refinement is necessary for broader applicability across variable sludge characteristics.

### 2.1.3. Toxins removal

Production of biochar through pyrolysis of locally available sugarcane bagasse using the steel tube furnace (Borgo Ticino, Italy) at 550 °C for 4 h, under nitrogen gas at 70 mL/min (the optimisation of this temperature is not discussed in this paper). The biochar was magnetised according to Li et al. [22], Son et al. [23]. This biochar will be termed magnetic biochar (MBC) going forward.

The HT sludge underwent adsorption, with the operating parameters being optimised using the RSM. The range of operating parameters included biochar dosage (5–15 g/L), equilibration/contact time (30–100 min), and pH (4–9). The runs were conducted at room temperature, with 150 mL of HT sludge used in each case. The removal efficiency of heavy metals and phenolics (collectively termed toxins in this study) were monitored as response factors. Heavy metals were determined using atomic absorption spectrometry (AES) after microwave-assisted digestion (4200 MP-AES, Agilent Technologies, USA). Phenolic compounds were determined using the Folin-Ciocalteu method with a UV-VIS spectrophotometer (HACH DR-3900) at 765 nm [24,25]. To remove the pregnant MBC, an electromagnet with a strength of 2000 Gauss, which was further treated for reuse (although this was not discussed in this study)

### 2.1.4. Precipitation of struvite

The effluent of the adsorption unit was charged to the precipitation unit. 100 mL of the adsorption effluent was charged to the 500 mL Erlenmeyer flasks. For struvite precipitation, the operating conditions were optimised using a central composite design. The pH was varied between 7 and 11, and the volume of  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$  stock solution (20 g/L) added ranged from 1 to 2.5 mL. This approach was selected to ensure efficient magnesium availability while minimising reagent costs.

A settling time of 2 hr. was allowed in each case and then filtered using a 25  $\mu\text{m}$  filter. The filtrate was analysed for  $\text{PO}_4\text{-P}$ ,  $\text{NH}_3\text{-N}$  using a Gallery Automated Photometric Analyser (Thermo Fisher Scientific, Waltham, MA, USA). The change from the initial concentration was recorded. The residue was dried at 35 °C and subsequently weighed. This dried residue was then dissolved in concentrated HCl, diluted with distilled water in a 1:9 ratio, and analysed for  $\text{PO}_4\text{-P}$ ,  $\text{NH}_3\text{-N}$ . A material balance for the nutrients was conducted. Experiments were performed under optimal conditions, with further validation experiments carried out to confirm these optimal conditions. Both the residue and filtrate were analysed for nutrients and Mg, Ca, Na, K and Fe using ICP-OES. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) were employed to determine the crystallography and morphology of the struvite formed.

### 2.1.5. Anaerobic digestion

The methane potential of the WAS stream was compared to the WAS after HT, HT sludge after the removal of toxins ( $\text{HT}_{\text{ads}}$ ) and HT removal after the removal of toxins and precipitation ( $\text{HT}_{\text{ads} + \text{prec}}$ ). Each stream was inoculated with the digester sludge withdrawn from the same WWTP, whose properties are shown in Tables 1 and in a 1:1(v/v). The digester's operating temperature was set at 37 °C in 1 L Schott bottles, with 0.7 L working volume in batch mode. The volume of the biogas produced was measured using a water displacement system with acidified water (pH-3) to avoid the dissolution of gases. The quality of the biogas products was determined using gas chromatography coupled with a thermal conductivity detector (GC-TCD), having the injector, column and detector temperatures of 120, 40 and 250 °C, respectively. Helium was used as the carrier gas at a flow rate of 10 mL/min. All AD reactors were run in duplicate, and the standard deviations were noted. The effluent of the digesters was characterised and recorded. Mass and energy balance calculations were performed based on the GC assay, influent and effluent characterisation of the anaerobic digesters in

respective scenarios. The organic loading in this study varied between 4 and 7 kg VS/ $\text{m}^3$  for batch laboratory scale digesters operating under mesophilic conditions. The calculation for determining the heat energy required to maintain the temperature of the digester was conducted using Equation (2), as cited by Deublein and Steinhauser [26].

$$Q_{AD} = [m_{HT}C_p(T_o - T_{HT})] + (k_dA_D\Delta T_D) \quad (2)$$

The heat energy required for anaerobic digestion is denoted as  $Q_{AD}$ . MHT represents the mass of the HT sludge, while  $C_p$  refers to the specific heat capacity of the HT sludge.  $T_o$  represents the operating temperature of the anaerobic digestion system, and  $T_{HT}$  signifies the inlet temperature of the HT sludge. The  $C_p$  of the waste-activated sludge and HT sludge were experimentally determined to be 3.93 kJ/kg·K and 3.96 kJ/kg·K, respectively. In Equation (2), the heat loss from the digester,  $Q_{AD-loss}$ , is represented by the second term. This term considers the k-factor (Thermal conductivity) of the digester material, the surface area of the digester  $A_D$ , and the average temperature difference between the heating medium and the substrate (HT sludge),  $\Delta T_D$ . The digester material's k-factor and the outside temperature were chosen as 14.2 W/m.K and 20 °C, respectively [27]. The surface area of the digester was determined by considering the height-to-diameter ratio of 0.5 to ensure stability and structural integrity, mixing efficiency, heat transfer, cost-effectiveness and ease of maintenance.

## 2.2. Process description

Fig. 1 displays the 4 process scenarios discussed in this study. Table 2 shows the parameters of the various scenarios, as shown in Fig. 1. It should be noted that the figures quoted in Table 2 are optimum values found through bench-scale operations.

Scenario 1: AD of WAS (without HT), the biogas was combusted for the plant needs and selling excess.

Scenario 2: AD of HT sludge (Consider hydrochar yielding (pelletisation) and recovery of heat during cooling)

Scenario 3: AD of HT sludge after adsorption (removal of toxins). The reuse of biochar was considered.

Scenario 4: AD of HT after adsorption and precipitation. Struvite fertiliser/nutrients recovery, heat recovery and hydrochar recovery were considered.

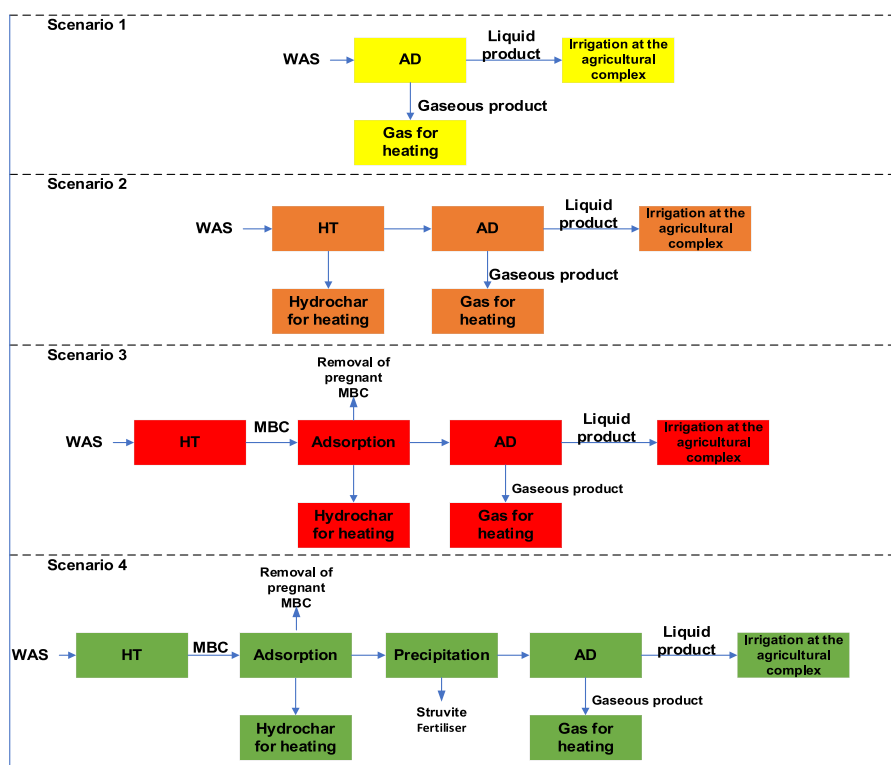
## 2.3. Evaluation of the techno-economic aspects

For the economic analysis, it is assumed that the profit will remain consistent throughout the project and that the product will be sold immediately after the initial batch. Additionally, it is commonly assumed that production starts immediately after erecting the critical components, such as the HTR and precipitator; in this case study, the biodigesters are already available.

### 2.3.1. Techno-economic analysis framework

A spreadsheet model using Microsoft Excel 365 (Microsoft Corporation, Redmond, WA, USA) was developed to evaluate the economic performance of all scenarios. Specifically, the impact of capital (CAPEX) and operational (OPEX) expenses on the management of wastewater sludge were examined. It must be noted that all the amounts were quoted in US dollars (\$). The focus of the process was on environmental management rather than solely prioritising energy and nutrient recovery. This viewpoint appears to be a more logical choice, particularly when comparing the prices of levelised cost of methane, 1.75–2.90 \$/kg [28], with the price of fossil-derived gas 1.74 to 2.40 \$/kg [29,30], Power-to-Gas (P2G) Technology from \$1.84 to \$2.44/kg [31], gasification 1.21 \$/kg [32], Sabatier Process from \$1.50 to \$1.90/kg [33].

It is reported that struvite fertiliser sells at about 517 \$/ton [34]. In contrast, popular technologies such as wet process phosphoric acid production and neutralisation process have produced ammonium and



Was = Waste activated sludge, MBC = Magnetic biochar, AD = Anaerobic digestion

Fig. 1. Process for various scenarios

Was = Waste activated sludge, MBC = Magnetic biochar, AD = Anaerobic digestion.

Table 2

Process parameters in various scenarios.

| Equipment              | Parameter (unit)                       | Scenario 1   | Scenario 2  | Scenario 3  | Scenario 4   |
|------------------------|----------------------------------------|--------------|-------------|-------------|--------------|
| HTR                    | T (°C)                                 | –            | 220         | 220         | 220          |
|                        | P (MPa)                                | –            | 3.3         | 3.3         | 3.3          |
|                        | Time (min)                             | –            | 20          | 20          | 20           |
|                        | Hydrochar yield (ton/day) <sup>a</sup> | –            | –           | 144 ± 3     | 144 ± 3      |
|                        | <b>Proximate analysis</b>              |              |             |             |              |
|                        | TS (mg/L)                              | 9108 ± 39    | 8430 ± 120  | 10273 ± 95  | 8515 ± 78    |
|                        | VS (mg/L)                              | 5408 ± 4     | 4745 ± 113  | 6215 ± 78   | 5155 ± 141   |
|                        | Ash (%)                                | 34.75 ± 0.25 | 39.9 ± 0.11 | 28.0 ± 3.91 | 43.99 ± 0.10 |
|                        | Moisture (w/w %)                       | 99.1         | 99.2        | 99.1        | 99.3         |
|                        | <b>Ultimate analysis</b>               |              |             |             |              |
|                        | C (%)                                  | 30.73        | 30.2        | 34.8        | 28.30        |
|                        | H (%)                                  | 7.87         | 4.97        | 5.03        | 4.54         |
|                        | N (%)                                  | 4.96         | 4.12        | 7.01        | 3.30         |
|                        | S (%)                                  | 3.38         | 2.11        | 2.04        | 2.00         |
| Adsorption of toxins   | O (%)                                  | 18.31        | 18.66       | 27.47       | 17.87        |
|                        | HHV of hydrochar (MJ/kg)               | 18.02        | 14.40       | 15.12       | 13.53        |
|                        | TOC (mg/L) <sup>b</sup>                | 472 ± 16     | 1836 ± 38   | –           | –            |
|                        | Biochar dosage (g/L)                   | –            | –           | 5           | 5            |
| Struvite precipitation | Time (mins)                            | –            | –           | 35          | 35           |
|                        | pH                                     | –            | –           | 6.5         | 6.5          |
|                        | Mg dosage (mL/L) <sup>b</sup>          | –            | –           | –           | 14.2         |
| Anaerobic digestion    | pH                                     | –            | –           | –           | 9.24         |
|                        | Temperature (°C)                       | 37 ± 1       | 37 ± 1      | 37 ± 1      | 37 ± 1       |
|                        | Pressure (atm)                         | 1            | 1           | 1           | 1            |
|                        | pH (initial)                           | 7            | 7           | 7           | 7            |
|                        | Residence time (day)                   | 21           | 21          | 21          | 21           |

<sup>c</sup> (mL/L HT sludge) – 20g/L MgCl<sub>2</sub>·6H<sub>2</sub>O.

<sup>a</sup> Mass of hydrochar per unit volume (g/L).

<sup>b</sup> In the bulk of the liquid phase.

phosphates fertiliser with prices ranging from 280 to 330 \$/ton [35].

Hydrochar has been documented to trade at 0.08–1.92\$/kg [36–38], in comparison to coal-derived solids fuels priced at 0.18–0.92 \$/kg [39,

40].

In addition, it has been widely recognised that wastewater and sewage management projects are often not profitable without public

subsidies, even when taking into account revenues from energy generation [41].

In this study, the methodology outlined by Towler and Sinnott [42] served as the main reference. The study is categorised as a Class 5 estimate with an accuracy of  $\pm 50.0\%$ , according to the classification by the Association for the Advancement of Cost Estimating International (AACE 56R-08, 2020); the cost data has been updated to August 2020. First, a thorough analysis was conducted to determine the cost of acquiring each piece of equipment. This involved utilising cost correlations or capacity ratios, such as Williams' rule. These estimates were derived from design parameters obtained from bench-scale experiments and simulations. Considering the presence of potential clogging by struvite, acidic substances, and corrosive materials, a material factor was applied as necessary. The construction material for all equipment was selected to be austenitic stainless Steel (304), except for the biogas digester made of reinforced concrete. Afterwards, the Lang factorial method was applied to calculate the Total Investment Cost (TIC). Operational costs were calculated by factoring in a portion of the initial capital expenditure and deducting the revenue generated from product sales. Upon thorough examination, the cost per ML of treated sludge was calculated, considering the projected lifespan of the plant as 30 years.

### 2.3.2. Total capital investment

An economic analysis was conducted on the scenarios presented in Fig. 1 to compare and determine the economic viability of integrating different processes, including HT, HT after adsorption, and HT after adsorption-precipitation with AD. The mass and energy balances determined in earlier sections were utilised in the scaling up of the equipment to the desired plant capacity, which consequently determined the capital investment required. The cost of the equipment was determined based on information found in previous literature [42,43]. However, the size of the equipment can vary depending on the plant's operating capacity. Therefore, the final cost for this study was determined using a scaling factor, as shown in Equation (3) [42,44].

$$C = C_0 \left( \frac{V}{V_0} \right)^n \quad (3)$$

Where the variables  $C$  and  $V$  represent the cost and capacity of the current equipment, while  $C_0$  and  $V_0$  represent the cost and capacity of the base equipment, respectively, the scaling factor is denoted by  $n$ , and typically, the  $n$  values range from 0.6 to 0.8 [45]. For this study, a scaling factor ' $n$ ' value of 0.77 was chosen in line with the previous data collected for waste-activated sludges for plants with capacity ranging from 4 to 450 ML/day [45–47]. The cost of equipment fluctuates from year to year, so it is necessary to adjust the cost data found in the literature to reflect the current year. This was calculated using data from the chemical engineering plant cost index (CEPCI) [45,48] using Equation (4). This study utilised the cost index data from March 2024 to represent the current year (800.3).

$$Cost_{Cur} = Cost_{Base} \times \frac{CEPCI_{Cur}}{CEPCI_{Base}} \quad (4)$$

$Cost_{Cur}$  and  $Cost_{Base}$  are the costs of equipment to be determined, and similar equipment is known in a certain reference year, respectively.  $CEPCI_{Cur}$  and  $CEPCI_{Base}$  represent the index for the current year and the reference year, respectively.

In this study, the cost data of various units were estimated from Chemical Engineering Magazine (CE), ICIS and other online vendors such as Alibaba and Amazon and use of Equation (2) [49,50]. Regarding the AD digester, it has been noted in the literature that the cost of the digester can range from 300 to 500 USD/m<sup>3</sup> [51]. In this study, only the cost of maintaining the anaerobic digestors was considered since the plant already has reactors, and the study did not put much emphasis on upgrading the biogas produced. The total cost of the equipment was determined by adding up the costs of all the major equipment shown in

Fig. 1. The total fixed capital investment (FCI) was calculated by adding capital investment on equipment (CIE) and other capital costs such as startup expenses (15 % of CIE), engineering and supervision (25 % of CIE) and contingency (10 % of CIE) [45].

Aside from the initial investment, sufficient working capital is necessary to establish and sustain the plant until the first revenue is generated. Based on previous studies conducted by Doddapaneni et al. [52], Manthos et al. [53], it has been found that the working capital for chemical plants typically ranges from 15 to 20 % of the FCI. For this study, a working capital of 15 % was chosen. Ultimately, the total capital investment (TCI) was determined by adding FCI and working capital [54,55].

### 2.3.3. Production costs

There are different categories of production costs, including direct variable costs, fixed costs, and general expenses. The revenue generated, utilities and other specific costs are outlined in Table 2. The labour needed to run the plant was determined using the methodology outlined in the literature [42,56]. It was determined that the plant availability was 330 days, running 24 hours a day and having three eight-hour working shifts per day. Given the highly automated nature of industrial manufacturing at this scale, a large workforce is not necessary to maintain a high level of processing control. Hence, 8 employees per shift were considered for the additional units, including the supervisors. The costs associated with supervising the staff were determined to be 20 % of the expenses related to operating labour [55,56]. 5 % of the FCI was pegged as the maintenance and repair costs [57]. The other operating costs, such as factory overheads, administration costs, and distribution and selling costs, were calculated using correlations presented by Martinovic et al. [54], Turton et al. [56]. The factory overheads consist of various expenses such as payroll, employee benefits, medical services, accounting services, and safety services. The reported cost of wastewater treatment for domestic and industry effluents (\$1–4/m<sup>3</sup>) was used to calculate the wastewater treatment costs [58–60]. The depreciation amount was determined using the straight-line method and a zero-salvage value over a span of 30 years.

### 2.3.4. Economic indicators and sensitivity analysis

The economic performance of the AD of the WAS and the other integration approaches were assessed using the Payback period, rate of investment (ROI), internal rate of return (IRR) and net present value (NPV).

One way to estimate the payback time is by dividing the total initial capital (fixed capital plus working capital) by the average annual cash flow. Equation (5) provides a simple method for calculation [67,68].

$$\text{Payback period} = \frac{\text{Total investment capital}}{\text{Average cash flow per annum}} \quad (5)$$

The payback period indicated in the cash-flow diagrams by Towler and Sinnott [42] does not align with the assumption that all the investment is made in year zero and revenues begin immediately. For most chemical plant projects, it is often not feasible to expect investments to be fully recovered within the first year of operation. Typically, investments are spread out throughout one to three years, and it may take until the second year of operation for revenues to reach their full potential. The simple payback time is typically calculated solely based on cash flow. However, to simplify the process, taxes and depreciation are often disregarded, and the average annual income is used instead of cash flow.

The NPV was calculated using equation (6) [69].

$$NPV = \left( \frac{(1+i)^n - 1}{i \times (1+i)^n} \times \text{net cashflow} \right) - TCI \quad (6)$$

Where  $i$  is the interest rate (8 %),  $n$  is the plant's lifespan (30 years). The net cash flow can be computed by equation (7):

$$\text{Net Cashflow} = ((R_T - PC_T) \times (1 - \text{tax rate})) + D \quad (7)$$

$R_T$  represents the total revenue, encompassing the revenue generated from all sources involved in the process;  $PC_T$  represents the total production cost, while depreciation ( $D$ ) is another factor to consider (all costs are quoted in US\$). A tax rate of 40 % was chosen for this study. The IRR (%) value was determined through an iterative process, finding the specific "i" value at which the NPV reaches zero in equation (6) [70].

The evaluation of the impact of integrating bioenergy and bio-resource recovery into the processes' products' selling price was conducted using data on minimum selling prices, as shown in Table 3. A methodology presented by Yang and Rosentrater [71] was used to calculate the minimum selling price of the struvite, biogas, hydrochar and liquid fertiliser. To achieve the breakeven point, the overall costs must be equivalent to the total revenue, as illustrated in Equation (8).

$$R_T = PC_T + ROI + IT \quad (8)$$

$$ROI = CRF \times TCI \quad (9)$$

$$IT = \text{taxation rate} \times (R_T - PC_T - D) \quad (10)$$

ROI is the return on investment, while IT is the income tax. The CRF is the capital recovery factor, which is calculated using equation (11).

$$CRF = \frac{i \times (1 + i)^n}{(1 + i)^n - 1} \quad (11)$$

A sensitivity analysis was conducted to examine how various cost parameters affect the economic performance of the cases shown in Fig. 1. For this study, the input parameters were adjusted within a range of  $\pm 25$  % to the base values. These parameters included the Fixed capital investment cost of raw materials and the selling price of the products. Parameters which have the most significant impact on economic performance indicators were determined. Parameters causing substantial changes in NPV or IRR when varied were identified as key drivers, as presented in Table 4.

#### 2.4. Ethical considerations

To ensure that this study does not exert a negative impact on the environment, this work strictly observes environmental policy and regulation [74]. The overall impacts of the hydrothermal treatment and valorisation steps in the pilot plant will be evaluated based on a life cycle analysis, which will provide the environmental saving potential. There are measures which have been put in place to ensure that emissions and effluents are demonstrated judiciously. There are specific measures for handling the waste, such as sewage sludge, and these measures are taken to reduce or even eliminate the risks associated with the health of workers handling the waste as well as the health of the common community. The final products, such as struvite fertiliser, biogas, and hydrochar, will also be tested before being sold to consumers and markets to meet the market and regulatory requirements. Public outreach sessions will involve explaining to the residents of the

**Table 3**

Cost parameters considered in the calculation of production costs and revenue generated.

| Parameter                | Unit   | Cost (US\$) | References |
|--------------------------|--------|-------------|------------|
| Water <sup>a</sup>       | \$/kL  | 0.48        | [61,62]    |
| Electricity (purchase)   | \$/kWh | 0.044       | [63]       |
| Salaries <sup>b</sup>    | \$/h   | 1.47        | [64]       |
| Struvite                 | \$/ton | 517         | [65]       |
| Hydrochar                | \$/ton | 450         | [36–38]    |
| Biomethane selling price | \$/kg  | 2.90        | [28]       |
| Raw materials: WAS       | \$/ML  | 14.22       | [66]       |

<sup>a</sup> National average.

<sup>b</sup> Minimum wage rate.

**Table 4**

Parameters and related assumptions in costing analysis.

| Parameters                                       | Comments                                                                      |
|--------------------------------------------------|-------------------------------------------------------------------------------|
| Base year                                        | 2019 (March)<br>CEPCI (720.1)                                                 |
| Currency and exchange rate                       | US\$; ZAR/US\$ = 18.86 <sup>a</sup>                                           |
| Plant site                                       | KwaZulu Natal (Sout Africa)<br>Location/site factor (0.85) <sup>b</sup>       |
| Lifespan of the plant                            | 30 years                                                                      |
| Material of construction                         | Austenitic stainless Steel (304)<br>Material Factor, $f_m$ (1.3) <sup>c</sup> |
| CAPEX estimates                                  | Lang factors for fluid-solid systems                                          |
| Inside battery limits (ISBL)                     | $C_E + C_{er} + C_p + C_{ic} + C_{el} + C_c + C_s + C_{sf}$                   |
| Purchase cost of major equipment ( $C_E$ )       | Total cost of all individual equipment cost                                   |
| Cost of erecting equipment                       | $f_{er} = 0.45$ ; then $C_{er} = C_E^* (f_{er}/f_m)$                          |
| Cost of pipework                                 | $f_p = 0.45$ ; then $C_p = C_E^* f_p$                                         |
| Cost of instrumentation and control              | $f_{ic} = 0.15$ ; then $C_{ic} = C_E^* (f_{ic}/f_m)$                          |
| Cost of Electrical work                          | $f_{el} = 0.1$ ; then $C_{el} = C_E^* (f_{el}/f_m)$                           |
| Cost of Civils                                   | $f_c = 0.2$ ; then $C_c = C_E^* (f_c/f_m)$                                    |
| Cost of buildings and structures                 | $f_b = 0.1$ ; then $C_b = C_E^* (f_b/f_m)$                                    |
| Cost of surface finishing                        | $f_{sf} = 0.1$ ; then $C_{sf} = C_E^* (f_{sf}/f_m)$                           |
| Outside batter limits (OSBL)                     | $f_{OSBL} = 0.4$ ; then $OSBL = ISBL^* f_{OSBL}$                              |
| Cost of engineering and design                   | $f_{DE} = 0.25$ ; then $DE = ISBL^* f_{DE}$                                   |
| Contingency (X)                                  | $f_X = 0.1$ ; then $X = ISBL^* f_X$                                           |
| Total Investment Cost (TIC)                      | $TIC = ISBL + OSBL + DE + X$                                                  |
| <b>Fixed production costs</b>                    |                                                                               |
| <b>Operating labour (OL)</b>                     |                                                                               |
| Supervisors' cost                                | 0.2*OL                                                                        |
| Direct salary overheads                          | 0.5*OL                                                                        |
| Maintenance cost                                 | 0.05*ISBL                                                                     |
| Tax and insurance                                | 0.02*ISBL                                                                     |
| Land rent and buildings                          | 0.02*(ISBL + OSBL)                                                            |
| General plant overheads                          | 0.65*(OL + Supervision)                                                       |
| Environmental tariffs                            | 0.01*(ISBL + OSBL)                                                            |
| Fees and royalties                               | 0.01*TIC                                                                      |
| Capital charges                                  | 0.01*TIC                                                                      |
| <b>Marketing costs</b>                           |                                                                               |
| <b>Estimates of the variable production cost</b> |                                                                               |
| Utilities                                        |                                                                               |
| Electricity                                      | \$0.044/kWh                                                                   |
| Water                                            | \$0.48/kL                                                                     |
| <b>Minimum selling price</b>                     |                                                                               |
| Struvite fertiliser                              | \$517/ton                                                                     |
| Hydrochar                                        | \$450/ton                                                                     |
| Biomethane                                       | \$2.90/kg                                                                     |
| Liquid fertiliser                                | \$0.14/ton                                                                    |

<sup>a</sup> Adapted from Nedbank [72].

<sup>b</sup> Methodology adopted from Intratec [73].

<sup>c</sup> Source of material factor.

respective communities what is being developed, resolving all issues that may arise and integrating the information received [75].

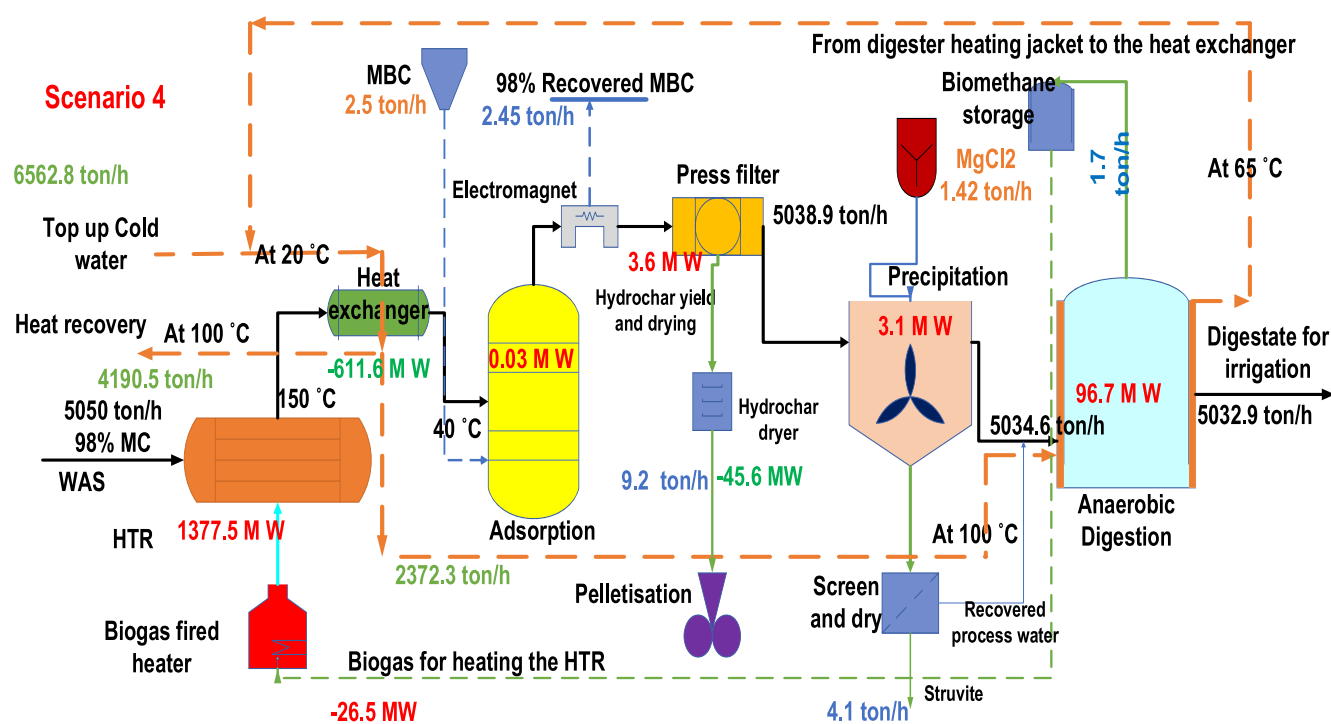
### 3. Results and discussion

#### 3.1. Mass and energy balance

Fig. 2 illustrates the material and energy flows for various cases that have been examined (scenarios 1, 2 and 3 are presented in Fig. S2). The hydrothermal treatment process, adsorption, precipitation of struvite, hydrochar yield, and anaerobic digestion are significant energy-consuming unit operations.

This study investigates the hydrothermal treatment (HT) of waste-activated sludge (WAS) in an industrial wastewater treatment plant designed to handle 100 ML/d. For this study, a flow rate of 5 ML/h was used as the basis for calculations and scenario analysis.

The energy requirement for hydrothermal treatment of waste-activated sludge was determined to be 0.98 MJ/kg. This is lower than the values reported by Aragón-Briceño et al. [76], which were between 3.3 and 5.9 MJ/kg, indicating a more efficient process in the current study. The density of the HT-treated sludge was measured at 1010 kg/m<sup>3</sup>, compared to 1009 kg/m<sup>3</sup> for the untreated WAS, indicating



compaction and partial dissolution of solids during the treatment process.

At a design flow rate of 5 ML/h, the feed mass flow rate to the HTR unit was approximately 5050 ton/h. The hydrothermal treatment unit was the primary energy consumer in the plant, accounting for over 90 % of the energy demands of the valorisation section. The heat losses due to conduction were calculated to be 34.1 MJ/kg, with convection and radiation losses considered negligible. The maximum pressure during HT at 220 °C was 3.3 MPa. To protect downstream equipment and prevent undesirable reactions at high temperatures in the presence of oxygen, the valve to the heat exchanger was opened when the bulk liquid temperature had dropped to 150 °C, somewhat deviating from the strict definition of hydrothermal treatment.

The heat recovered through the heat exchanger was calculated to be 611.6 MW (Fig. 2). To achieve this, the mass flow rate of the cooling stream was computed to be 6562.8 ton/h, sufficient to reduce the HTR contents' temperature to approximately 40 °C before the adsorption processes. The cold stream exiting the heat exchanger was divided into two: one stream, at a flowrate of 2372.3 ton/h, was directed to the anaerobic digester to meet its energy needs, and the other, at 4190.5 ton/h, was used for preheating and other plant applications. This heat recovery strategy successfully met all the biodigester's energy demands. The high energy recovery from the heat exchanger plays a crucial role in reducing overall operational costs, particularly in the context of scaling up and commercialising the process. In a study by Knötig et al. [77], hydrothermal treatment contributed to thermal energy savings of 53 %, slightly higher than the 44 % heat recovery in this study. This discrepancy could be due to differences in heat exchanger efficiency, hydrothermal treatment conditions, system scale, and energy loss considerations. Factors such as insulation, preheating strategies, and heat exchanger fouling may also influence recovery rates. Despite this variation, the substantial heat recovery observed underscores the potential of integrating efficient heat exchange systems to enhance energy sustainability and economic viability in wastewater treatment.

After cooling, the post-HT sludge was fed into the adsorption unit at a rate of 2.5 ton/hr, where magnetic biochar (MBC) was used.

Experimental data indicated a 98 % recovery rate of MBC (The elution and treatment for reuse are not discussed in the present study). However, it is anticipated that large-scale operations may encounter lower recovery rates due to different hydrodynamic behaviours at higher flow rates [78]. The adsorption unit's power consumption was minimal, at 0.03 W.

The adsorbed HT sludge (termed adsorption sludge) was processed through a press filter operating at 500 kPa, with a power consumption of 3.6 MW. This step was essential for yielding hydrochar and removing particulates that could hinder subsequent struvite and hydrochar separation. The hydrochar, post-filtration, had a moisture content of 31 w/w % and was naturally dried before packaging. Its higher heating value (HHV) was calculated to be 17.8 MJ/kg from the ultimate analysis of the hydrochar. This value closely aligns with other forms of coal, such as sub-bituminous coal and lignite, which have an HHV of approximately ranging between 16 and 19 MJ/kg [79]. This similarity highlights the potential of hydrochar as a viable solid fuel, demonstrating its suitability for meeting the energy demands of the plant and enhancing overall energy efficiency.

The filtered adsorption sludge, with particles less than 25  $\mu\text{m}$ , required flocculation to reduce pumping pressure and enabled the use of larger aperture size filters. The mass flow rate was 5038.9 ton/h, dissipating 3.1 MW of energy for optimal struvite precipitation. To produce 4.1 ton/h of struvite, 1.42 ton/h of  $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$  was injected on a dry basis. Sourcing alternative magnesium sources could reduce consumable costs. The resulting sludge, post-filtration, was termed precipitation sludge.

The precipitation sludge, at a flowrate of 5034.6 ton/h, was fed into the anaerobic digester and inoculated with biodigester sludge from the same WWTP. With a SCOD of 1722 mg/L and a VS of 5155 mg/L, the biogas production rate was calculated to be 1.7 ton/h. The AD temperature was maintained at 37 °C using a heating jacket with water circulating from the heat exchanger, entering at 100 °C and exiting at 65 °C. Experimental observations showed a maximum methane concentration of 71 %. After a retention time of 21 days, the AD effluent was pumped to agricultural fields for irrigation purposes.

This study demonstrates the efficiency and practicality of integrating hydrothermal treatment within a wastewater treatment plant. By optimising energy recovery and process parameters, the plant achieves significant reductions in waste volume and energy consumption while producing valuable by-products such as biogas and struvite [80]. These findings highlight the potential of hydrothermal treatment as a sustainable and economically viable solution for wastewater management.

### 3.2. Profitability analysis

A comprehensive economic analysis was conducted to evaluate the feasibility of valorising waste-activated sludge (WAS) through the integration of hydrothermal treatment (HT) and anaerobic digestion (AD) of the HT effluent. To ensure consistency in the economic evaluation, the selling prices of the products, as outlined in Table 2, were held constant across all scenarios.

Fig. 3 illustrates the net revenue generated from the sale of struvite, hydrochar, biomethane, and digestate at the established selling prices. Fig. 3(a) depicts the annual net revenue across various scenarios. All integrated approaches demonstrated higher revenues compared to the standalone anaerobic digestion setup (Scenario 1). Notably, in Scenarios 3 and 4, hydrochar sales contributed significantly to the revenue, each generating \$10.9 million. This indicates that the exclusion of the precipitation unit in Scenario 3 did not impact the revenue from hydrochar. The total revenue generated in Scenarios 1, 2, and 3 was 19 %, 35 %, and 48 % of Scenario 4, respectively. These results underscore the substantial profitability gains achieved by integrating hydrochar production and struvite precipitation with traditional anaerobic digestion.

Fig. 3(b) reveals that the highest production costs were associated with biomethane production across all scenarios, ranging from \$3.8 million to \$4.7 million. The costs related to liquid fertiliser production were also significant due to stringent measures for ensuring safe sludge disposal. This study allocated more personnel (4 per shift) to this section than any other. Scenario 4 exhibited the highest total annual production costs, approximately \$9.84 million, largely due to the high usage of  $MgCl_2$  and  $NaOH$ , which together accounted for \$2.63 million. This highlights the urgent need for alternative chemicals to either supplement or replace these commercial inorganic raw materials. Interestingly, the total production costs in Scenarios 1, 2, and 3 were comparable, ranging between \$4.2 million and \$6.9 million, further emphasising that the chemical costs for struvite precipitation in Scenario 4 are a major contributor to operating expenses.

Fig. 3(c) presents the minimum selling prices of various products across different scenarios required to achieve breakeven at a Capital Recovery Factor (CRF) of 9 % ( $i = 8\%$ ,  $n = 30$  years). The integration of HT, toxin adsorption, and struvite precipitation reduced the minimum selling prices of biomethane, with Scenarios 4, 3, 2, and 1 having minimum selling prices of \$337.49/ton, \$619/ton, \$473.72/ton, and \$2883.85/ton, respectively. The observed drop in the MSP in Scenario 2 is attributable to the high SCOD content of the HT effluent feeding the

anaerobic digester, which enhances biomethane yield in comparison to untreated waste-activated sludge and thus reduces the selling price compared to Scenario 3 (Fig. S4 supplementary data). This finding aligns with existing literature, which suggests that HT significantly improves biomethane yields [81]. The enhanced methane yield from HT-treated sludge not only improves energy recovery but also supports the development of energy-neutral WWTPs. This could substantially reduce the energy burden on municipalities while contributing to circular economy efforts by transforming waste material into bioenergy and nutrients.

The Net Present Value (NPV) is a crucial metric for assessing the economic feasibility of a project, representing the cumulative cash flow over its operational lifespan. Fig. 4(a) illustrates the NPVs for four distinct scenarios over a 30-year plant lifetime. Among these, the standalone process scenario 1 yielded the lowest NPV. In contrast, scenarios 2, 3, and 4 exhibited an exponential increase in NPV, with scenario 4 approaching an NPV of approximately \$2.5 billion. Kassem et al. [16] reported a net present value (NPV) of \$1.5 billion over a 40-year plant lifespan for a system integrating only hydrothermal treatment (HT) and anaerobic digestion (AD). This finding underscores the economic viability of HT-AD integration, even without additional valorisation steps such as toxin removal or nutrient recovery.

The substantial increase in this study can be attributed to the enhanced production of valuable by-products such as struvite and hydrochar, which significantly offset the high operating costs typically associated with wastewater treatment plants (WWTPs).

Fig. 4(b) presents a comparative analysis of the NPV behaviour in scenario 4, focusing on the sensitivity to changes in the prices of the two major products. Biomethane production was excluded from this analysis, as the valorisation studies primarily examine struvite and hydrochar. The selling price of struvite was incrementally increased by 0 %, 20 %, 40 %, and 60 %, while the hydrochar price was held constant, and vice versa.

The results indicate that increasing the selling price of these products positively impacts the NPV across all scenarios. Although the NPVs were generally comparable, hydrochar demonstrated a marginally greater influence on NPV enhancement than struvite. Specifically, price increases of 20 %, 40 %, and 60 % in hydrochar resulted in NPV increases by factors of 1.01, 1.02, and 1.03, respectively. These findings underscore the critical role of product pricing in enhancing the economic viability of the WWTP project, highlighting the potential for optimised by-product utilisation to improve project outcomes substantially.

The Internal Rate of Return (IRR) is intimately linked to Net Present Value (NPV) and is a critical financial metric for evaluating the design and construction of plants. Expressed as a percentage, the IRR is pivotal in decision-making, comparative analysis, capital budgeting, and risk assessment.

Fig. 4(c) presents the IRR for the four scenarios at predetermined minimum selling prices (MSPs). MSPs for each product in the mix were incrementally increased by 0 %, 20 %, 40 %, and 60 %. It was observed that price increases for each product positively impacted the IRR across

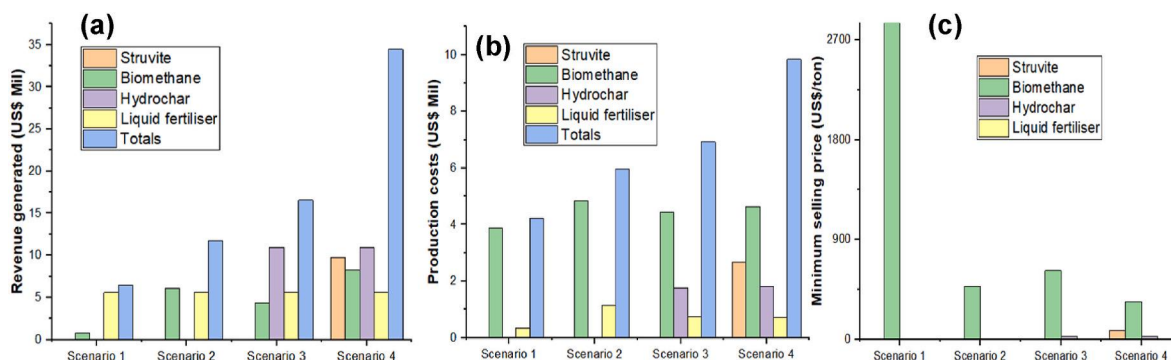
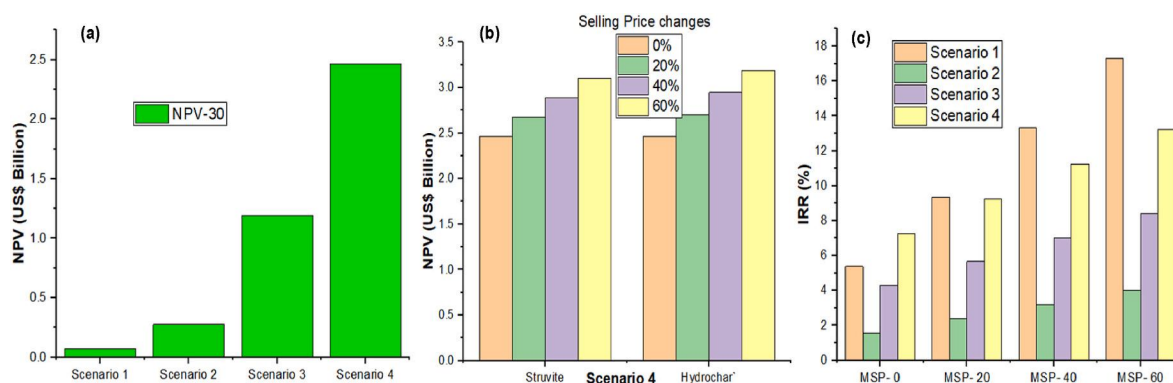


Fig. 3. Profitability analysis for four scenarios: (a) Revenue generated, (b) Production costs, (c) minimum selling price to break even.



**Fig. 4.** NPV and IRR behaviour subject to increase in the selling prices (a) NPV for various scenarios (b) NPV relative to struvite and biochar price alteration (c) IRR response to MSP increase.

all scenarios. Initially, Scenario 4 exhibited the highest IRR, followed by Scenarios 1, 3, and 2, with IRRs of 7.25 %, 5.38 %, 4.29 %, and 1.56 %, respectively. The standalone scenario demonstrated a lucrative IRR due to the simplicity of the process, as it did not necessitate highly specialised equipment. However, this approach does not align with the objective of valorising sewage sludge to extract valuable resources for waste management.

The profitability analysis indicates that Scenario 4 was the most economically viable integration route across all price increases, as shown in Fig. 4(c). This superior performance can be attributed to the inclusion of struvite in the product mix, a feature unique to Scenario 4. The other three scenarios did not incorporate struvite.

Table 5 outlines the major parameters in the economic analysis of the four scenarios. Notably, only Scenario 4 achieved a positive rate of return on investment.

### 3.3. Sensitivity analysis

The cost of resource recovery and energy production in the proposed plant is influenced by numerous parameters, which can be broadly categorised into process-related and cost-related factors. A sensitivity analysis was conducted to pinpoint the key parameters among them. This section delves into the sensitivity analysis of various parameters affecting the NPV after the end of the equipment life for optimal capacity. The analysis was performed by varying selected critical parameters by  $\pm 25$  % of their proposed values while keeping all other variables constant. For the process-related parameters, the unit costs of

electricity, biochar, and  $\text{MgCl}_2$  were considered. As for the cost-related parameters, the analysis included fixed capital investment, struvite selling price, and income tax rate. By examining these parameters, the study aims to identify their relative impact on the NPV and understand the robustness of the proposed plant's economic performance.

The results illustrated in Fig. 5 demonstrate the impact of varying cost parameters on the percentage change in NPV. Each scenario exhibited distinct responses to the administered changes. Notably, altering production costs by 25 % in both directions significantly affected the NPV values across all scenarios. Specifically, scenarios 1, 2, 3, and 4 showed changes in NPV values by 226 %, 92 %, 23 %, and 13 %, respectively. This indicates that the annual production cost in scenario 4 is less sensitive to changes compared to the other scenarios, a finding supported by other studies by Kassem et al. [16], who observed that system scale-up improves the financial parameters such as the NPV. This lower sensitivity in scenario 4 could be attributed to the economic benefits of a full-capacity valorisation process over standalone setups, highlighting the robustness of integrated approaches. This shows that stabilising or enhancing the market value of by-products could significantly improve the economic sustainability of integrated approaches in developing regions.

When all process-related costs were increased by 25 %, the NPV decreased across all scenarios. This underscores the necessity for processing plants to minimise utility costs to ensure profitability. On the other hand, the Fixed Capital Investment (FCI) had a minimal impact on NPV sensitivity, with changes of 3 %, 7 %, 2 %, and 1 % for scenarios 1, 2, 3, and 4, respectively, when FCI was altered by  $\pm 25$  %. This minimal impact further illustrates the project's robustness and its relative insensitivity to plant purchasing costs.

Furthermore, alterations in the costs of magnetic biochar and  $\text{MgCl}_2$  in scenario 4 resulted in negligible changes in NPV (0.2 % and 0.3 %), while scenarios 1 and 2 reported a 0 % change for a  $-25$  % alteration due to the absence of these raw materials in these scenarios. Similar observations were made for all cases with zero change.

## 4. Conclusion

This study presents the first comprehensive techno-economic evaluation of integrating hydrothermal treatment (HT), adsorption, precipitation, and anaerobic digestion (AD) for sewage sludge management. Our analysis revealed that the HT unit was the largest energy consumer, requiring 1337.5 MW in scenarios 3 and 4. However, approximately 50 % of this energy was recovered through a heat exchanger, supporting the preheating of waste-activated sludge (WAS) and other plant operations. Future research should focus on enhancing HT insulation and heat integration to minimise heat losses and energy demands.

Economically and environmentally, integrating AD with HT and struvite fertiliser production demonstrated clear advantages.

**Table 5**  
Major parameters in economic analysis.

| Parameter                                    | Scenario 1  | Scenario 2 | Scenario 3 | Scenario 4 |
|----------------------------------------------|-------------|------------|------------|------------|
| Total Purchase Cost of Major Equipment (PCE) | \$220       | \$1 976    | \$2 075    | \$2 358    |
| VARIABLE COSTS                               | \$4 120     | \$6 144    | \$6 592    | \$7 967    |
| Raw materials and utilities (\$)             | 131.80      | 582.22     | 182.77     | 622.77     |
| Annual cost of operating labour (\$)         | \$90 720.00 | \$7 510    | \$191      | \$231      |
| Direct production cost (\$)                  | \$4 323     | \$6 689    | \$7 246    | \$8 738    |
| Indirect Production cost (\$)                | 404.91      | 421.85     | 615.47     | 294.09     |
| Annual Production Costs (\$)                 | \$371       | \$821      | \$932      | \$1 103    |
| Break-even production                        | 754.87      | 459.85     | 180.66     | 657.97     |
| ROI                                          | \$4 695     | \$7 510    | \$8 178    | \$9 841    |
| Simple payback period (years)                | 159.77      | 881.70     | 796.13     | 952.06     |
|                                              | \$13 774    | \$15 300   | \$12 247   | \$13 772   |
|                                              | 382.53      | 955.85     | 240.99     | 085.63     |
|                                              | -78.29 %    | -67.65 %   | -10.37 %   | 45.04 %    |

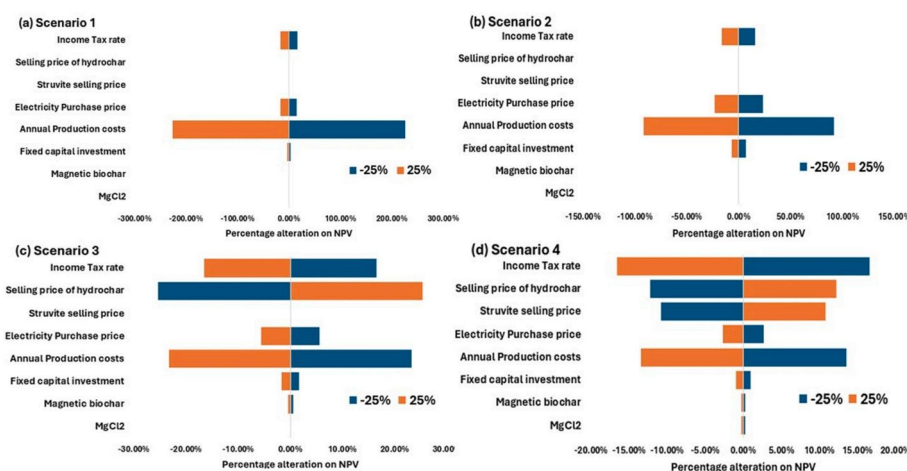


Fig. 5. Sensitivity analysis for various scenarios (a) Scenario 1 (b) Scenario 2 (c) Scenario 3 (d) Scenario 4.

Profitability could further improve with a more sustainable source of magnesium ions. Biomethane production was consistent across all scenarios, with HT substantially reducing production costs to \$2883.85, \$473.72, \$619.00, and \$337.49 per ton in cases 1, 2, 3, and 4, respectively.

This study concludes that integrating AD with HT and advanced valorisation technologies is essential for improving profitability in waste management. This combined approach not only addresses wastewater treatment challenges but also advances circular economy objectives by converting waste into valuable resources. Economic indicators highlight scenario 4 as particularly cost-effective, based on projected expenses, revenues, and investments. Nevertheless, the analysis relied on a Class 5 capital cost estimate ( $\pm 50\%$ ), suggesting the need for further technical advancements to optimise costs, and the study recommends the use of higher accuracy estimation classes as more data is availed, even through pilot scale operations.

The findings indicate that the integrated process of HT, toxin removal, and struvite precipitation with AD is technically and economically superior to standalone AD methods. However, limited research exists on the anaerobic digestion of effluent post-precipitation, necessitating further investigations into potential benefits and challenges during scale-up. Sensitivity analysis revealed that income tax significantly impacts process economics, with scenario 4 being the least affected by variations in material and utility costs.

This research contributes to understanding HT's potential for sustainable wastewater recycling and resource recovery. By prioritising environmental sustainability and resource efficiency over profit, this study aligns with the triple-bottom-line approach, promoting a more sustainable strategy. The findings enrich ongoing research in sustainable wastewater utilisation, addressing critical global issues of water scarcity and environmental pollution.

#### 4.1. Policy recommendations

- Policymakers and authorities in regions with constrained resources should consider incentivising integrated waste management technologies, such as HT-AD systems, which provide dual benefits of waste reduction and resource recovery, aligning with SDGs on clean water (SDG 6) and climate action (SDG 13) and enhance economic resilience.
- There is a need for the formulation of policies on technology transfer, procurement, and implementation by government agencies and funding institutions to support the deployment of HT-AD systems. This could encompass tax incentives, subsidies, or grants to offset start-up capital costs, most importantly for wastewater treatment facilities in developing areas.

- Cooperation with academic and research institutions may facilitate the continuation of these programs for refining and fine-tuning these technologies, ensuring they remain cost-effective and environmentally sustainable in diverse local contexts. That presents a major shift towards the sustainable and effective use of the circular economy principle for waste management with broad-reaching benefits for both environmental health and economic growth.

#### 4.2. Limitations

- Only conduction was considered in heat loss calculations for the hydrothermal reactor (HTR), which may affect the accuracy of profitability estimates.
- Equipment quotations were not sourced from official vendors, and duty tax was not included. Additionally, the commercialisation of HT may face regulatory and market acceptance challenges.
- It was beyond the scope of this to address the treatment of used magnetic biochar (MBC) after adsorption, which may pose secondary pollution risks if not properly managed and hence have an overall impact on the technoeconomic evaluations.
- There is limited large-scale, long-term data on integrating HT with toxin removal, struvite precipitation, and anaerobic digestion, making it difficult to predict long-term operational efficiency and maintenance needs.
- The study was designed to aim at sustainability and resource recovery as the key objectives; many times, satisfying the triple bottom-line objectives will not be easy. There could be some compromises, and managing to balance the results in all three aspects can be quite difficult. The life cycle assessment related to this study was conducted somewhere else [82].

#### CRediT authorship contribution statement

**Boldwin Mutsvene:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Maggie Chetty:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Faizal Bux:** Writing – review & editing, Supervision, Software, Resources, Funding acquisition, Formal analysis. **Sheena Kumari:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation.

#### Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly to improve the grammar of the write-up. After using this tool/service, the

author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cscee.2025.101182>.

## Data availability

Data will be made available on request.

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