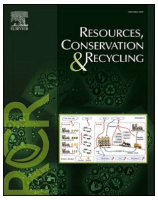
Resources, Conservation & Recycling 204 (2024) 107496

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec



Life cycle assessment of traditional and innovative sludge management scenarios in Australia: Focusing on environmental impacts, energy balance, and economic benefits

Zhenyao Wang [a], Xuan Li [a,*], Huan Liu [a], Jibin Li [a], Dan Cristian Vodnar [b], Carol Sze Ki Lin [c], Qilin Wang [a,*]

[a] *Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology Sydney, Ultimo, NSW 2007, Australia*
[b] *Department of Food Science and Technology, Life Science Institute, University of Agricultural Sciences and Veterinary Medicine, Calea Mănăştur 3-5, Cluj-Napoca, 400372, Romania*
[c] *School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, China*

ARTICLE INFO

Keywords:
Life cycle assessment
Sewage sludge
Lignosulfonate
Anaerobic digestion
Aerobic composting
Sensitivity analysis

ABSTRACT

Sludge, as a sustainable energy source and pollutant matrix, necessitates effective management. The environmental, energy and economic impacts of sludge management practices in Australia remained unknown. Furthermore, lignosulfonate addition was recently reported as a promising approach to enhance the energy production from sludge, the environmental, energy and economic benefits of which on sludge management have not been explored. Life cycle assessment of four scenarios: two traditional (A: land application of digested sludge, B: composting of digested sludge before land application) and two innovative (A and B with lignosulfonate addition during the digestion process - C and D) was conducted. Traditional scenario A outperformed scenario B, with a 2.24-fold reduction in environmental footprints, 16.28-fold higher energy recovery, and reduced expenditure reaching $78.23/t dry sludge (DS). Scenario C demonstrated superior results with a 1.26-fold decrease in environmental footprints, 1.51-fold more energy recovery than A, and a shift to economic benefits of $5.36/t DS. Sensitivity analysis revealed scenario C was sensitive to sludge's total and volatile solids content, highlighting the importance of optimization for best performance. These findings guide environmentally and economically viable sludge management, emphasizing efficient energy recovery.

1. Introduction

Sewage sludge, being the byproduct of sewage treatment plants, is generated extensively, with Australia alone producing approximately 327,000 tons of sludge (dry weight) in 2017 (McGrath et al., 2020). With the rapid development of industrialization and urbanization, coupled with a significant population increase, the production amount of sewage sludge has remarkably increased in recent years (Ghanbari et al., 2021; Seleiman et al., 2020; Wang et al., 2017). Sewage sludge has a dual nature, being a pollutant for the environment due to the presence of numerous contaminants, such as pathogens, metal ions, polycyclic hydrocarbon, and other toxic substances (Li et al., 2021; Wang et al., 2024, 2023c; Zhou et al., 2024), but also a carbon source and nutrients for energy recovery and valuable fertilizer for plant growth (Khan et al., 2023; Li et al., 2023b). Furthermore, sludge treatment/disposal is expensive, accounting for up to 60 % of the total operational costs for sewage treatment plants (Wang et al., 2023a). Therefore, effective management of sewage sludge is crucial for environmental, energy, and economic considerations.

In Australia, anaerobic digestion stands out as the predominant technical option for sewage sludge treatment, with around 31 % of sewage treatment plants adopting this approach (Fig. S1) (Paul and Trevor, 2011). Anaerobic digestion can not only remarkably decrease the volume of sewage sludge (Li et al., 2023a; Liu et al., 2024) but also mitigate potential environmental and human health risks associated with pathogens (Wang et al., 2023d). Moreover, the end product of biogas obtained from anaerobic digestion can be further utilized for heat and electricity production (Zareh et al., 2018). After anaerobic digestion, about 70 % of digested sludge is directly used on land, while 25 % undergoes aerobic composting before being applied to the land (Paul

---

* Corresponding authors.
E-mail addresses: Xuan.Li@uts.edu.au (X. Li), Qilin.Wang@uts.edu.au (Q. Wang).

https://doi.org/10.1016/j.resconrec.2024.107496
Received 9 January 2024; Received in revised form 12 February 2024; Accepted 12 February 2024
Available online 22 February 2024

and Trevor, 2011). The application of digested sludge residue on land not only provides nutrients to the soil but also helps reduce the need for synthetic chemical fertilizers, contributing to sustainable agriculture practices (Kumar et al., 2017). The effective management of sludge is thus imperative to achieve environmental, energy and economic benefits.

Life cycle assessment and costing are recognized as standardized and multicriteria tools for comprehensive environmental and economic impact assessments in sludge management (Hong et al., 2009; Medina-Martos et al., 2020). For example, a previous study assessed the economic and environmental impacts of six sludge management strategies most frequently adopted by Japan (Hong et al., 2009). Medina-Martos et al. (2020) compared the integrated anaerobic digestion and hydrothermal processes for sludge treatment and disposal from the same perspectives (Medina-Martos et al., 2020). However, a detailed analysis focusing on existing sludge treatment and disposal practices in Australian sewage treatment plants, is yet to be conducted. Moreover, life cycle inventory data in previous studies often derived from literature or previous reports rather than actual operational data from sewage treatment plants (Hong et al., 2009; Medina-Martos et al., 2020). Additionally, while assessing the impacts of economic and environmental factors, cumulative energy demand analysis, an essential indicator for evaluating energy-saving potentials, has been widely employed to determine energy balance in sludge management (Chen et al., 2019). Nonetheless, comprehensive research that concurrently addresses energy, environmental, and economic impacts in sludge management remain scarce.

Furthermore, the complex sludge flocs structure often leads to restricted anaerobic digestion performance, compromising sludge treatment effectiveness and influencing sludge disposal direction, especially with potentially adverse environmental impacts (Nguyen et al., 2021). Recently, our previous research introduced an innovative sludge treatment approach by adding lignosulfonate into the anaerobic digestion process, resulting in a 22.2 % enhancement in methane production compared to the control group (Wang et al., 2023a). Meanwhile, the digested sludge residues benefit agricultural applications by promoting plant growth (Wang et al., 2023a, 2023b). Although the promising performance was achieved through lignosulfonate addition, the environmental impacts, energy balance, and economic benefits of our approach remain unknown.

This study aims to investigate and compare the environmental, energy, and economic impacts of existing sludge management practices in Australia, and the potential improvement caused by the lignosulfonate addition approach. Four sludge management approaches in Australia without and with the integration of lignosulfonate in the anaerobic digestion process were systematically evaluated using life cycle assessment, with special focus on environment, cumulative energy demand, and economy. The sensitivity analysis was also conducted based on the optimal scenario for sludge management, with parameters including volatile solids and total solids content of sewage sludge. The findings of this study offer valuable scientific insights into sludge treatment and disposal strategies that minimize environmental impact and maximize resource recovery, aiming for comprehensive sustainability across environmental, energy, and economic dimensions.

2. Materials and methods

2.1. Functional unit

The chosen functional unit in this work is 1 ton of dry sludge (DS). All calculations related to chemical consumption, energy input/output, and

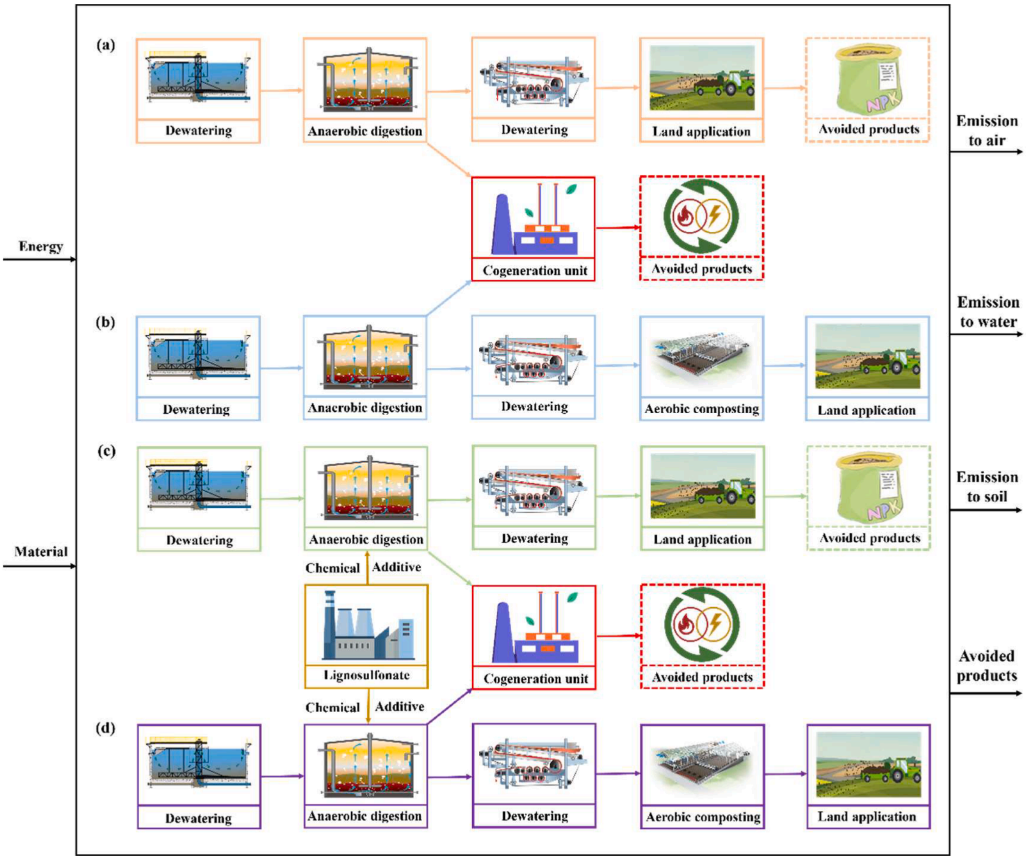


Fig. 1. System boundary for the four sludge management scenarios: (a) and (b) depict traditional sludge management scenarios commonly employed by sewage treatment plants in Australia; (c) and (d) represent proposed innovative sludge management with lignosulfonate addition during anaerobic digestion process, sharing the same unit processes as those in (a) and (b), respectively.

emissions throughout the entire sludge management scenario were conducted using this functional unit.

2.2. System boundary

Four scenarios for sludge management were considered in this study (Fig. 1a-d). The detailed subprocesses of each sludge management scenario are outlined below (1) thickening, anaerobic digestion, cogeneration unit, dewatering, land application (A); (2) thickening, anaerobic digestion, cogeneration unit, dewatering, aerobic composting, and land application (B); (3) thickening, anaerobic digestion with lignosulfonate addition, cogeneration unit, dewatering, land application (C); and (4) thickening, anaerobic digestion with lignosulfonate addition, cogeneration unit, dewatering, aerobic composting, and land application (D). The system boundaries included various elements, including energy, materials, avoided products (i.e., energy recovery, fertilizers), and emissions (i.e., air, soil, and water). This study did not consider the environmental impacts of the construction and installation of treatment facilities in sewage treatment plants, given that numerous studies have indicated their negligible contribution to the overall environmental footprint (Singh et al., 2020).

2.3. Data sources

2.3.1. Thickening

The initial solid content of the sewage sludge was 1 %, which was subsequently increased to 5 % (sourced from the operational data of Sydney Water) following the thickening process (Water, 2020). Polyacrylamide, commonly added at a dosage of 3.5 kg/t DS, was employed in the thickening process to enhance flocculation and optimize solid-liquid separation (Water, 2020).

2.3.2. Anaerobic digestion

The input volatile solids content of sewage sludge in the anaerobic digestion process was set as 80 % based on our previous study (Wang et al., 2023a). The initial temperature of the sewage sludge was set as 18 ℃ to match the annual average temperature of Sydney, New South Wales, Australia (sourced from Google), and the anaerobic digestion temperature of the local sewage treatment plant was maintained at 35 ℃. The anaerobic digestion efficiency for both traditional and innovative sludge management scenarios (without and with lignosulfonate addition) was according to our previous study, with values of 33.0 % and 40.3 %, respectively (Wang et al., 2023a). Biogas composition, as measured in our earlier experiments (Text S1), includes CH_4 (60 %), CO_2 (35 %), N_2 (1.2 %), H_2 (1.2 %), and H_2S (0.05 %). Notably, there was no remarkable difference in biogas composition between the traditional and innovative sludge management scenarios (Wang et al., 2023a). Additionally, the biogas leakage during the anaerobic reactor was estimated at 3 % (consultation with the technician from the local sewage treatment plants). The heat and electricity demand calculation during anaerobic digestion was performed based on Section 2.4.2.

2.3.3. Cogeneration unit

Local sewage treatment plants commonly utilize the JMS 420 GS-B.L cogeneration unit, simultaneously converting biogas into heat and power (Water, 2020). The overall efficiency of this cogeneration unit was 69.6 %, with 42.7 % converted to electricity and the remaining portion transformed into heat (Jenbacher, 2023). Additionally, the specific consumption of lubricating oil during the operation of the cogeneration unit was 2.0×10^{-4} kg/kWh of electricity production from biogas combustion (Jenbacher, 2023). The calorific value of biogas during the combustion process was approximately 23 MJ/m^3 (equal to 6.39 kWh/m^3) (Alex and William, 2021). It is important to note that there are also emissions of exhaust gases during biogas combustion, including CO_2, CO, SO_2, CH_4, NO_x, NO, N_2O, and particulate matter (Alengebawy et al., 2022). The specific emission factors are shown in Table S1 of Supplementary Materials.

2.3.4. Dewatering

Electricity consumption during the dewatering process was computed using Eq. (1), as outlined in Section 2.4.1. The dosage of flocculant (polyacrylamide) used to improve the dewaterability of digested sludge was 5.5 kg/t DS (Water, 2020).

2.3.5. Aerobic composting

Data on diesel (9.6 kg/t DS) and electricity consumption (534 kWh/t DS) during aerobic composting were obtained from a preceding study (Zhuang, 2021). Moreover, information on avoided product production (NPK 15–15–15) and emission factors for exhaust gases (i.e., CH_4, N_2O, and CO_2) were also extracted from the same research.

2.3.6. Land application

The transportation distance from the sewage treatment plant to the sludge land application site was approximately 250 km (Paul and Trevor, 2011). Moreover, the percentage of nitrogen, phosphorus, and potassium content in dewatered sludge was 4 %, 2.5 %, and 1.5 %, respectively (Paul and Trevor, 2011). The permissible limits for metal ions in digested sludge and composted sludge for land application were in accordance with government official documents (Authority, 2019; Chye and John, 2000). Applying digested or composted sludge can also release pollutants into the surrounding environment, including air, water, and soil (do Amaral et al., 2018), and the specific emission factors related to this process are outlined in Table S1 of Supplementary Materials.

2.4. Unit process and inventory analysis

2.4.1. Dewatering

The energy consumption of the mechanical dewatering process was calculated using Eq. (1):

$$E = E\_Coeff \times \left(\frac{1}{w_1} - \frac{1}{w_2}\right) \tag{1}$$

where E means energy consumption during the dewatering process (kWh), E_Coeff represents the coefficient of energy consumption, with a value of 0.632 kWh/t DS, and w_1 and w_2 denotes solid content in sludge before and after the dewatering process, respectively.

2.4.2. Anaerobic digestion

The anaerobic digestion process demands a substantial energy input to maintain system operation, and the input energy was computed based on Eq. (2):

$$P = C_s \times (M_s + M_w) \times (T_A - T_s) \tag{2}$$

where P means the theoretical heat demand for sustaining the operation of anaerobic digestion (MJ), C_s represents the heat capacity of the sewage sludge, equal to 4.186 $MJ/(t \times K)$ (Wang et al., 2023), M_s and M_w represent the mass of sludge (DS) and water that was entering anaerobic digestion (t), respectively, T_A and T_s denote the anaerobic digestion temperature (35 ℃), and sludge temperature (18 ℃, equivalent to the average temperature of Sydney).

The actual energy demand during the anaerobic digestion process was calculated using Eq. (3):

$$P' = \frac{P}{\alpha} \tag{3}$$

where P' represents the actual energy demand for maintaining the operation of anaerobic digestion (MJ), and α means the conversion coefficient between actual and theoretical energy demand during anaerobic digestion, with a value of 80 % (consultation with the technician from the local sewage treatment plants).

2.4.3. Cogeneration unit

The volume of biogas produced during the anaerobic digestion process was calculated according to Eq. (4):

$$V_{biogas} = 0.35 \times D_{\mathrm{COD}} \tag{4}$$

where V_{biogas} means the yield of biogas volume (m^3), D_{COD} represents the degraded chemical oxygen demand of sludge during anaerobic digestion process (kg), and its calculation was based on Eq. (5), 0.35 denotes the conversion coefficient between biogas volume and degraded chemical oxygen demand (m^3/kg COD) (Zhao et al., 2023).

$$D_{\mathrm{COD}} = 1.42 \times Eff \times M_s \times VS \tag{5}$$

where *Eff* represents the anaerobic digestion efficiency, M_s denotes the dry solid of sludge entering the anaerobic digestion process (kg), and VS means sludge volatile content (%).

Heat and electricity production during the cogeneration unit (JMS 420) was calculated based on Eqs. (6), (7):

$$P_{Heat} = V_{\mathrm{biogas}} \times CV_{\mathrm{biogas}} \times Eff\_\mathrm{heat} \tag{6}$$

$$P_{electricity} = V_{\mathrm{biogas}} \times CV_{\mathrm{biogas}} \times Eff\_\mathrm{electricity} \tag{7}$$

where P_{heat} (MJ) and $P_{\mathrm{electricity}}$ (kWh) mean heat and electricity production during cogeneration unit, CV_{biogas} represents the calorific value of biogas, with the value of 6.39 kWh/m^3 (Alex and William, 2021), *Eff*_heat and *Eff*_electricity mean the heat and electricity conversion coefficient during cogeneration unit, equal to 26.9 % and 42.7 %, respectively, according to the technical description of JMS 420 (Jenbacher, 2023).

2.5. Methodology for environmental analysis

Previous studies have commonly utilized the ReCiPe Midpoint method to assess potential environmental impacts stemming from sludge treatment and disposal (Corbala-Robles et al., 2018; Gourdet et al., 2017; Mayer et al., 2021), highlighting its effectiveness. In alignment with this established practice, the ReCiPe 2016 Midpoint method in SimaPro 9.4.0.1 was chosen to evaluate the environmental impacts of the four sludge management scenarios (traditional and innovative) mentioned above. From the eighteen impact categories in the ReCiPe method, six most pertinent to sludge treatment and disposal were selectively focused on, as consistently highlighted in prior studies (Corbala-Robles et al., 2018; Gourdet et al., 2017; Mayer et al., 2021). These quantified impact categories encompass global warming, terrestrial acidification, freshwater eutrophication, human carcinogenic toxicity, human non-carcinogenic toxicity, and fossil resource scarcity. Moreover, the impact magnitude within each category was characterized using equivalence (eq) factors. Specifically, CO_2 eq, SO_2 eq, phosphorus (P) eq, and oil eq were applied for global warming, terrestrial acidification, freshwater eutrophication, and fossil resource scarcity, respectively. Additionally, 1,4-Dichlorobenzene (1,4-DCB) was utilized for representing both human carcinogenic and non-carcinogenic toxicity. Furthermore, life cycle inventory data for the four sludge management scenarios were detailed in Table S1. Additionally, normalization results were obtained by comparing characterization results with normalization reference values (provided by SimaPro software). The overall environmental impact results were the sum of the normalized results for the selected impact categories.

2.6. Methodology for energy analysis

In this study, cumulative energy demand for the four sludge management scenarios was calculated to evaluate the net energy balance of each sludge treatment and disposal scenario. The data collected was based on the information presented in Sections 2.3 and 2.4.

2.7. Methodology for life cycle costing analysis

The life cycle costing analysis for the four sludge management scenarios was conducted based on the cost per treated ton of DS. This approach aligns with the principles outlined in ISO 14,040, an internationally standardized method. The life cycle costing was computed according to Eq. (8) (Awad et al., 2019):

$$LCC = AAC + MC + ODC \tag{8}$$

where *ACC, MC*, and *ODC* represent actual amortization costs, maintenance costs, and operation & disposal costs, respectively. Noteworthy, *MC* was assumed to be 2 % of the amortization costs, according to a previous study (Awad et al., 2019). *ODC* encompassed raw materials consumption (i.e., chemicals), energy consumption (i.e., electricity, heat), and the disposal of sludge (i.e., land application), and the specific costs for *ODC* were detailed in Table S2. Labor costs were excluded in this study due to significant variations based on plant locations. Notably, the *AAC was* calculated based on Eq. (9):

$$AAC = IAC \times \left(\frac{(1+IR)^L \times IR}{(1+IR)^L - 1}\right) \tag{9}$$

where *IAC* denotes initial amortization costs, derived by dividing the initial investment for constructing a sewage treatment plant (excluding land cost) by the amount of treated sludge during the 20-year lifespan (*L*) (Table S2). *IR* represents the interest rate in Australia, set at 4.1 % (sourced from google).

2.8. Sensitivity analysis

The sensitivity analysis aimed to assess parameters that significantly influence the outcomes of environmental impacts. This study focused on two crucial parameters: the volatile and total solid contents of the sewage sludge, ranging from 50 % to 80 % and 4 % to 7 %, respectively. The specified range was confirmed through communication with the local sewage treatment plant technician. Additionally, previous studies have highlighted that anaerobic digestion efficiency is a critical factor influencing assessment outcomes (Zhao et al., 2023). However, it is crucial to emphasize that this study aims to evaluate the economic benefits, energy balance, and environmental impacts of traditional and innovative sludge management scenarios. The innovative scenarios involve introducing lignosulfonate in the anaerobic digestion process, informed by our previous studies indicating its positive impact on anaerobic digestion efficiency (Wang et al., 2023a). Consequently, anaerobic digestion efficiency was not taken into account in our study. Additionally, it is essential to highlight that the volatile and total solid contents of the sewage sludge were adjusted within a 10 % interval to reveal their impact on the assessment outcomes.

3. Results and discussion

3.1. Life cycle environmental impacts based on four sludge management scenarios

3.1.1. Characterization results of four sludge management scenarios

1) Global warming

The traditional sludge management scenarios in Australia (A and B), resulted in 5.37 % and 6.22 % lower global warming burdens, respectively, than their corresponding innovative approach using lignosulfonate addition in anaerobic digestion (C verses A and D verses B) (Fig. 2a). Additionally, scenarios with aerobic composting (B and D), exhibited environmental burdens 6.40-fold and 6.38-fold higher, respectively, than those without aerobic composting (A and C). Scenario A displayed the lowest environmental burdens in terms of global

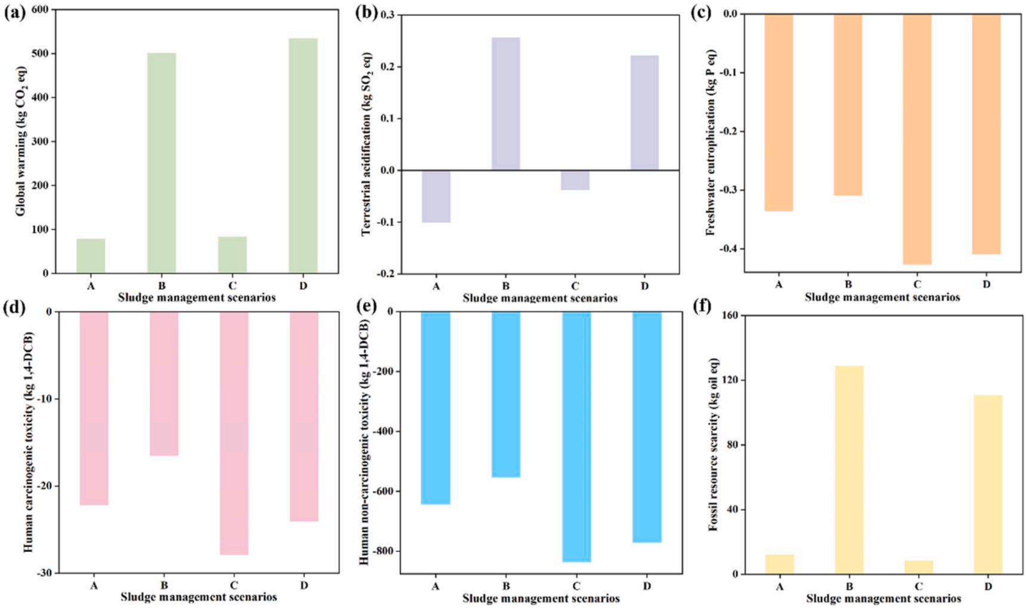


Fig. 2. Characterization results for each sludge management scenario across various environmental impact categories: (a) Global warming; (b) Terrestrial acidification; (c) Freshwater eutrophication; (d) Human carcinogenic toxicity; (e) Human non-carcinogenic toxicity; and (f) Fossil resource scarcity. Note: A: Thickening, anaerobic digestion, cogeneration unit, dewatering, and land application; B: Similar to A but additionally included aerobic composting before land application; C/D: Similar to A/B, but incorporated lignosulfonate during anaerobic digestion.

warming, with a value of 78.28 kg CO_2 eq, followed by scenario C (82.71 kg CO_2 eq). In contrast, scenarios B and D presented higher values, reaching up to 500.66 kg CO_2 eq and 533.91 kg CO_2 eq, respectively. These findings were in accordance with a previous study, which indicated that the aerobic composting steps were energy-intensive processes, entailing substantial fossil fuel energy consumption (Pace et al., 2018), consequently leading to additional greenhouse gas emissions, as observed in scenarios B and D.

In addition, within the sludge management process, anaerobic digestion (163.25 kg CO_2 eq in scenarios A and B, 184.53 kg CO_2 eq in scenarios C and D) and aerobic composting processes (192.13 and 239.27 kg CO_2 eq in scenarios B and D, respectively) were identified as the most significant contributors to global warming (Fig. S2). Although the cogeneration unit process reduced greenhouse gas emissions by 89.55 kg CO_2 eq in scenarios A and B to 111.16 kg CO_2 eq in scenarios C and D through energy recovery (i.e., heat and power), it cannot fully offset the emissions caused by anaerobic digestion and aerobic composting. Furthermore, thickening and dewatering processes across all sludge management scenarios resulted in increased environmental burdens in the global warming category, amounting to 27 kg CO_2 eq and 29 kg CO_2 eq, respectively (Fig. S2a). These findings align with those presented by Kamizela and Kowalczyk (2019), suggesting that the contribution of thickening and dewatering processes to global warming was much lower than that of anaerobic digestion and cogeneration units.

2) Terrestrial acidification

The impact of terrestrial acidification resulting from sludge management follows the order A<C<D<B, from the most negative impact to the positive effects: A (−0.10 kg SO_2 eq), C (−0.038 kg SO_2 eq), D (0.22 kg SO_2 eq), and B (0.26 kg SO_2 eq). Scenarios B and D, with aerobic composting unit, elevated the burden of terrestrial acidification by 353.49 % and 689.33 %, respectively, compared to their corresponding management approaches without aerobic composting unit (A verses C, B verses D) (Fig. 2b). Scenario C exhibited a 62.77 % reduction in effectiveness in mitigating terrestrial acidification than scenario A, while scenario D showed a 13.48 % decrease in this impact category compared to scenario B (Fig. 2b). Scenarios A and C demonstrated environmental benefits by mitigating terrestrial acidification impacts in sludge management, with scenario A showed the maximum mitigation effect compared to scenario C (Fig. 2b). A previous study defined terrestrial acidification as the phenomenon where atmospheric acidic substances like sulfides and nitrogen oxides deposit onto the soil surface or are washed into surface waters (Tasca and Puccini, 2019). The high energy consumption, particularly from fossil fuels during the composting process results in higher emissions of nitrogen and sulfide oxides, thus heightening the terrestrial acidification burden in scenarios B and D. Moreover, the production of lignosulfonate also involved the release of acidic gases (Tsvetkov and Salganskii, 2018), which can explain less effectiveness mitigation of terrestrial acidification in scenario C than in scenario A (−0.10 kg SO_2 eq VS −0.038 kg SO_2 eq). Conversely, scenario D with lignosulfonate addition showed a smaller increase in terrestrial acidification than scenario B (Fig. 2b). This can be attributed to high energy recovery (268.68 kWh in scenario D versus 25.72 kWh in scenario B), reduced fossil fuel use and mitigating the negative environmental impacts from lignosulfonate production.

Among the four scenarios for sludge management, the cogeneration unit played a dominant role in mitigating terrestrial acidification impacts, with values ranging from −0.48 kg SO_2 eq to −0.56 kg SO_2 eq (Fig. S2b). Moreover, the land application process was pivotal in amplifying terrestrial acidification in scenarios A and C, with values of 0.16 kg SO_2 eq and 0.14 kg SO_2 eq, respectively. This can be ascribed to the emission of ammonia (NH_3, 3.75 kg in scenario A verses 3.45 kg in scenario C) followed by the emission of dinitrogen (N_2O, 0.11 kg in scenario A verses 0.10 kg in scenario C) during the land application of digested sludge (Neumann et al., 2022). Notably, the combined impact of land application and aerobic composting processes increased this impact category positivity in scenarios B and D, with values of 0.29 kg SO_2 eq and 0.22 kg SO_2 eq for scenario B and 0.26 kg SO_2 eq and 0.14 kg SO_2 eq for scenario D.

3) Freshwater eutrophication

All four sludge management scenarios mitigated the risk of freshwater eutrophication, with innovative methods C and D, performing 27.13 % and 32.42 % greater effectiveness, respectively, compared to traditional approaches A and B (Fig. 2c). Furthermore, scenarios without aerobic composting process (A and C) demonstrated improved effectiveness, with enhancements of 8.55 % and 4.16 %, respectively, over those including aerobic composting (B and D) (Fig. 2c). The specific order of the four sludge management scenarios in reducing freshwater eutrophication impacts was: C<D<A<B, with values of −0.43, −0.41, −0.34 and −0.31 kg P eq, respectively (Fig. 2c). The enhanced performance of innovative scenarios C and D in mitigating freshwater eutrophication can be attributed to lignosulfonate addition. This additive not only improved the breakdown of organic matter, decreasing the release of untreated substances and nutrients (i.e., N and P) into the environment, but also elevated sludge quality for land application, thus minimizing nutrient loss when used as soil amendment or fertilizer (Usman et al., 2012). Moreover, employing aerobic composting as a post-treatment in sludge management lessened the effectiveness in mitigating freshwater eutrophication (A<B, C<D) (Fig. 2c). This effect was due to the increased levels of soluble nitrogen and phosphorus in the composting process, which enhanced the likelihood of these nutrients leaching from the compost (Liew et al., 2022).

The analysis of each unit process in sludge management for its impact on freshwater eutrophication revealed that the cogeneration unit as a key contributor, with its impact ranging from −0.39 kg P eq in traditional sludge management to −0.48 kg P eq in innovative sludge management scenarios (Fig. S2c). This finding was supported by Gourdet et al. (2017), who noted that cogeneration units could remarkably mitigate the impact of freshwater eutrophication through the reuse of heat and power generated by this unit (Gourdet et al., 2017).

4) Human carcinogenic toxicity

The impacts of the four sludge management scenarios on human carcinogenic toxicity closely align with their effects on freshwater eutrophication, in the order of C<D<A<B (Fig. 2d). Specifically, the mitigation impacts on human carcinogenic toxicity were −22.15, −16.50, −27.85, and −24.01 kg 1,4-DCB for scenarios A, B, C, and D, respectively (Fig. 2d). In these scenarios, the innovative methods (C and D) outperformed their corresponding traditional ones (A and B) by 25.62 % and 45.52 %, respectively. This enhanced performance was largely attributed to improved anaerobic digestion efficiency, leading to fewer metal ions remaining in the sludge (Geng et al., 2022). This, in turn, minimizes their release into the environment, consequently reducing human carcinogenic toxicity. Additionally, scenarios that excluded aerobic composting (A and C) showed superior performance, enhanced effectiveness by 34.24 % and 15.99 %, respectively, compared to those including it (B and D), (Fig. 2d). This is primarily due to the elevated concentration of heavy metals, such as nickel, cadmium, and mercury, which were key contributors to human carcinogenic toxicity (Mayer et al., 2021). Anaerobic digestion has been shown to increase the bioavailability of heavy metal ions, like nickel, cadmium, by approximately 50 %, leading to a significant reduction and stabilization of residual metal ions in the sludge (Dong et al., 2013). In contrast, the concentration of cadmium and nickel raised by 36.0 % and 30.4 % during aerobic composting (Zheng et al., 2007), explaining the lower efficacy of scenarios involving composting process in reducing human carcinogenic toxicity. Notably, cogeneration units played a dominant role in mitigating this category across all four sludge management scenarios, with values reaching −24.61 and −30.58 kg 1,4-DCB in scenarios A/B and scenarios C/D, respectively (Fig. S2d). The impact of the residue unit processes in each sludge management scenario was negligible (Fig. S2d).

5) Human non-carcinogenic toxicity

The mitigation impact was higher in innovative sludge management scenarios compared to traditional ones (C/D<A/B), and directly applied digested sludge showed greater effectiveness than further composted sludge (A<B, C<D). The most effective sludge management strategy in reducing the impact category of human non-carcinogenic was scenario C, achieving −834.81 kg 1,4-DCB, followed by scenario D (−769.97 kg 1,4-DCB), A (−643.42 kg 1,4-DCB), and B with the least effect (−552.60 kg 1,4-DCB) (C<D<A<B). Trends in human non-carcinogenic toxicity across the four sludge management scenarios mirror those observed human carcinogenic toxicity, as discussed earlier. Human non-carcinogenic toxicity was largely driven by heavy metals, with zinc contributing approximately 98 % (Mayer et al., 2021). Anaerobic digestion reduced zinc and copper bioavailability in digestates, thereby decreasing environmental risks (Le Bars et al., 2018). Conversely, aerobic composting increased zinc bioavailability (bioavailability factor increased from 14.11 in raw sludge to 22.02 in composted sludge), heightened potential hazards (Miaomiao et al., 2009). Therefore, sludge management scenarios without aerobic composting proved more effective in reducing human non-carcinogenic toxicity.

The cogeneration unit consistently showed the greatest contribution to all sludge management scenarios, accounting for −778.82 kg 1,4-DCB in scenarios A and B, and −967.65 kg 1,4-DCB in scenarios C and D (Fig. S2e). This highlighted the consistent and notable role of the cogeneration unit in mitigating the environmental burden associated with human non-carcinogenic toxicity across all scenarios. Khaki et al. (2023) also observed similar results, noting that the presence of cogeneration unit in sludge treatment process remarkably reduced the impact of human non-carcinogenic by up to 38 % (Khaki et al., 2023).

6) Fossil resource scarcity

Regarding fossil resource scarcity, sludge management scenarios with aerobic composting (B and D) showed a substantial increase in resource usage, at 9.26-fold and 15.30-fold, respectively, compared to those without aerobic composting (A and C). Meanwhile, scenarios C and D reduced dependence on fossil resources by 42.14 % and 16.16 %, respectively, compared to their corresponding traditional ones. Scenario C had the least impact on fossil resource scarcity, followed by scenario A, scenario D, and finally scenario B (C<A<D<B), with values of 8.40, 11.94, 110.61, and 128.48 kg oil eq, respectively. Sludge treatment and disposal scenarios incorporating aerobic composting (B and D) showed a tendency to increase fossil resource scarcity compared to those without it (A and C), primarily due to extensive energy consumption involved in this process (further discussed in Section 3.2) (Pace et al., 2018). Additionally, all the innovative approaches exhibited a lesser reliance on fossil resource than their corresponding traditional approach with the same unit processes (i.e., C<A, D<B). This was primarily due to increased energy recovery in the cogeneration unit, which outweighed the energy consumption required for other processes (the content will be detailed in Section 3.2). Notably, all the innovative approaches led to reduced fossil resource scarcity compared to traditional methods (Fig. 2f), yet in terms of global warming potential, traditional approaches showed lower impacts (Fig. 2a). This finding contradicts previous studies that suggested a proportional relationship between the impact categories of fossil resource scarcity and global warming potential (Mayer et al., 2021). The increased greenhouse gas emissions in innovative approaches can primarily be attributed to the lignosulfonate production process, which led to higher release of greenhouse gases.

Unit process analysis revealed that anaerobic digestion (26.24 kg oil eq) and aerobic composting (75.54–98.79 kg oil eq) predominantly exacerbate fossil resource scarcity, while cogeneration units remarkably mitigate this issue, contributing reductions ranging from −19.14 to 23.79 kg oil eq (Fig. S2f). Notably, characterization results solely determine the impact of different sludge management scenarios on specific environmental impact categories. However, these results did not facilitate a comparison of the relative magnitudes of impact across the selected impact categories. Subsequently, these characterization results underwent normalization, as detailed in Section 3.1.2.

3.1.2. Normalized results of four sludge management scenarios

The relative environmental impact, based on normalized results, was assessed across four sludge management scenarios (both innovative and traditional methods), using the maximum value of impact categories within each management scenario as the baseline (Fig. 3). Human carcinogenic toxicity served as the dominant impact category in all sludge management scenarios. It was thus regarded as the baseline, with a relative impact of −100 %, representing the reference point for other impact categories. All four sludge management technologies discussed in this study contribute to the reduction of human carcinogenic toxicity (Fig. 3a-d). Subsequently, the contribution to freshwater eutrophication was −24.01 %, −29.68 %, −24.27 %, and −27.03 % in scenarios A, B, C, and D, respectively. Additionally, scenarios B and D, which involve aerobic composting, intensified fossil resource scarcity, with relative impacts of 7.04 % and 5.62 %, respectively, while the impact in other categories remained negligible across all sludge management scenarios (A-D).

3.1.3. Total environmental impacts of four sludge management scenarios

The total environmental impacts of the four sludge management scenarios, encompassing both traditional and innovative approaches, were depicted in Fig. 4. The results revealed that those four scenarios all contribute to reducing the environmental burdens caused by sludge management, with values ranging from −1.91 to −3.37 (Fig. 4). Scenario C was the preferred choice for sludge management, minimizing the environmental impact most effectively, evidenced by a value of −3.37. Scenarios A and D demonstrated comparable effects on the total environmental impacts, with respective values of −2.67 and −2.78. However, scenario B exhibited the lowest mitigation effect on environmental impact among the four sludge management scenarios, suggesting that this option was not preferable compared to the other three alternatives.

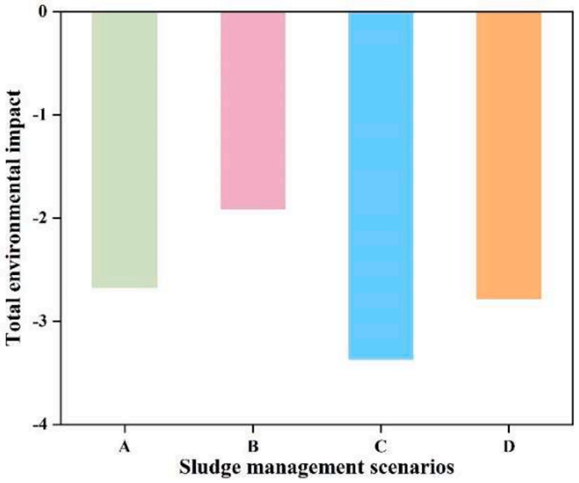


Fig. 4. Total environmental impact of each sludge management scenario. Note: A: Thickening, anaerobic digestion, cogeneration unit, dewatering, and land application; B: Similar to A but additionally included aerobic composting before land application; C/D: Similar to A/B, but incorporated lignosulfonate during anaerobic digestion.

3.2. Energy balance analysis based on four sludge management scenarios

Each of the four sludge management scenarios positively impacts net energy balance, with scenario C leading at 620.81 kWh, making a substantial 1.48-fold to 24.14-fold improvement over other methods (Fig. 5b). The net energy balance was ranked as C>A>D>B, with respective values of 620.81, 418.72, 268.68, and 25.72 kWh (Fig. 5b). Furthermore, the innovative approach (C and D) for sludge management outperformed the traditional methods (A and B), which use the same unit processes, achieving enhancements of 1.48-fold and 10.45-fold, respectively. The superior performance was primarily due to the addition of lignosulfonate in anaerobic digestion, which enhanced methane production (Wang et al., 2023a). This led to heightened energy recovery in cogeneration units, with scenarios A and B achieving 942.86 kWh and

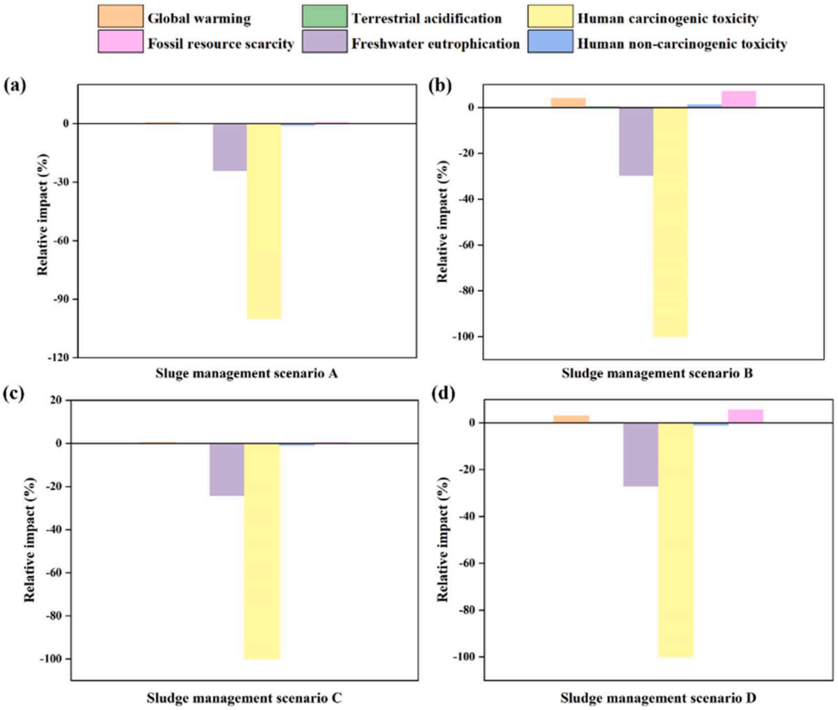


Fig. 3. Relative impact of four sludge management scenarios (traditional and innovative), using the maximum value for each category as the baseline. (a)-(d) represent sludge management scenarios A-D, respectively. Note: A: Thickening, anaerobic digestion, cogeneration unit, dewatering, and land application; B: Similar to A but additionally included aerobic composting before land application; C/D: Similar to A/B, but incorporated lignosulfonate during anaerobic digestion.

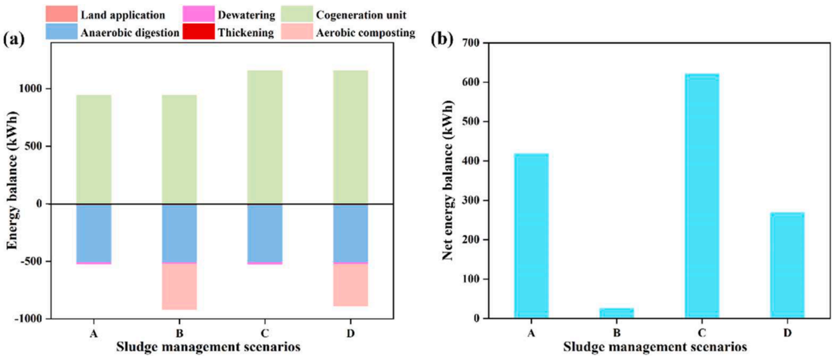


Fig. 5. Energy balance of four sludge management scenarios. (a) Energy balance of unit process of each sludge management scenario; (b) Net energy balance of four sludge management technologies. Note: A: Thickening, anaerobic digestion, cogeneration unit, dewatering, and land application; B: Similar to A but additionally included aerobic composting before land application; C/D: Similar to A/B, but incorporated lignosulfonate during anaerobic digestion.

scenarios C and D reaching 1155.87 kWh (Fig. 5a). Meanwhile, sludge management scenarios without aerobic composting (A and C) surpassed those with this process (B and D), showed enhancements of 16.28 times and 2.31 times, respectively. This phenomenon can be explained by the high energy consumption associated with aerobic composting (Pace et al., 2018), as demonstrated by the energy demands of 393 kWh for scenario B and 361.52 kWh for scenario D, respectively (Fig. 5a).

In scenarios A-D, cogeneration units played crucial roles in energy recovery, contributing 942.86 kWh in scenarios A and B, and 1155.87 kWh in scenarios C and D, respectively (Fig. 5a). Meanwhile, anaerobic digestion in all four scenarios, along with aerobic composting in scenarios B and D were the major energy consumers. Across all scenarios (A-D), anaerobic digestion consumed 496.13 kWh (Fig. 5a), while aerobic composting in scenarios B and D consumed an additional 393 kWh, 361.52 kWh, respectively (Fig. 5a).

3.3. *Life cycle costing analysis based on four sludge management scenarios*

Life cycle costing analysis, including actual amortization costs, maintenance costs, and operational and disposal costs, was conducted to evaluate the economic benefits of each sludge management scenario, as depicted in Fig. 6. Scenario C, with a negative value in life cycle costing, indicated that this approach could generate profits for sewage treatment plants, amounting to $5.36/t (Fig. 6d). The main reason can be attributed to the substantial energy recovery during the cogeneration unit, reaching up to 1155.87 kWh, including 708.65 kWh of electricity and 1610 MJ of heat. This substantial energy recovery greatly reduced overall energy expenditure and enabled surplus electricity to be fed back into the electricity grid. Conversely, the other scenarios all escalated expenses for sewage treatment plants in sludge management, with costs

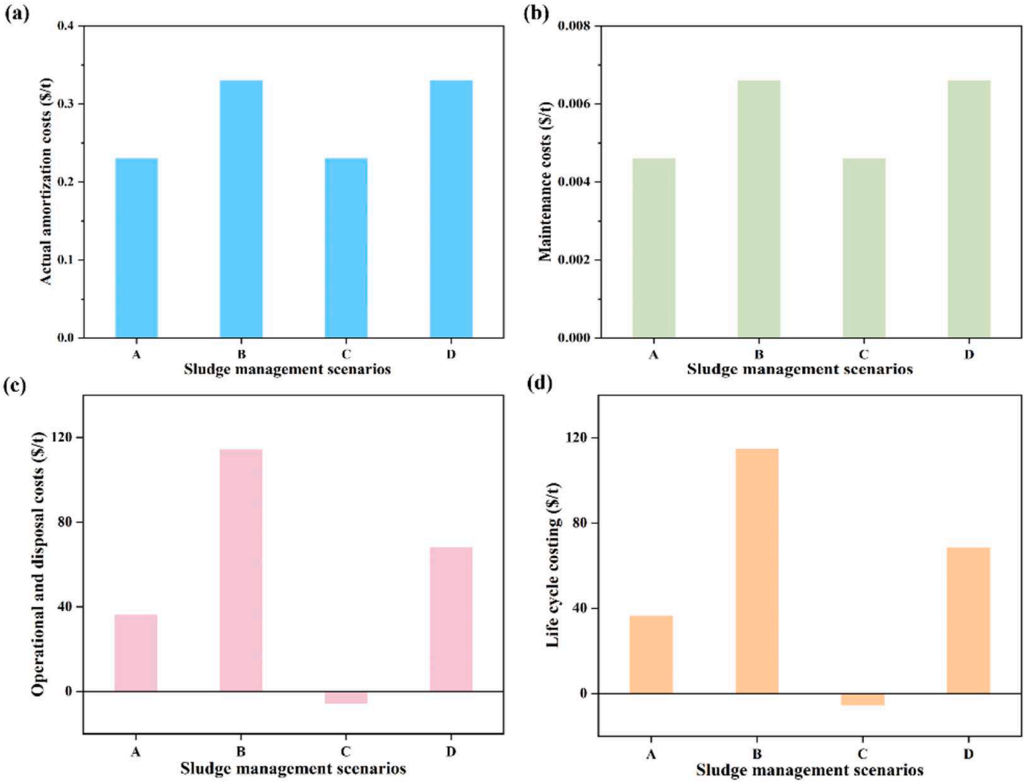


Fig. 6. Economic analysis of different sludge management scenarios. (a) Actual amortization costs; (b) Maintenance costs; (c) Operational and disposal costs; and (d) Life cycle costing. Note: A: Thickening, anaerobic digestion, cogeneration unit, dewatering, and land application; B: Similar to A but additionally included aerobic composting before land application; C/D: Similar to A/B, but incorporated lignosulfonate during anaerobic digestion.

ranging from \$36.29/t to \$114.52/t (Fig. 6d). The operation and disposal costs played a dominant role in the life cycle costing of the four sludge management scenarios A, B, C, and D, with values of \$36.06/t, \$114.18/t, -\$5.59/t, and \$67.92/t, respectively (Fig. 6c). While the expenses associated with actual amortization costs, maintenance costs during sludge treatment and disposal process were negligible in the four sludge management scenarios, with amortization costs and maintenance costs both below \$0.33/t, and \$0.0066/t, respectively (Fig. 6a-b).

3.4. *Comparison of four different management scenarios*

A comprehensive comparison of the four sludge management scenarios, focusing on total environmental impacts (Section 3.1), net energy balance (Section 3.2), and life cycle costing (Section 3.3) simultaneously, was performed and illustrated in Fig. 7. Scenario C exhibited the best performance, followed by scenarios A and D, with scenario B ranking as the least favorable performance. Scenario C (thickening, anaerobic digestion with lignosulfonate addition, cogeneration unit, dewatering, land application) stood out with its maximum net energy balance (630.2 kWh), the only negative value in life cycle costing (-\$5.36/t). This indicates the potential profitability, and the least total environmental impacts (−3.37), highlighting its positive contribution to environmental mitigation for sludge management in sewage treatment plants. Following this, scenario A (sharing identical unit processes with scenario C) exhibited superior performance in total environmental impacts, net energy balance, and life cycle costing, with respective values of −2.67, 418.72 kWh, and \$36.29/t. However, these values remained lower than those of scenario C. Moreover, scenario D exhibited a comparatively modest impact on total environmental categories, life cycle costing, and net energy balance, with values of −2.78, 268.68 kWh, and \$68.26/t, respectively. In contrast, scenario B ranked the least preferable among the four sludge management scenarios, with only a marginal reduction in total environmental impact by 1.91, a minimal net energy balance of 25.72 kWh from sludge treatment and disposal, and a significant increase in expenditure on the sludge of sewage treatment plants, reaching up to \$114.52/t. These findings suggested that the innovative scenario was preferable for sludge management within the treatment and disposal scenarios sharing the same unit processes (i.e., C>A, D>B). Additionally, scenarios without the aerobic composting process outperformed those with post-treatment aerobic composting in terms of total environmental impacts, life cycle costing, and net energy balance (i.e., C>D, A>B). Therefore, for future sludge management, dewatering, anaerobic digestion with lignosulfonate addition, dewatering, and land application is more preferred.

3.5. *Sensitivity analysis*

The sensitivity of volatile and total solid contents of sewage sludge on the impacts of environmental, energy balance, and economic was assessed using scenario C, given its proven best performance for sludge management scenario as elaborated in Sections 3.1–3.4. The increase of volatile solids content from 50 % to 80 % reduced the total environmental impacts and life cycle costing, while simultaneously increased energy benefits (Fig. 8a-c). Specifically, increasing the volatile solids content from 50 % to 80 % led to a 1.22 to 1.69 times enhancement in environmental impacts reduction, transformed costs from \$71.65/t to a benefit of \$5.36/t, and improved net energy balance by 1.71 to 3.16 times (Fig. 8a-c). The reduction in total environmental impacts can be primarily attributed to cogeneration units (Fig. S3), which had high energy recovery (ranging from 722.26 kWh to 1155.87 kWh) resulting from the degradation of organic matter (Fig. S5a). This process not only diminished the dependence on fossil-based fuels but also generated surplus electricity that can be integrated into the electricity grid, consequently yielding economic benefits for sewage treatment plants.

Furthermore, as the total solids content in sewage sludge increased from 4 % to 7 %, there was a modest reduction in both total environmental impacts and life cycle costing, as well as a slight improvement in energy balance when compared with the impacts caused by volatile solids contents (Fig. 8d-f). More specifically, the total environmental impact experienced a minor reduction, moving from −3.37 to −3.47, as the total solids content rose from 5 % to 7 %, marking a 1.03- to 1.05-fold improvement relative to 4 % total solids content baseline of −3.29 (Fig. 8d). Additionally, the net energy balance saw a modest increase, improving a 1.26 to 1.55 times with a total solids content range of 5 % to 7 %, compared to 4 % total solids content (502.03 kWh) (Fig. 8e). Concurrently, the increase in total solids content shifted the sludge management scenario from a cost expenditure to cost benefits, ranging from -\$6.64/t to \$19.02/t (Fig. 8f). Notably, the slightly reduction in total environmental impacts resulting from the variation in total solids content was primarily attributed to anaerobic digestion process (Fig. S4), which reduced energy consumption from 619.68 kWh to 355.04 kWh as the total solids content increased from 4 % to 7 % (Fig. S5b). In contrast, the impact of other processes in the sludge management scenarios was negligible, aligning with findings from a previous study (Li and Feng, 2018).

3.6. *Future recommendation for sludge management scenarios*

Sensitivity analysis results revealed that increasing the volatile solids content in sewage sludge from 50 % to 80 % resulted in a 2.61 times

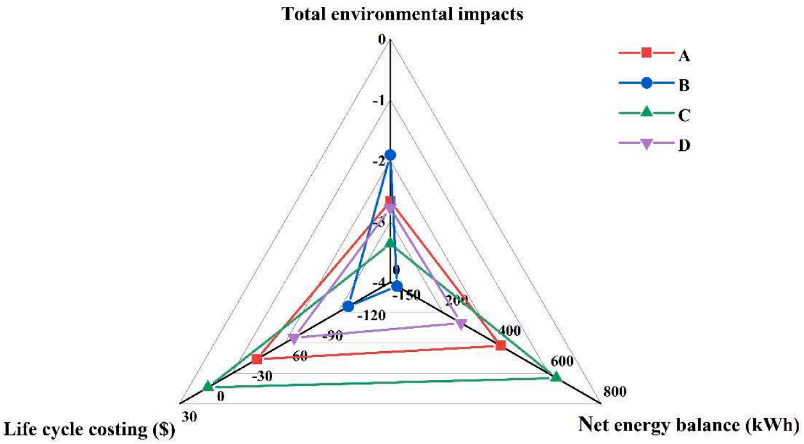


Fig. 7. Radar plot of the four sludge management scenarios, highlighting the aspects of total environment impacts, net energy balance, and life cycle costing. Note: A: Thickening, anaerobic digestion, cogeneration unit, dewatering, and land application; B: Similar to A but additionally included aerobic composting before land application; C/D: Similar to A/B, but incorporated lignosulfonate during anaerobic digestion.

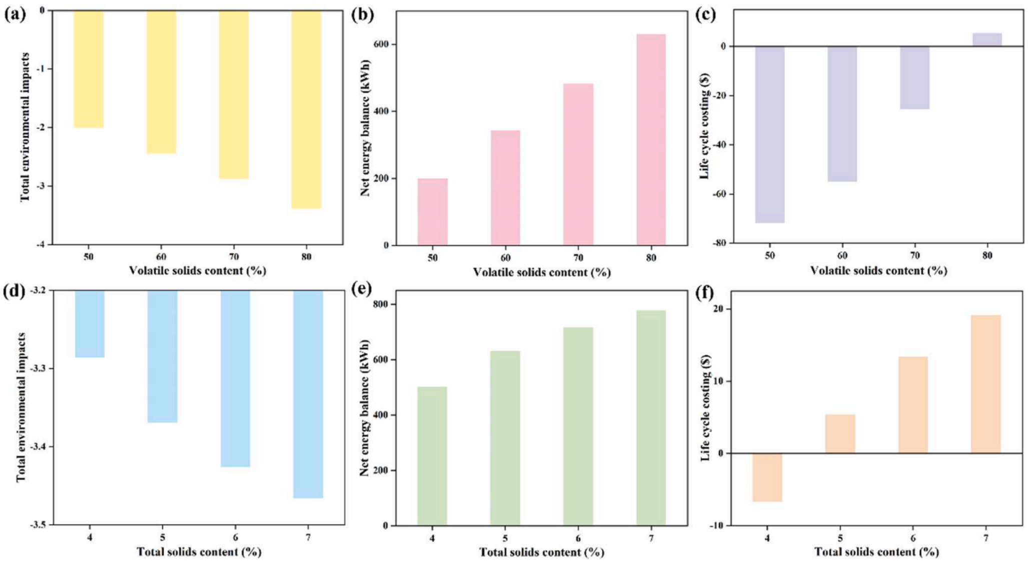


Fig. 8. Sensitivity analysis results for scenario C (the best performance for sludge management). a-c represents the total environmental impacts, net energy balance, and life cycle costing, varying with volatile solids content ranging from 50 % to 80 %; and e-f represents these same metrics but with total solids content ranging from 4 % to 7 %.

enhancement in energy recovery during cogeneration unit, reaching 1155.87 kWh energy recovery (708.65 kWh electricity production and 1610 MJ heat production) at 80 % volatile solids content. The total environmental impacts remarkably decreased from −1.99 to −3.48, with an increase in volatile solids from 50 % to 80 %. This indicated that a higher volatile solids content led to increased energy recovery, which provided sustainable alternatives to the reliance on fossil fuels and consequently benefiting the environment (Moya et al., 2017). Therefore, optimizing the proportion of volatile solids content in sewage sludge is advantageous for effective sludge management. Various strategies can be employed to increase the volatile solids content in sewage sludge. Previous study indicated that primary sludge has a higher concentration of biodegradable organic matter than secondary sludge (Azarmanesh et al., 2020), suggesting that balanced biodegradable content in mixed sludge could effectively increase volatile solids for enhanced treatment. Moreover, within the sewage treatment process, enhancing the removal efficiency of biodegradable organic substances and adjusting the sludge recirculation ratio to extend residence time have been demonstrated as effective strategies for increasing the volatile solids content in sewage sludge (Fredenslund et al., 2023; Nges and Liu, 2010). Additionally, by elevating the total solids content of sewage sludge in anaerobic digestion, a significant reduction in energy consumption was achieved (from 619.68 kWh to 355.04 kWh), coupled with a decrease in total environmental impact (from −3.28 to −3.16).

Although anaerobic digestion with high solids content presents numerous benefits, this strategy still faces some challenges, including slower mass transfer efficiency and the presence of higher concentrations of harmful substances (Cheng and Li, 2015; Zhang et al., 2016). The rheological properties of sewage sludge undergo changes as the total solid content of sludge increases, with viscosity rapidly escalating, resulting in a much slower mass transfer efficiency within the anaerobic digestion system (Cheng and Li, 2015). For example, a previous study reported that with an increase in total solids content from 6 % to 12 %, the diffusion coefficients reduced from 1.06×10^{-9} m^2/s to 2.66×10^{-10} m^2/s, respectively (Zhang et al., 2016). Furthermore, the concentrations of harmful and toxic substances (i.e., ammonia) contained in sewage sludge were found to be higher in high solids anaerobic digestion compared to the traditional anaerobic digestion system (Westerholm et al., 2020). Therefore, there is a need to strike a balance between total solids content and anaerobic digestion performance. Increasing the total solids content without compromising the efficiency of anaerobic digestion can potentially reduce energy consumption and environmental impact, this aspect requires further exploration and enhancement in future research.

This study validates the sustainability of scenario C, an innovative method encompassing thickening, anaerobic digestion with lignosulfonate addition, dewatering, and land application, for effective sludge management. It achieves maximum energy recovery, highest environmental benefits, and profitability in the sludge management process. However, the data on anaerobic digestion (with and without lignosulfonate addition) were from laboratory-scale tests, so it is imperative to expand the scope of the research through comprehensive pilot-scale and full-scale tests. This will provide a more robust understanding of the innovative sludge management strategy under industrial application conditions, allowing for a more accurate assessment of its feasibility and effectiveness. Furthermore, future research endeavors could optimize the dosage and application of lignosulfonate (sourced from lignosulfonate-containing waste from pulp and paper plants), ensuring an optimal balance between enhanced anaerobic digestion efficiency and cost-effectiveness. Additionally, considering the dynamic nature of environmental and technical factors, continuous monitoring and assessment are recommended to capture any potential variations in performance over time.

4. Conclusions

This study is the first to investigate the traditional (A-B) and innovative sludge management scenarios (C-D) distinguished by the absence or presence of lignosulfonate, through a life cycle assessment. It emphasizes economic benefits, energy balance, and environmental impacts, yielding the following key insights:

1) In traditional sludge management scenarios, scenario A was markedly superior to scenario B. It demonstrated a 2.24-fold greater reduction in total environment impacts and a 16.28-fold higher efficiency in energy recovery, while also reduced expenditure reaching $78.23/t, compared to scenario B.
2) In innovative sludge management scenarios, scenario C, sharing the same unit processes as scenario A, emerged as the most effective. It achieved a 1.26-fold reduction in total environmental impacts and a 1.51-fold improvement in energy recovery compared to scenario A,

transforming cost expenditure to economic benefits of \$5.36/t in scenario C.

3) Sensitivity analysis indicated that increasing volatile solids content from 50 % to 80 % remarkably reduced both environmental impact and life cycle costing, and amplified energy benefits, with enhancements ranging from 1.22 to 1.69 times in environmental impacts, a shift from a cost of \$71.65/t to a profit of \$5.36/t, and a 1.71 to 3.16 times increase in energy benefits compared to the 50 % volatile solids baseline. Additionally, increasing total solids content from 4 % to 7 % led to modest enhancements in environmental impact reduction, energy balance, and cost efficiency, 1.03–1.05 times enhance in total environmental impact reduction, 1.26–1.55 times increase in energy recovery, and a transition from \$6.64/t cost to \$19.02/t benefits.

Overall, this study contributes valuable scientific evidence that can assist policymakers in identifying the most sustainable sludge management strategy, taking into consideration energy, environmental, and economic sustainability aspects.

CRediT authorship contribution statement

Zhenyao Wang: Writing – review & editing, Writing – original draft, Software, Methodology, Data curation, Conceptualization. **Xuan Li:** Writing – review & editing, Supervision, Methodology. **Huan Liu:** Writing – review & editing. **Jibin Li:** Writing – review & editing. **Dan Cristian Vodnar:** Writing – review & editing. **Carol Sze Ki Lin:** Writing – review & editing. **Qilin Wang:** Funding acquisition, Supervision, Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Acknowledgments

Qilin Wang acknowledges Australian Research Council (ARC) Future Fellowship (FT200100264) and ARC Discovery Project (DP200100933).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107496.

References

Alengebawy, A., Mohamed, B.A., Ghimire, N., Jin, K., Liu, T., Samer, M., Ai, P., 2022. Understanding the environmental impacts of biogas utilization for energy production through life cycle assessment: an action towards reducing emissions. Environ. Res. 213, 113632.

Alex, R., William, W., 2021. Wastewater treatment planning guidelines https://www.sydneywater.com.au.

Authority, E.P., 2019. Compost guideline. https://www.epa.sa.gov.au.

Awad, H., Alalm, M.G., El-Etriby, H.K., 2019. Environmental and cost life cycle assessment of different alternatives for improvement of wastewater treatment plants in developing countries. Sci. Total Environ. 660, 57–68.

Azarmanesh, R., Zonoozi, M.H., Ghiasinejad, H., 2020. Characterization of food waste and sewage sludge mesophilic anaerobic co-digestion under different mixing ratios of primary sludge, secondary sludge and food waste. Biomass Bioenerg. 139, 105610.

Chen, G., Wang, X., Li, J., Yan, B., Wang, Y., Wu, X., Velichkova, R., Cheng, Z., Ma, W., 2019. Environmental, energy, and economic analysis of integrated treatment of municipal solid waste and sewage sludge: a case study in China. Sci. Total Environ. 647, 1433–1443.

Cheng, Y., Li, H., 2015. Rheological behavior of sewage sludge with high solid content. Water Sci. Technol. 71 (11), 1686–1693.

Chye, A., John, S., 2000. Use and disposal of biosolids products https://www.epa.nsw.gov.au.

Corbala-Robles, L., Sastafiana, W.N.D., Volcke, E.I., Schaubroeck, T., 2018. Life cycle assessment of biological pig manure treatment versus direct land application— a trade-off story. Resour. Conserv. Recy. 131, 86–98.

do Amaral, K.C., Aisse, M.M., Possetti, G.R.C.P., Marcelo, R., 2018. Use of life cycle assessment to evaluate environmental impacts associated with the management of sludge and biogas. Water Sci. Technol. 77 (9), 2292–2300.

Dong, B., Liu, X., Dai, L., Dai, X., 2013. Changes of heavy metal speciation during high-solid anaerobic digestion of sewage sludge. Bioresour. Technol. 131, 152–158.

Fredenslund, A.M.G., Einar, Falk, J.M., Scheutz, C., 2023. The Danish national effort to minimise methane emissions from biogas plants. Waste Manage 157, 321–329.

Geng, H., Xu, Y., Zheng, L., Liu, H., Dai, X., 2022. Cation exchange resin pretreatment enhancing methane production from anaerobic digestion of waste activated sludge. Water Res. 212, 118130.

Ghanbari, F., Wang, Q., Hassani, A., Wacławek, S., Rodríguez-Chueca, J., Lin, K.Y.A., 2021. Electrochemical activation of peroxides for treatment of contaminated water with landfill leachate: efficacy, toxicity and biodegradability evaluation. Chemosphere 279, 130610.

Gourdet, C., Girault, R., Berthault, S., Richard, M., Tosoni, J., Pradel, M., 2017. In quest of environmental hotspots of sewage sludge treatment combining anaerobic digestion and mechanical dewatering: a life cycle assessment approach. J. Clean. Prod. 143, 1123–1136.

Hong, J., Hong, J., Otaki, M., Jolliet, O., 2009. Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. Waste Manage 29 (2), 696–703.

Jenbacher, 2023. Technical description cogeneration unit JMS 420GS-B.L. https://zorg-biogas.com.

Kamizela, T., Kowalczyk, M., 2019. Sludge Dewatering: Processes for Enhanced Performance, Industrial and Municipal Sludge. Elsevier, pp. 399–423.

Khaki, E., Boleydei, H., Abyar, H., Nowrouzi, M., 2023. Integrating eco-environmental assessment with energy recovery for petrochemical wastewater treatment technologies: a transition towards green and sustainable management. J. Water Process Eng. 55, 104103.

Khan, R., Shukla, S., Kumar, M., Zuorro, A., Pandey, A., 2023. Sewage sludge derived biochar and its potential for sustainable environment in circular economy: advantages and challenges. Chem. Eng. J. 471, 144495.

Kumar, V., Chopra, A., Kumar, A., 2017. A review on sewage sludge (Biosolids) a resource for sustainable agriculture. Arch. Agr. Environ. Sci. 2 (4), 340–347.

Le Bars, M., Legros, S., Levard, C., Chaurand, P., Tella, M., Rovezzi, M., Browne, P., Rose, J., Doelsch, E., 2018. Drastic change in zinc speciation during anaerobic digestion and composting: instability of nanosized zinc sulfide. Environ. Sci. Technol. 52 (22), 12987–12996.

Li, H., Feng, K., 2018. Life cycle assessment of the environmental impacts and energy efficiency of an integration of sludge anaerobic digestion and pyrolysis. J. Clean. Prod. 195, 476–485.

Li, J., Li, X., Liu, H., Gao, L., Wang, W., Wang, Z., Zhou, T., Wang, Q., 2023a. Climate change impacts on wastewater infrastructure: a systematic review and typological adaptation strategy. Water Res. 242, 120282.

Li, W., Li, X., Han, C., Gao, L., Wu, H., Li, M., 2023b. A new view into three-dimensional excitation-emission matrix fluorescence spectroscopy for dissolved organic matter. Sci. Total Environ. 855, 158963.

Li, X., Zhang, S., Shi, J., Luby, S.P., Jiang, G., 2021. Uncertainties in estimating SARS-CoV-2 prevalence by wastewater-based epidemiology. Chem. Eng. J. 415, 129039.

Liew, C.S., Yunus, N.M., Chidi, B.S., Lam, M.K., Goh, P.S., Mohamad, M., Sin, J.C., Lam, S.M., Lim, J.W., Lam, S.S., 2022. A review on recent disposal of hazardous sewage sludge via anaerobic digestion and novel composting. J. Hazard. Mater. 423, 126995.

Liu, H., Li, X., Zhang, Z., Li, J., Zhou, T., Wang, Z., Wang, Q., 2024. Urine pretreatment enhances energy recovery by boosting medium-chain fatty acids production from waste activate sludge through anaerobic fermentation. Chem. Eng. J. 482, 148842.

Mayer, F., Bhandari, R., Gäth, S.A., 2021. Life cycle assessment of prospective sewage sludge treatment paths in Germany. J. Environ. Manage. 290, 112557.

McGrath, T.J., Kolobaric, A., Lee, E., Clarke, B.O., 2020. Brominated flame retardants (BFRs) in Western Australian biosolids and implications for land application. Chemosphere 260, 127601.

Medina-Martos, E., Istrate, I.R., Villamil, J.A., Gálvez-Martos, J.L., Dufour, J., Mohedano, Á.F., 2020. Techno-economic and life cycle assessment of an integrated hydrothermal carbonization system for sewage sludge. J. Clean. Prod. 277, 122930.

Miaomiao, H., Wenhong, L., Xinqiang, L., Donglei, W., Guangming, T., 2009. Effect of composting process on phytotoxicity and speciation of copper, zinc and lead in sewage sludge and swine manure. Waste Manage 29 (2), 590–597.

Moya, D., Aldás, C., López, G., Kaparaju, P., 2017. Municipal solid waste as a valuable renewable energy resource: a worldwide opportunity of energy recovery by using Waste-To-Energy Technologies. Energy Procedia 134, 286–295.

Neumann, P., Riquelme, C., Cartes, J., Kuschel-Otárola, M., Hospido, A., Vidal, G., 2022. Relevance of sludge management practices and substance modeling in LCA for decision-making: a case study in Chile. J. Environ. Manag. 324, 116357.

Nges, I.A., Liu, J., 2010. Effects of solid retention time on anaerobic digestion of dewatered-sewage sludge in mesophilic and thermophilic conditions. Renew. Energy 35 (10), 2200–2206.

Nguyen, V.K., Chaudhary, D.K., Dahal, R.H., Trinh, N.H., Kim, J., Chang, S.W., Hong, Y., La, D.D., Nguyen, X.C., Ngo, H.H., 2021. Review on pretreatment techniques to improve anaerobic digestion of sewage sludge. Fuel 285, 119105.

Pace, S.A., Yazdani, R., Kendall, A., Simmons, C.W., VanderGheynst, J.S., 2018. Impact of organic waste composition on life cycle energy production, global warming and Water use for treatment by anaerobic digestion followed by composting. Resour. Conserva. Recy. 137, 126–135.

Paul, D., Trevor, B., 2011. Biosolids snapshot. https://www.agriculture.gov.au.

Seleiman, M.F., Santanen, A., Mäkelä, P.S., 2020. Recycling sludge on cropland as fertilizer–advantages and risks. Resour. Conserv. Recy. 155, 104647.

Singh, A.D., Upadhyay, A., Shrivastava, S., Vivekanand, V., 2020. Life-cycle assessment of sewage sludge-based large-scale biogas plant. Bioresour. Technol. 309, 123373.

Tasca, A.L., Puccini, M., 2019. Leather tanning: life cycle assessment of retanning, fatliquoring and dyeing. J. Clean. Prod. 226, 720–729.

Tsvetkov, M., Salganskii, E., 2018. Lignin: applications and ways of utilization. Russ. J. Appl. Chem. 91, 1129–1136.

Usman, K., Khan, S., Ghulam, S., Khan, M.U., Khan, N., Khan, M.A., Khalil, S.K., 2012. Sewage sludge: an important biological resource for sustainable agriculture and its environmental implications. Am. J. Bot. 3, 12–26.

Wang, Q., Wei, W., Gong, Y., Yu, Q., Li, Q., Sun, J., Yuan, Z., 2017. Technologies for reducing sludge production in wastewater treatment plants: state of the art. Sci. Total Environ. 587, 510–521.

Wang, X., Lei, Z., Zhang, Z., Shimizu, K., Lee, D.J., Khanal, S.K., 2023. Use of nanobubble water bioaugmented anaerobically digested sludge for high-efficacy energy production from high-solids anaerobic digestion of corn straw. Sci, Total Environ. 863, 160825.

Wang, Z., Li, X., Liu, H., Zhou, T., Li, J., Li, Y., Lin, C.S.K., Wang, Q., 2024. Triclosan in sludge: exploring its journey from the sewage treatment plants to land application and potential impacts on the environment. Crit. Rev. Environ. Sci. Technol. 54, 1–24.

Wang, Z., Li, X., Liu, H., Zhou, T., Li, J., Siddiqui, M.A., Lin, C.S.K., Hatshan, M.R., Huang, S., Cairney, J.M., 2023a. Enhancing methane production from anaerobic digestion of secondary sludge through lignosulfonate addition: feasibility, mechanisms, and implications. Bioresour. Technol. 390, 129868.

Wang, Z., Li, X., Liu, H., Zhou, T., Li, J., Siddiqui, M.A., Lin, C.S.K., Huang, S., Cairney, J. M., Wang, Q., 2023b. Enhanced short-chain fatty acids production from anaerobic fermentation of secondary sludge by lignosulfonate addition: towards circular economy. J. Clean. Prod. 434, 140252.

Wang, Z., Li, X., Liu, H., Zhou, T., Qin, Z., Mou, J., Sun, J., Huang, S., Chaves, A.V., Gao, L., Wang, Q., 2023c. Bioproduction and applications of short-chain fatty acids from secondary sludge anaerobic fermentation: a critical review. Renew. Sust. Energ. Rev. 183.

Wang, Z., Li, X., Siddiqui, M.A., Liu, H., Zhou, T., Zheng, L., Huang, S., Gao, L., Lin, C.S. K., Wang, Q., 2023d. Effect of humic substances on the anaerobic digestion of secondary sludge in wastewater treatment plants: a review. Environ. Chem. Lett. 21 (5), 3023–3040.

Water, S., 2020. Wastewater treatment plant technical data sheet https://www.sydneywater.com.au.

Westerholm, M., Liu, T., Schnürer, A., 2020. Comparative study of industrial-scale high-solid biogas production from food waste: process operation and microbiology. Bioresour. Technol. 304, 122981.

Zareh, A.D., Saray, R.K., Mirmasoumi, S., Bahlouli, K., 2018. Extensive thermodynamic and economic analysis of the cogeneration of heat and power system fueled by the blend of natural gas and biogas. Energ. Convers. Manage. 164, 329–343.

Zhang, Y., Li, H., Cheng, Y., Liu, C., 2016. Influence of solids concentration on diffusion behavior in sewage sludge and its digestate. Chem. Eng. Sci. 152, 674–677.

Zhao, S., Yan, K., Wang, Z., Gao, Y., Li, K., Peng, J., 2023. Does anaerobic digestion improve environmental and economic benefits of sludge incineration in China? Insight from life-cycle perspective. Resour. Conserv. Recy. 188, 106688.

Zheng, G.D., Gao, D., Chen, T.B., Luo, W., 2007. Stabilization of nickel and chromium in sewage sludge during aerobic composting. J. Hazard. Mater. 142 (1–2), 216–221.

Zhou, T., Li, X., Liu, H., Dong, S., Zhang, Z., Wang, Z., Li, J., Nghiem, L.D., Khan, S., Wang, Q., 2024. Occurrence, fate, and remediation for per-and polyfluoroalkyl substances (PFAS) in sewage sludge: a comprehensive review. J. Hazard. Mater., 133637

Zhuang, Z., 2021. Environmental and Economic Life Cycle Assessment of Sewage Sludge Treatment Processes. University of British Columbia.