AQUA
Water Infrastructure, Ecosystems and Society

 AQUA — Water Infrastructure, Ecosystems and Society Vol 74 No 1, 1 doi: 10.2166/aqua.2024.410

Excess bio-sludge and contamination load minimisation: A comparative study on conventional activated sludge (CAS) and integrated treatment of CAS–AnMBR for environmental optimisation

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ABSTRACT

Slaughterhouse wastewater (SWW) contains high levels of biodegradable organic compounds, posing significant environmental hazards. The wastewater often exceeds regulatory discharge limits for contaminants, exacerbating eutrophication. Thus, biological treatment methods like activated sludge and anaerobic digestion remain preferable over physical or chemical processes for handling this wastewater. This study evaluated an integrated conventional activated sludge (CAS) and anaerobic membrane bioreactor (AnMBR) system for SWW to achieve high treatment efficiency while minimising excess sludge production. The wastewater was initially treated by a CAS system operated at a food-to-microorganism ratio of 0.2; the effluent then underwent anaerobic digestion in the AnMBR with an organic loading rate of 0.5 g COD/L/h. The integrated system achieved over 90% removal for COD and suspended solids and over 80% for nitrogen and phosphorus removal. It also reduced excess sludge by 30% compared to standalone CAS. Estimated biogas production was 0.6 m^3/h with 50–70% methane content. The high pollution removal, sludge minimisation, and renewable energy generation indicate that the integrated CAS–AnMBR system is a promising sustainable SWW treatment approach. The positive initial results warrant further examinations of methane yields, cost-effectiveness, and optimisation.

Key words: anaerobic membrane bioreactor (AnMBR), biogas production, conventional activated sludge (CAS), renewable energy, slaughterhouse wastewater, resource recovery, sludge disposal and management

HIGHLIGHTS

- Conventional activated sludge–anaerobic membrane bioreactor achieved >90% removal of COD and suspended solids from slaughterhouse wastewater.
- The system removed >80% nitrogen and phosphorus, preventing eutrophication in water bodies.
- Excess sludge production was reduced by 30% compared to the conventional activated sludge process.
- Estimated biogas yield of 0.6 m^3/h with 50–70% methane content for energy recovery.

1. INTRODUCTION

The constant influx in the growth of urbanisation and industrialisation has dramatically increased the consumption of services and goods. One of these goods is the industry of slaughterhouses, which, in recent years, has been known to be one of the most growing and environmentally threatening industries (Gutu *et al.* 2021). Thus, in government slaughterhouses originating in the Central Delta region in Egypt, a study is made to elucidate and evaluate slaughterhouse wastewater (SWW) (Viet *et al.* 2023). The samples were taken to be tested at the National Research Center. The threat of SWW is high mainly due to the massive amount of water being consumed in the industrial process, where, in the process of cleaning slaughtered animals by drenching the blood off them, 26 L of potable water are used per bird (Yaakob *et al.* 2018), generating steam, chilling, and another cleaning process such as the abattoir surfaces and the secondary products used. This fact threatens the scarcity and quality of water and causes death to aquatic creatures, where the process of the industry causes water pollution consisting of dangerous organic matter that is biodegradable. In addition, according to a study of the global water demand, it was estimated that by 2050, the global water demand is expected to be 20–30% higher than at present.

The organic matter in SWW causes massive water pollution, contaminating groundwater, and deoxygenating rivers. The SWW is also known as trade wastewater, where it is rich in total nitrogen (TN), total suspended solids (TSSs), volatile suspended solids (VSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total phosphorus (TP), and turbidity and contains a considerable number of organic matters such as fats, oil, grease (FOG), animal-derived protein and blood (Jensen *et al.* 2014). According to the data published by the Environmental Protection Agency (EPA), the second largest industry that discards more than 27% of nitrogen into rivers and waterways is the abattoir industry (Environmental Protection Agency 2022). However, researchers have developed treatments that decrease the COD, TSS, and TN, thus improving the output water quality and reducing land use, energy, chemicals, and sludge production to reduce environmental harm throughout the SWW treatment lifecycle.

SWW can undergo treatment using either biological or chemical technologies. However, researchers recently found that the chemical process is expensive due to the ineffectiveness of chemicals in removing the chemical sludge, and they are unfriendly to the environment. The physiochemical most commonly used pre-treatment process method in treating the SWW is the coagulation–flocculation of dissolved air floatation. However, the characteristics of chemical technologies made it clear that this choice is unfavourable and uneconomical. Sequential batch reactors (SBRs), constructed wetlands, and conventional activated sludge (CAS) were recently researched widely for SWW treatment. However, they were found unsustainable due to their high footprints and the ample space they require.

While CAS is a commonly used technique for treating both industrial and domestic wastewater (WW) on a global scale, it demands considerable volume to ensure optimal water quality. CAS systems are highly susceptible to variations in hydraulic loading rate (HLR) and organic content within the treatment utility. Furthermore, CAS treatment plants entail expensive management practices, especially regarding the disposal of waste activated sludge.

The process of choosing the best values for particular system characteristics to satisfy all design requirements and minimise costs is known as optimisation. Optimisation techniques – in particular, meta-heuristic algorithms – are well-known for their capacity to reach optimal or nearly optimal solutions in a reasonable amount of time and are very effective in optimising and boosting efficiency across various models and systems (Abdollahzadeh *et al.* 2024). Optimisation involves identifying the most effective solution to a problem from possible alternatives. Optimisation algorithms are generally categorised into two main types: deterministic algorithms, which follow a predictable path to find the solution, and stochastic intelligent algorithms, which use probabilistic techniques and randomness in the search process (El-kenawy *et al.* 2024a). We achieved notable and insightful results using the binary particle swarm optimisation–whale optimisation algorithm for feature selection and linear regression for predictive modelling (Towfek *et al.* 2024).

Accordingly, in the last decade, numerous anaerobic processes have been researched extensively, such as anaerobic sequencing batch reactor (ASBR), anaerobic floatation reactor, anaerobic baffled reactor (ABR), and anaerobic membrane bioreactor (AnMBR). These methods are indulgent in treating fat and organic solids. In addition, some of the most popular high-rate anaerobic treatment systems are fixed-bed reactors and upflow anaerobic sludge blanket (UASB) digestion. However, they were found to be less popular for SWW wastes because of the treatment efficiency and performance drops and their weak tolerance of treating the WW in the presence of oil, fat, and suspended matters present in high levels in the influent. Moreover, the AnMBR method was highly recommended as the most sustainable pre-treatment of WW due to the food industry. The great advantage of using AnMBR treatment is that it decreases sludge production by higher rates, has adequate eco-friendly removal of organic matter, uses lower energy consumption, needs fewer chemicals and nutrients, requires minimal footprints, and has high efficiency in removal rates of TN, TP, COD, TSS, and VSS (Monsalvo *et al.* 2013; Wong *et al.* 2020). Other researchers proved that it is a vital treatment in biogas production as a valuable form of renewable energy, resulting in an overview of the life cycle inventory (LCI) with promising results compared to other methods. However, some researchers stated that some limitations should be considered in the AnMBR process, such as sensitivity to higher temperature conditions and difficulties in treating the FOGs and suspended solids, resulting in reduced biomass and sludge washout as well as methanogenic activity. Even this issue can be solved by having a pre-treatment that removes the FOG, feathers, and any suspended solids (Carrere *et al.* 2010).

Selection of the CAS–AnMBR system against other technologies, such as aerobic digestion, presents different advantages in terms of energy efficiency, sludge management, and environmental burdens. Different from the continuously energy-intensive aeration of the aerobic systems, in CAS–AnMBR, biogas is generated that not only reduces operational energy demands but also helps to attain energy neutrality. Also, the anaerobic process in AnMBR yields much less sludge, again reducing the costs and environmental burdens of sludge disposal. It is, therefore, also more tolerant of organic load fluctuations and hence more robust owing to its efficiency in degrading complex pollutants. All these benefits – energy efficiencies, reduced sludge generation, and better adaptability – make CAS–AnMBR a sustainable and economically viable option compared to conventional aerobic digestion technologies.

The CAS and AnMBR systems combination generally achieves a better reduction of sludge and higher biogas production compared to other aerobic–anaerobic systems. The conventional SBR + AD (aerobic digestion) and ABR + AS configurations produce biogas effectively and reduce sludge but normally cannot reduce sludge yield as much as the AnMBR systems do (Kong *et al.* 2021). Systems containing a UASB or ABR followed by aerobic treatment, as well as inter-stage thermophilic aerobic digestion with both anaerobic stages, also improve the biogas yield. They also generally present more complex configurations and more land-intensive footprints when compared to CAS + AnMBR (Hafner *et al.* 2018). Direct integration of the AnMBR with CAS streamlined this train since it coupled the positive aspects of anaerobic digestion, namely low sludge yield and high energy recovery, with operational familiarity and robustness of CAS. The membrane in the AnMBR provides excellent effluent quality, which other means may require additional polishing steps to achieve (Pretel *et al.* 2016). In all, CAS + AnMBR systems represent an integrated approach with merit in resource recovery and minimisation of environmental impacts, therefore making them more desirable in cases where minimised sludge production and a high recovery of energy are sought (Smith *et al.* 2014).

In the context of the present study, the primary aim and objective are to assess the influent characteristics after its immediate treatment and secondary treatment, CAS outflow results, and finally, the CAS + AnMBR outflow. The discharge characteristics are subject to compliance with Egyptian law 48 of 1984, which is dedicated to protecting the water channels and the Nile River against pollution. To improve the capabilities of the treatment process based on the CAS treatment, we choose the AnMBR treatment process to optimise the WW quality by eliminating and decreasing the contaminant concentrations regarding the physical, chemical, and biological characteristics.

2. MATERIALS AND METHODS

2.1. Treating method description and analysis

The treatment process of SWW was collected from a governmental abattoir located in the Central Delta region of Egypt, which requires an additional and advanced treatment stage. Both plants act as a secondary treatment, where the SWW proceeds into a plain sedimentation stage that is responsible for removing significant matters from the SWW. The samples were taken daily for 45 days; thus, 45 samples were studied. The secondary treatment process included the CAS plant and the AnMBR plant. The SWW from primary sedimentation is discharged to the CAS and AnMBR plants for biological treatment. Supplementary material Table S1 summarises most operating parameters and limitations achieved for CAS and CAS + AnMBR systems configurations. The selection of the natural treatment type to an anaerobic rather than aerobic is due to the limited advantages of the aerobic process compared to the anaerobic in terms of its high demand of energy consumption and excessive sludge/biomass production that leads to disposal and handling problems (De Vela 2021). Both plants operated separately and sequentially in order, where the SWW enters the CAS plant, and the pre-treated water is then discharged from the CAS to the AnMBR plant.

A combined aerobic–anaerobic treatment system requires COD, BOD, and VSS monitoring since these parameters show organic load reduction, microbial activity, and general system efficiency. COD measures the total amount of oxidisable organic and inorganic substances, all of which present the load on both aerobic and anaerobic processes involved and allow for the appraisal of the treatment effectiveness of the system. BOD measures the biodegradable fraction of organic matter, directly presenting the oxygen demand in the aerobic stage and the effectiveness of organic matter breakdown in meeting the discharge standards. VSS, on the other hand, being a measure of organic solids, primarily reflects the active microbial biomass needed for degradation processes; it thus allows the operator to monitor the health and growth of biomass that in turn impacts the rate of sludge production and in-process stability. Together, these parameters ensure that both treatment stages perform optimally and that the system can consistently meet environmental standards.

2.2. Pilot plant conditions and limitations

The treatment above can be limited or affected due to the influence of some design variables and operational situations such as temperature, pH, COD, BOD, TSS, VSS, TN, TP, sludge retention time (SRT), and food-to-microorganism ratio (F/M); thus, these factors were controlled and managed to prevent any failure throughout the treatment process. The equivalence of some of the parameters was preserved to achieve an accurate comparison of the CAS + AnMBR efficiency and sludge removal rate. The samples were taken from three stages: SWW discharged from the primary sedimentation (SWW-Inflow) stage, the outflow of the CAS stage (CAS), and the flow after adding the AnMBR (CAS + AnMBR) stage. The samples were studied and tested on a lab scale in the National Research Center to meet the standards and maximum allowable limitations (illustrated in Supplementary material Table S2) according to law 93/62 for WW disposal from industrial buildings to be discharged in the public sewage networks.

The CAS + AnMBR setup has a total volume of 69 L, compared to the 48 L for the CAS-only setup, which means the additional volume needed to accommodate the AnMBR. Both systems have the same operating duration of 100 days, out of which 45 days are earmarked specifically for sampling operations. Notably, the integrated system uses a longer HRT of 12 h, which is double that of the CAS-only system at 6 h; this may signal a longer processing time and is probably set to provide sufficient time for microbial activity and treatment in the AnMBR part. This was indeed the change in volume and retention time required when switching from a CAS-only to an integrated treatment scheme to improve the performance of the wastewater treatment. Apart from volume and retention time, there is also a difference in operational flow rates between CAS and CAS + AnMBR systems. The integrated system is operated with the same flow rate of 6 h for both the CAS and AnMBR units, denoted as 6 CAS + 6 AnMBR, and thus splits the load between both systems evenly. This increased flow rate helps to render the microbial processing time superior in the AnMBR. This enhances treatment outcomes by optimising both aerobic and anaerobic processes in the integrated system.

2.3. Analytical methods

The American standard methods are the primary guidance method applied to all physical and chemical analyses of all wastewater samples taken during the study period (APHA AWWA & WEF 2020). It includes the analysis to get concentrations of BOD, COD, VSS, TSS, TN, TP, MLSS, MLVSS, F/M ratio, and SRT. During the research period, the analysis was done for all collected influent and effluent samples in both treatment scenarios, CAS runflow and CAS + membrane bioreactor (MBR). Dissolved oxygen (DO) concentrations and pH values were measured daily using a fixed pH meter on the pilot plant model. We used outlier detection with interquartile range analysis in order to achieve robust and reproducible results, which allowed us to find and handle the extreme data points without losing the integrity of the data. Data imbalances were managed by using the Synthetic Minority Over-sampling Technique, hence balancing the dataset and improving the model performance over all the classes.

2.4. Environmental impact analysis

According to ISO 14040, the environmental impact analysis of both systems mainly outlined the LCI in terms of the inputs (raw influent, transportation inputs, material, and energy sourcing) and outputs (emissions to water, soil, and atmosphere) that were schematically studied (Liu *et al.* 2021). Figure 1 shows the LCI flow diagram and helps map out numerous inputs and outputs through the entire life cycle of treating the WW. The methodology will elucidate the inputs, while the outputs will be discussed in the results section.

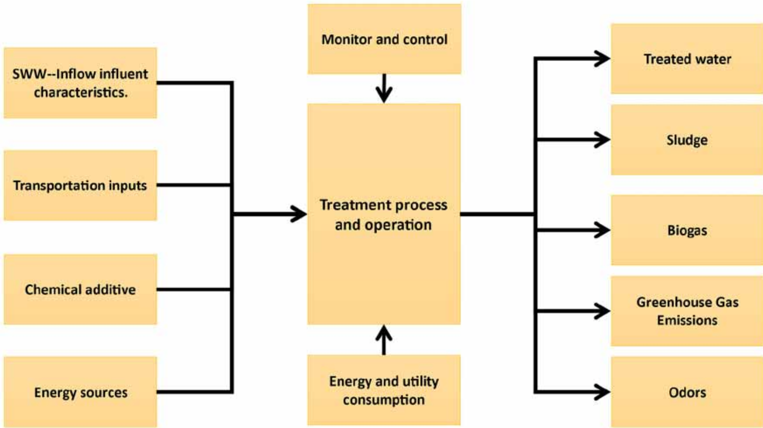

Figure 1 | LCI flow diagram of treating SWW.

2.5. Factors affecting sludge removal rate

The factors affecting the sludge degradation rate and the process performance are elucidated to maintain a stable system with lucrative and sustainable results. These factors include the characterisation of wastewater, pre-treatment process, CAS system role, AnMBR system role, process parameters optimisation, understanding and evaluating the kinetic parameters, such as observed yield cell, membrane fouling effect and control, monitoring and analysing performance, training and expertise, regular audits, and reuse/recycle plans. The biomass parameters are essential to evaluate and monitor the CAS + AnMBR system performance, ensuring efficient WW treatment and making required adjustments to maintain optimal microorganism conditions responsible for the treatment flow and process. Moreover, monitoring and controlling these parameters help to achieve the desired treatment goals.

2.5.1. Characterisation of wastewater

The treatment process was guided by conducting a thorough analysis of the SWW in terms of its composition, nutrient content, organic load, and SRT and identifying any potential toxic components in the influent illustrated in Figure 2. Careful adjustments were required in our case while using CAS + AnMBR in the desludging process, where the SWW is high-strength WW with complex organic compounds (Pirmoradi *et al.* 2021). Thus, it is vital to understand the challenges associated with excess sludge production by understanding the essential parameters that directly affect the sludge minimisation process and how to avoid process failure by controlling these parameters.

In the batch inflow tank with a volume of 300 L, the SWW-Inflow influent characteristics are presented in Table 1, with a 5.5 L/h flow rate. The HRT was adjusted to be 6 h. It was noticed that the longer SRT in the AnMBR helps reduce sludge

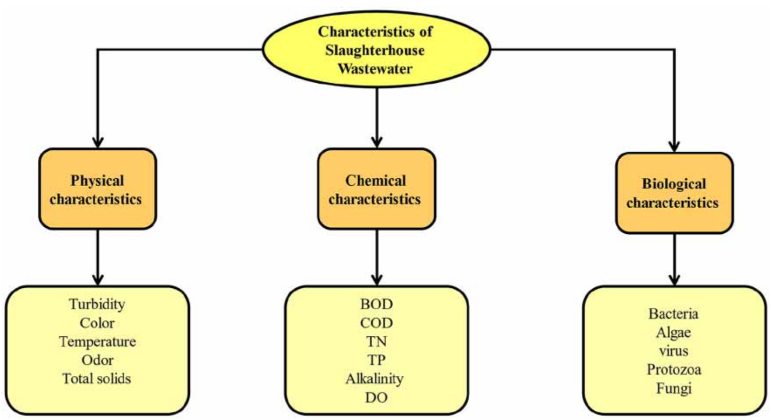

Figure 2 | Characterisation of influent wastewater.

Table 1 | Characteristics of SWW-inflow

Parameter	Range
HRT (h)	6
Suspended solids (mg/L)	62–188
Temperature (°C)	23–32
pH	6.12–7.71
BOD (mg/L)	1,058–1,458
COD (mg/L)	2,645–3,645
TSS (mg/L)	1,385–1,936.7
VSS (mg/L)	1,040–1,474
TN (mg/L)	33–64
Total phosphorus (mg/L)	44–76

wasting and causes higher biomass retention. The settled sludge (SS) refers to the number of solid particles at the settling tank's bottom (Abdelrahman *et al.* 2022), which ranges between 62 and 188 mg/L. The pH level was adjusted to be almost neutral; thus, it was not highly considered in the treatment process, so the risk of its influence on the anaerobic digestion in the AnMBR treatment and microbial activity is obsoleted, unlike the temperature, BOD, COD, TSS, VSS, TN, and TP. Low DO levels were maintained to support the AnMBR's anaerobic conditions and maintain healthier desludging efficiency. However, in CAS, DO levels were held to be sufficient to promote aerobic microbial activity (Banti *et al.* 2020). The influent BOD, COD, TSS, VSS, TN, and TP ranges are presented in Table S3 (Supplementary material) and Figure 3. Elevated organic constituents, COD and BOD, influence the compositions as well as the acclimation of the microbial community in both plant systems. The influent values of SWW contained high concentrations of COD and BOD. Thus, it was crucial to decrease these values to achieve proper sludge removal and prevent membrane fouling. An enhanced nutrient removal process was accomplished since the influent contained elevated TN and TP.

Like the DO and pH, temperature affects the microbial activity and growth rate in the CAS + AnMBR treatment. Thus, it was adjusted along the treatment top range between 23 and 32 °C. Temperature stabilises sludge, achieved through mesophilic anaerobic digestion (MAD) (Wahaab *et al.* 2020). MAD is a type of AD that optimally operates at a temperature of 20–450 °C. On the contrary, other AD systems, known as thermophilic digestion, work with higher temperature levels.

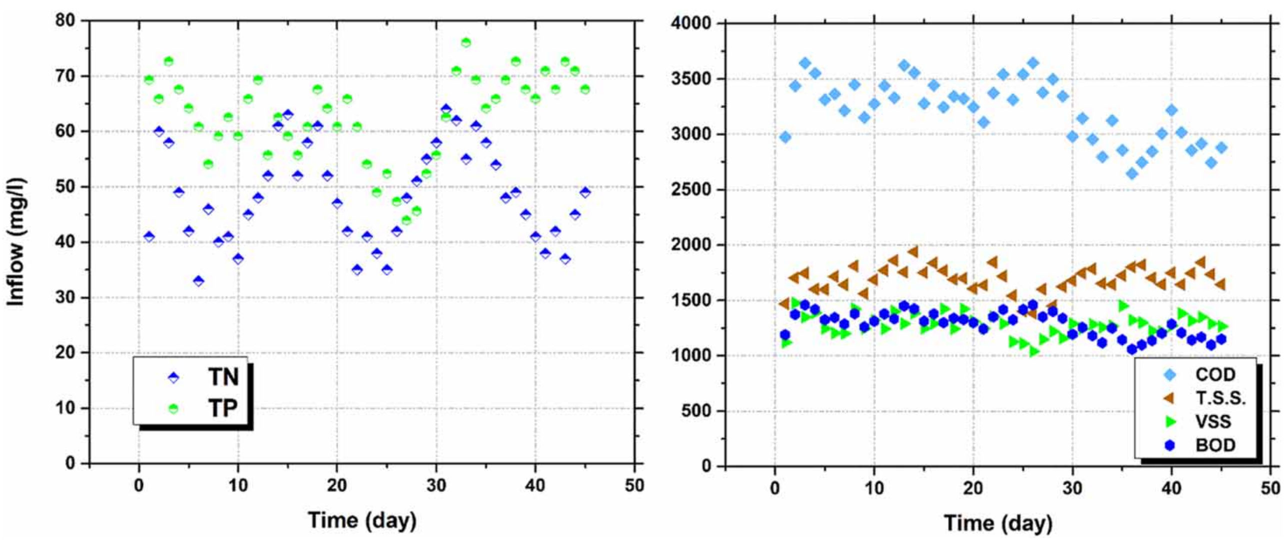

Figure 3 | Total solids and nutrient content present in SWW-influent before treatment.

The temperature of the treatment plays an essential role in the viscosity of the solubilisation rate and the filtered liquor of various composites. This occurs due to the effect of temperature on membrane filtration performance. Researchers reported that the sludge's rheological properties were affected by raising the temperature. As a result of thermophilic conditions, a higher solubilisation rate caused a notable increase in the minorly sized particles, showing the extensive distribution of particle size as well as minor viscosity values compared to the MAD. However, the thermophilic lower viscosity conditions allowed better filtration performance, yet there was a pore blocking in the membrane due to small particles, which caused the increase of permanent fouling, and thus, it required regular chemical cleaning. Therefore, it causes an increase in the treatment cost. Thus, MAD was the most efficient and economical type to use in this study, wherein the temperature was above an optimal growth in the microorganisms, which are the primary microorganisms present known as mesophiles.

2.5.2. Pre-treatment process

The raw influent is transported from the SWW to the primary sedimentation phase plant, where it undergoes the needed pre-treatment, which includes screening, grit removal, and grease traps that are responsible for removing the sizeable solid matter, debris, FOG (Adou *et al.* 2023). By removing these materials in the early stages of the treatment process, the load on the subsequent treatment units is reduced and prevents future operational issues from occurring (Shende *et al.* 2022). Moreover, skipping this stage causes an increase in the sludge production. After this phase, the water is discharged to the aeration tank in the CAS plant.

2.5.3. Role of the CAS and AnMBR system

The design and setup of both systems were according to the data collected regarding the influent characteristics. The CAS system plays a vital role in breaking down organic pollutants. This is achieved when SWW is mixed with the activated sludge in the aeration tank, where a diverse group of microorganisms consumes organic matter. This is accomplished only if the process parameters are adjusted: HRT, SRT, F/M ratio, MLSS, MLVSS, and DO levels. Moreover, by maintaining optimal levels of the SRT and MLSS, reducing excess sludge is easily attained (de Oliveira *et al.* 2018). Before the water is discharged to the AnMBR process, a final stage of sludge wasting is used in the CAS plant: the stepped wasting method. Furthermore, the stepped annihilating method refers to a periodic practice of removing excess sludge from the biological reactor by applying multiple stages or steps rather than continuously washing off the sludge. It serves several benefits in the operational process, such as augmented sludge settling, diminished sludge formation, improved nutrient removal system, energy saving, and enhanced process stability (Corsino *et al.* 2019).

In AnMBR, the organic matter breaking down process is achieved by the microorganisms in the anaerobic digestion stage where the oxygen is absent. As a result, biogas is generated during this process and is mainly composed of carbon dioxide and methane. The four stages of the anaerobic digestion process, as represented in Figure 4, are hydrolysis, acidogenesis, acetogenesis, and finally, methanogenesis, as illustrated in Figure 4. SWW contains high proteins, polysaccharides, monosaccharides, lipids, fatty and amino acids; they are also known as high molecular weighted compounds and represent the insoluble organic matter. Consequently, the hydrolysis stage reduces and diminishes them (Dyosile *et al.* 2021). In the second stage, acidogenesis, bacteria known as acidogenic generate products using the formed components from the hydrolysis stage, such as carbon dioxide, volatile fatty acids, ammonia, and hydrogen sulphide (Yuan *et al.* 2019). In the third stage, acetogenesis, products such as carbon dioxide, acetic acid, and hydrogen are formed due to the digestion of organic acids and higher alcohols. Methanogenesis occurs in the final stage. The production of biogas was projected using different techniques, but it was unscientifically measured and is minorly considered in the scale of the study. However, decades ago, sludge stabilisation using AD showed promising and lucrative opportunities to generate renewable energy appearing as biogas. This arises from the bioconversion of complex organic matter, anaerobically, located in the sludge through various volatile organic acids in the biogas and methanogens (mixture of methane and carbon dioxide) (Philipp *et al.* 2021).

In the CAS + AnMBR combined process, the microorganisms in the anaerobic microbial community responsible for the anaerobic digestion in the AnMBR component and the CAS-activated sludge component presented the biomass in the treatment. Figure S1 (Supplementary material) shows the configuration of the CAS and AnMBR integrated treatment process. The biomass in these systems was highly monitored and controlled to secure the health and activity of the microorganisms, where these microorganisms work together to effectively treat the WW by removing the contaminants, nutrients, and organic pollutants (Gutu *et al.* 2021). In case of carelessness in monitoring and governing the biomass population in the systems, the

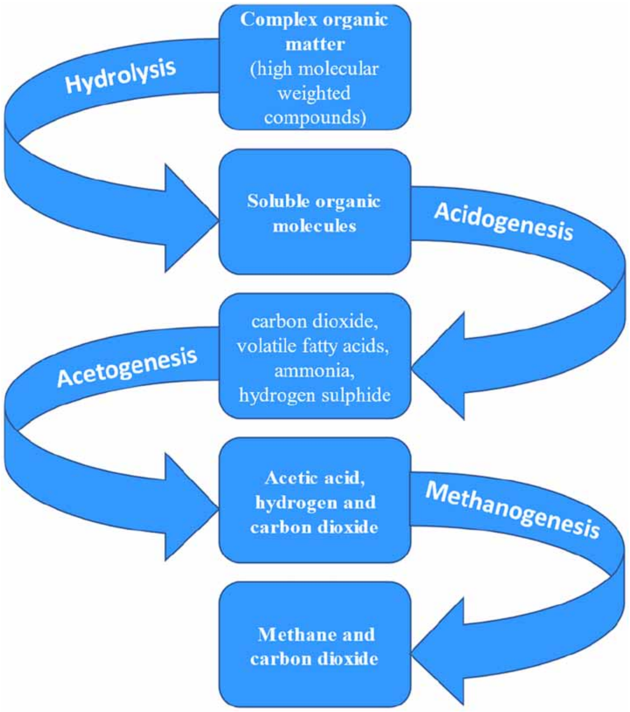

Figure 4 | The anaerobic digestion process follows four main stages in an anaerobic reactor.

treatment performance drops and misplaces its stability and performance optimisation. MLSS, MLVSS, and other biological indicators were used to assess both systems' biomass concentration and activity to achieve restricted control.

2.5.4. Biomass parameter model

- F/M ratio

In the CAS reactor, the appropriate F/M ratio is maintained at 0.75 (gBOD/g VSS d), thus ensuring that the microorganisms efficiently consume the available organic matter to prevent the production of excessive biomass (Zhang *et al.* 2022). It was determined by calculating the ratio between the influent organic concentration. S_0 and the microorganism concentration in VSS $\mathcal{X}_m$:

$$\text{F/M ratio} = \frac{S_0}{\text{HRT} \cdot \mathcal{X}_m} \quad (1)$$

- Observed yield cell coefficient (Y_{obs})

Y_{obs} play a crucial role in assessing the operation performance in terms of mass balance and stoichiometry. This is achieved by measuring the association among the organic matter (substrate consumed) and the biomass being produced (microbial cells) along the biological reactions that occur in the form of activated sludge in the CAS process and anaerobic digestion in the AnMBR process. The Y_{obs} resulting from CAS varied from 0.54 to 0.95 (mg VSS/mg COD), while in CAS + AnMBR it ranged from 0.43 to 0.76 (mg VSS/ mg COD). By monitoring as well as adjusting Y_{obs}, operators can optimise the biological treatment process. At the same time, the optimal Y_{obs} indicated that the microorganisms are efficiently exploiting the available substrate for cell growth. This helps reduce operational costs and sustains the system performance and flocs disposal system.

Moreover, Y_{obs} is used to estimate the biomass concentration present in the mixed liquor of the biological reactor. Equation (2) is used to calculate and estimate the biomass using Y_{obs}. The substrate removal rate, influent concentration, and effluent concentrations are measured (Morello *et al.* 2022). The changes that might occur in the Y_{obs} coefficient can indicate issues with the treatment process. Thus, it can be used in diagnostics and troubleshooting where a sudden drop in the yield coefficient proposes a stressed microbial population change or changes in the WW composition. This advances the operators in addressing and identifying potential problems:

$$Y_{\mathrm{obs}} = \frac{\Delta\mathcal{X}_{\mathrm{MBR}} \cdot V_{\mathrm{MBR}} + \Delta\mathcal{X}_{\mathrm{An}} \cdot V_{\mathrm{An}} + (\mathcal{Q}_{\mathrm{MBR},w} \cdot \mathcal{X}_{\mathrm{MBR},w} + \mathcal{Q}_{\mathrm{An},w} \cdot \mathcal{X}_{\mathrm{An},w} + \mathcal{Q}_e \cdot \mathcal{X}_e) \cdot \Delta t}{(\mathcal{Q}_0 \cdot S_0 - \mathcal{Q}_e \cdot S_e) \cdot \Delta t} \tag{2}$$

where $\Delta\mathcal{X}_{\mathrm{MBR}}$ is the variation in microorganism concentration inside the MBR reactor module during the reference time Δt (mg VSS/L). $\Delta\mathcal{X}_{\mathrm{An}}$ is the variation in microorganism concentration inside the anaerobic reactor module during the reference time Δt (mg VSS/L). V_{MBR} is the MBR volume (m^3). V_{An} is an anaerobic holding tank volume (m^3). $\mathcal{Q}_{\mathrm{MBR},w}$ is the waste sludge flow rate from MBR (m^3/days). $\mathcal{Q}_{\mathrm{An},w}$ is the waste sludge flow rate from the anaerobic holding tank (m^3/days). $\mathcal{X}_{\mathrm{An},w}$ is the waste sludge biomass concentration from the anaerobic holding tank (mg VSS/L). $\mathcal{X}_e$ is an effluent microorganism concentration (mg VSS/L). $\mathcal{X}_{\mathrm{MBR},w}$ is the waste sludge biomass concentration from the MBR (mg VSS/L). S_0 is an influent organic substrate concentration (mg BOD/L). S_e is an effluent organic substrate concentration (mg BOD/L). $\mathcal{Q}_0$ is an influent flow rate (m^3/days). $\mathcal{Q}_e$ is an effluent flow rate (m^3/days). Δt is the reference time (days).

- Sludge volume index (SVI)

The SVI was used to provide valuable information regarding the biomass settling characteristics in the CAS process, indicating the performance level of microorganisms and other solids that are settled in the secondary clarifiers. The SVI values ranged between 50 and 172 (mL/L). Minor SVI indicates healthier settling, while higher SVI reflects poor settling and clarifier potential issues. To calculate the SVI, a representative sample of the mixed liquor VSSs from both plants was taken from a point where the sludge was well-mixed (Viet *et al.* 2023). In addition, after a specific settling time, a settling inspection was performed to evaluate the occupied volume of the SS. The settling inspection was achieved through sequential steps:

A graduated cylinder with known volume was filled with the MLVSS sample.

The sample was left for 30 min to subside.

After settling, the volume of SS at the bottom of the cylinder was recorded and measured to attain the sludge volume.

After measuring the SS and MLVSS concentrations ($\mathcal{X}_{\mathrm{SS}}$ and $\mathcal{X}_{\mathrm{MLVSS}}$), it was possible to calculate SVI in (mg/L) using the following formula:

$$\mathrm{SVI} = \frac{\mathcal{X}_{\mathrm{SS}}}{\mathcal{X}_{\mathrm{MLVSS}}} \tag{3}$$

- Mixed liquor suspended and volatile solids (MLSS and MLVSS)

These parameters' concentrations must be maintained appropriately, where their concentrations affect minimising the fouling process. Moreover, the higher these parameters' concentrations get, the greater the particulate matter and biomass accumulation increase on the membrane surface. MLVSS concentration plays a vital role in the nutrient removal process, where its concentration reflects the biological phosphorus and nitrogen removal rates. MLSS and MLVSS levels contribute to the process stability, thus measuring them where they ranged between 1,226–1,694 and 981–1,355 (mg/L) (Table 2), respectively. It was calculated using the following formulas:

$$\mathrm{MLSS\ (mg/L)} = \frac{W_{\text{dry solids}} - W_{\text{empty filter}}}{V_{\mathrm{ML}}} \times \mathcal{Y}_{\mathrm{DF}} \tag{4}$$

$$\mathrm{MLVSS\ (mg/L)} = \frac{W_{\text{dry ash}} - W_{\text{empty filter}}}{V_{\mathrm{ML}}} \times \mathcal{Y}_{\mathrm{DF}} \tag{5}$$

where $W_{\text{dry ash}}$ is the weight of filter with non-volatile (ash) solids after drying (mg). $W_{\text{dry solids}}$ is the weight of dry solids (mg). $W_{\text{empty filter}}$ is the weight of empty filter (mg). V_{ML} is the volume of mixed liquor sample collected (L). $\mathcal{Y}_{\mathrm{DF}}$ is the dilution factor.

Table 2 | Biomass parameters and biogas estimation range

Parameter	Range
OLR (g COD/L/h)	0.42–0.57
MLSS (mg/L)	1,226–1,694
MLVSS (mg/L)	2,645–3,645
Y_{obs} (mg/L)	1,385–1,936.7
SVI (mg/L)	1,040–1,474
Biogas yield (L/g COD removed)	0.34–0.76
Biogas produced (m^3/day)	0.11–0.14

2.5.5. Biogas production

The biogas production rate can be calculated based on several parameters, including the type and amount of feedstock used, the efficiency of the digestion process, and environmental factors like temperature. In anaerobic digestion, biogas production is often linked to reducing volatile solids (VS). The biogas production rate can be calculated based on the amount of VS reduced during digestion.

The formula is:

$$\text{Biogas Production Rate} = \frac{\text{Biogas Produced (m}^3\text{/day)}}{\text{Volatile Solids Removed (kg/day)}} \tag{6}$$

where: Biogas Produced is the total biogas generated. Volatile Solids Removed is the amount of VS consumed during digestion, typically measured in kg/day.

This approach is commonly used in wastewater treatment and biogas plants where VS reduction is a crucial indicator of digestion efficiency

2.5.6. Membrane fouling

The membrane fouling process highly impacts and challenges the efficiency and performance of the AnMBR treatment. Therefore, it can lead to treatment failure if not adequately managed. The fouling results from accumulating microorganisms, particles, and other substances inside its pores or on the membrane surface, decreasing its permeability and obstructing the treated water flow through the membrane. As a result, the hydraulic resistance accumulates. Thus, higher transmembrane pressures are required to maintain the desired stream rate (de Oliveira *et al.* 2018). However, an elevated transmembrane pressure causes higher energy consumption and hypothetically strains the membrane, leading to system downtime and dramatic operational costs.

Moreover, the active membrane surface area available for filtration decreases under the effect of fouling, thus decreasing the treatment capacity of the AnMBR system (de Oliveira *et al.* 2018). When this happens, the system is at risk of being unable to handle the WW flow required, leading the downstream treatment units to potential overloading. Process instability is one of the risks that can be shown due to membrane fouling, for instance, sludge bulking, floating sludge layers, or rising sludge, which affect the overall efficiency of the treatment, requiring additional process adjustments (Khuong & Luu 2022). However, this case occurrence is only possible in extreme cases. To avoid these risks and the challenges of the fouling process, regular cleaning and maintenance of the membrane is crucial to prevent its occurrence. Controlling and monitoring the crossflow velocity, temperature, and aeration rates results in minimising the occurrence of fouling. This control of membrane fouling was done by applying operating limitations of temperature of 25 °C, transmembrane pressure of 90 psi, and crossflow velocity of 2.6×10^{-2} m/s.

2.6. Sludge management in Egypt

In the studied area, the Nile Delta region, there is a lack of amenities for sludge stabilisation. This is due to the limited areas and financial constraints for treating immense sludge within most WW treatment plants. Thus, the sludge resulting from the treatment plants is dried in a plain sludge drying bed. Research findings indicated that most of the bulked excess-dried sludge retrieved from WW treatment facilities in Egypt is being marketed to local sellers at an average rate of $4–6 per metric ton. However, according to the national legislation for sludge disposal/reuse, it is an obligation for the vendors to store the sludge for six months before consuming it in land applications. The responsibility is mainly to prevent using non-stabilised sludge in agriculture, which involves edible products such as fruits and vegetables.

Nevertheless, a previous research paper revealed that the primary and secondary excess sludge is vented to agriculturalists lacking firm supervision and control since these regulations are not reinforced in practice (Wang *et al.* 2023). However, Egypt is struggling to manage the sludge and faces numerous challenges in controlling its disposal, yet in this study, the resulting sludge is full of lucrative nutrients and is stabilised. This is due to the double processing and the integrated system of activated sludge and anaerobic digestion.

To achieve this, proper management and control of the whole process were required in the government's new policy of 2030, which focuses on sludge management and disposal to minimise and eliminate the elevated risks accompanied by the current discharging and disposal technologies and to generate renewable and clean energy. Accordingly, the Egyptian government is highly concerned with fast-tracking the adoption of disposal technologies to alter WW sludge into distinguished and lucrative outputs for the users. This includes renewable energy, soil enhancers, and nutrient boosters for agricultural utilisation and farming applications. Comprehensive research on the potential safety and value of using sludge on agricultural land showed promising scientific analysis that illustrates using the sludge as a soil conditioner, and fertiliser is possible due to the Egyptian warm climatic conditions as well as other aspects such as soil, economic, and operational factors favour agricultural use of sludges in Egypt (Konbr *et al.* 2022).

3. RESULT AND DISCUSSION

3.1. Removal efficiency of treatment process

The primary treatment removal efficiency was monitored and calculated twice weekly throughout the research period. It ranged between 30 and 37% removal of organic matter and suspended solids. During the experiments, the aforementioned biomass concentrations were maintained in both systems. According to the law and limitations of the effluent discharged, the treated water quality matched the effluent regulations. The nutrient depletion rates of TN and TP via the integrated system CAS + AnMBR are marked at over 90%.

Meanwhile, the CAS plant individually resulted in 86 and 77% TN and TP removal, respectively. The suspended solids in terms of TSS and VSS removal rates concluded from CAS + AnMBR discharge were over 90%, while the CAS rates failed to exceed 81% of removal. The outflow COD ranged between 542 and 1,013 mg/L in CAS and dropped to 508–271 mg/L after adding the AnMBR. Thus, up to 84% of COD was removed using the activated sludge and over 94% after exposure to anaerobic digestion (Figure 5 and Table 3). In addition to the economic and environmental advantages that led to the expansion of the use of AnMBR, this system worked with double efficiency in treating wastewater, as it combines the efficiency of anaerobic biological treatment and treatment using membrane technology.

According to ISO 14040, the key steps that were taken to achieve the LCI of the environmental impact analysis included a data collection of all inputs, such as the raw influent characteristics (shown in Table 3 and Figure 2) and the materials used for the treatment process. An assessment and evaluation of the transportation impact on the raw SWW in the proposed treatment where it had a meagre influence on the LCI. After collecting the data, an LCI flow diagram (Figure 1) was developed to map the various inputs and outputs throughout the WW's entire life cycle.

3.2. Sludge reduction and disposal

During the biological treatment, sludge concentration is essential to ensure the natural treatment's efficiency and ability. As illustrated in Figure 6, the TSSs and VSS represent the changes in the sludge concentration in the CAS and CAS + AnMBR over the experimental period. The initial biomass concentration increased rapidly and then slowly declined, stabilising sludge. The biomass growth declination represents the occurrence of maintenance metabolism. In contrast, the ratio of VSS to TSS resulted in constant values of around 0.7 from both treatments. This result indicates that along the SRT conditions of the treatment, the occurrence of the inorganic compounds did not accumulate. The low values of Y_{obs}, as demonstrated in Figure 6, revealed minimisation within the rates of surplus bio-sludge formation. The depletion rate of excess bio-sludge achieved up to 30%, as illustrated in Figure 7, without adding any chemicals or using expensive biological methods. The sludge disposal technique (Figure 8) is as follows: mixed sludge resulting from primary and secondary treatment is circulated into gravity

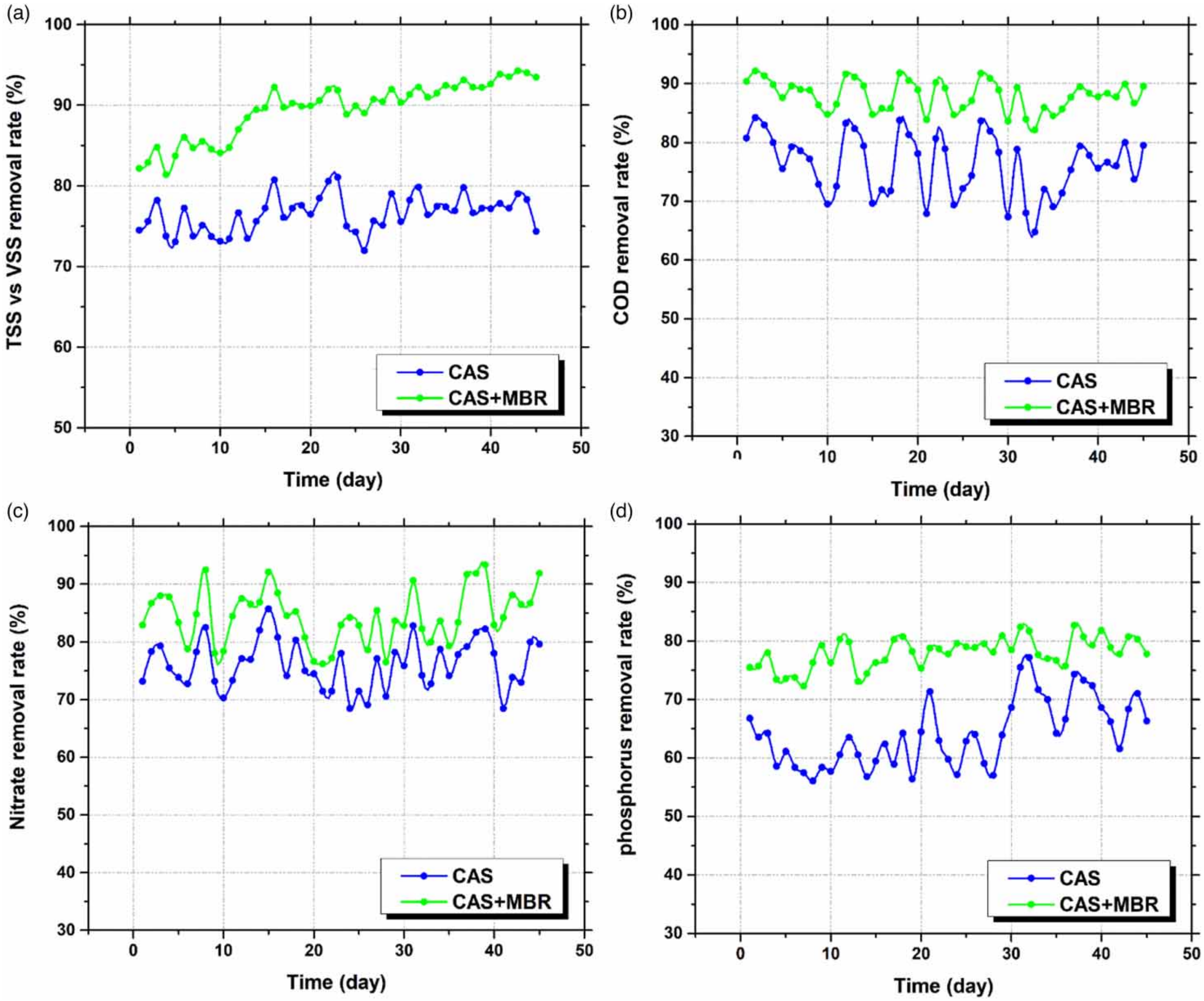

Figure 5 | Removal rates in CAS effluent and CAS + AnMBR discharge: (a) TSSs and VSSs removal, (b) COD removal, (c) TN, and (d) total phosphorus.

Table 3 | Nutrient and suspended solids removal rates (%) using activated sludge and rates after integrating it with anaerobic digestion (AnMBR)

Parameter	CAS removal rates (%)	CAS + AnMBR removal rates (%)
COD (mg/L)	84	92
TSS (mg/L)	81	94
VSS (mg/L)	82	94
TN (mg/L)	86	93
Total phosphorus (mg/L)	77	83

thickeners, where the solid content increases from 1–2 to 4–6%. The succeeding step is to pump the thickened sludge to natural-drying basins where dry solids density is increased to 40–50% (Liu *et al.* 2021). Moreover, it is calculated that 2–3 weeks during summer at a temperature of 40 °C and 6–8 weeks in winter at an average temperature of 10 °C is the required period to attain optimised dewatering efficiency rates.

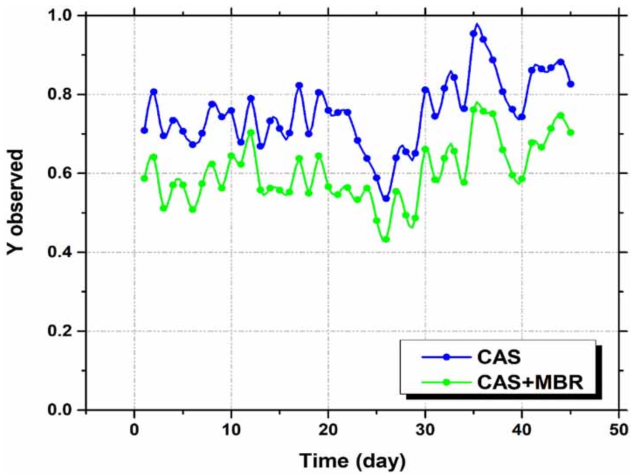

Figure 6 | Observed yield cell coefficient resulting from CAS and CAS + AnMBR treatment process.

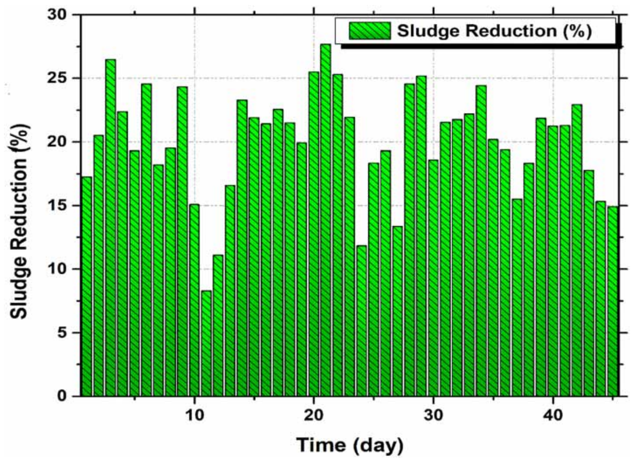

Figure 7 | Excess bio-sludge removal rate using CAS + AnMBR treatment.

3.3. Benefit–cost analysis

The CAS + AnMBR system presents an initial high capital investment, which is estimated to range from 20 to 30% higher than the standalone CAS because of the presence of the membrane modules in AnMBR and the infrastructure related to handling the biogas. This situates the capital expenditure for a new AnMBR plant at approximately \$0.07–\$0.12/m^3, whereas the capital expenditures of CAS alone were comparably low (Pretel *et al.* 2016). With CAS + AnMBR, the costs of energy consumption are drastically reduced because methane production in the anaerobic part offsets energy demands. Energy requirements for as low as 0.07 kWh/m^3 for AnMBR might translate to 10–15% energy savings during mixed CAS + AnMBR operations and reduce the cost to circa \$0.20–\$0.40/m^3 (Ferrer *et al.* 2015).

Sludge yield from AnMBR systems is around 40–50% lower than CAS, and thus, sludge handling and disposal costs can be considerably decreased. Savings in operation due to reduced generation and sludge disposal amount to around \$0.10–\$0.15/m^3 (Pretel *et al.* 2014). The combination of CAS and AnMBR yields higher pollutant removal efficiency, meeting higher stringency in discharge standards and contributing towards an economic advantage by reducing 5–10% of regulatory and environmental fees. The front-end costs of the CAS + AnMBR system are much higher, but the long-term economies through energy efficiency and reduced sludge disposal costs make this an economically attractive solution, with estimated long-term costs in the range from \$0.20 to \$0.40/m^3, depending on local energy and sludge disposal costs.

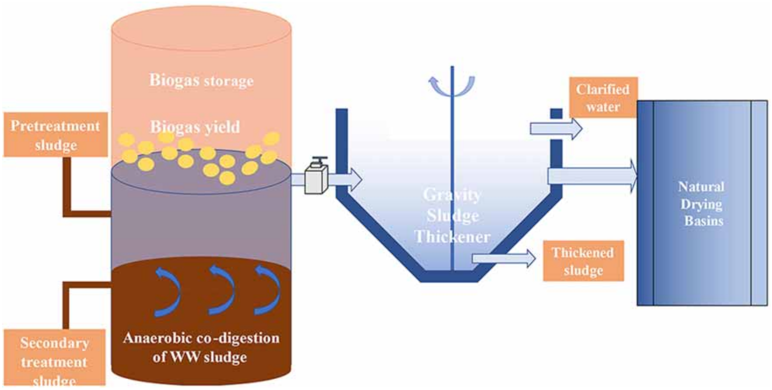

Figure 8 | SWW sludge treatment and disposal process.

3.4. Sustainability and environmental analysis (CAS + AnMBR LCI analysis of resulting by-products)

Organic loading rate (OLR) resulted in 0.5 g COD/L/h on average, which strongly indicates the energy potential, indicating that methane is detected and captured, as well as carbon emission where methane is not charged. The elevated OLR assessed represents an excellent potential for resource recovery. The estimated average biogas produced is 0.6 m^3/h. As mentioned, biogas is a renewable energy source. Thus, it can be a substitute for natural gas, reducing dependence on fossil fuels and a source of green energy while mitigating greenhouse gas emissions and the carbon footprint (Carrere *et al.* 2010). These results are due to the characteristics of the AD by-product, a methane-rich product containing 50–70% or even higher amounts of methane (CH_4), making it suitable for generating energy. For example, by applying AD technology, fossil fuels were reduced to about 50% in Europe. This is because biogas is flammable, and thus, it can be a fuel source. Therefore, it is expected that turning it into fossil fuels that can support the energy needs of the wastewater treatment plants, as a result, will help in the current energy shortages in Egypt. However, the advantages seem promising, yet it should be considered that biogas needs certain modifications in gas utilisation systems to achieve the same energy output (Liang *et al.* 2022). This is due to the characteristic fact that biogas has a lower energy density than natural gas. AD used in SWW eliminated and controlled foul odours by reducing the production of odorous compounds. Aside from reducing the waste and pathogens in the treatment, the adaptation of organic matter converges to biogas, which reduces the formation and generation of sludge volume, leading to lower disposal costs and potential operational cost recovery.

3.5. Future perspectives and opportunities

The research provided an insightful overview of the current practice of treating SWW, improving the WW quality, and minimising the excess bio-sludge produced, yet certain areas warrant further investigation. Notably, the biogas resulting from the CAS + AnMBR integrated system was not studied/examined in terms of precisely identifying and quantifying methanogenesis products. Thus, conducting a comprehensive study of this domain is highly recommended to benefit and gain optimal utilisation of the resulting by-products (Abdelrahman *et al.* 2020).

Both activated sludge and anaerobic digestion stand out as highly feasible and viable treatment methods, particularly for industrial wastewater, due to their cost-effectiveness and practicality compared with other treatment methods (Kumar Gautam *et al.* 2023). Thus, studying the cost of the treatment's life cycle is suggested. Thus, the integration of cost and feasibility assessments within the present treatment framework while concurrently considering an exceptionally sustainable, lean, and resource-efficient system (Wahaab *et al.* 2020). Moreover, advanced artificial intelligence (AI) technology can be utilised to optimise the treatment processes, enhance predictive capabilities, and further improve the resource recovery and operational efficiency of the system (Abdollahzadeh *et al.* 2024; Ali *et al.* 2024; El-Kenawy *et al.* 2024b; Zerouali *et al.* 2024).

4. CONCLUSION

This study investigated an integrated activated sludge (CAS) and AnMBR system to achieve high treatment efficiency while minimising excess sludge production. The wastewater was initially subjected to CAS treatment operated at a F/M ratio of 0.2.

The CAS wastewater was then treated by anaerobic digestion in the AnMBR with an organic loading rate of 0.5 g COD/L/h. LCI analysis determined the treatment cycle's main inputs, outputs, and environmental impacts.

The integrated system achieved 94% COD removal, 93% TN removal, 83% total phosphorus removal, and over 90% removal of natural and VSSs. This exceeded the performance of the standalone CAS treatment, which achieved 84% COD removal, 86% nitrogen removal, 77% phosphorus removal, and 81% suspended solids removal. It also reduced the generation of excess sludge by 30% compared to CAS treatment through the anaerobic digestion process. The estimated biogas production rate was 0.6 m^3/h with 50–70% methane content.

The study showed lucrative nutrient removal rates as well as minimising excess bio-sludge generation in light of the miniature Y_{obs} values, which made it possible to study the environmental impacts and create a sustainable analysis of the discharged water, sludge, and the by-products in general. Full-scale implementation of CAS–AnMBR would require significant infrastructure changes, such as more resistant solid membranes operating at usual high solid concentrations of SWW and further anaerobic digestion for higher yields of biogas. High initial capital and operational costs of the membrane bioreactors and their maintenance against fouling limit large-scale use without corresponding investment. Further areas of research could thus be explored by finding out how such operations might implement renewable energy sources, such as solar or wind, as an offset to their actual energy demands and optimise the process for biogas production through co-digestion with other organic waste streams to improve methane yields. This might include an assessment of the extent to which the CAS–AnMBR system is resilient against wastewater volume and composition variability from various industrial fields. This will further extend its practical applications in the design of modular systems with scalable design, which suits diverging industrial needs.

CAS treatment with AnMBR technology shows promise as an integrated SWW management strategy. This study's high pollution removal efficiencies, substantial biosolids minimisation, and potential renewable energy generation demonstrate sustainability benefits compared to standalone methods.

FUNDING

This research was funded by the Taif University, Taif, Saudi Arabia (TU-DSPP-2024-14)

ACKNOWLEDGEMENTS

The authors extend their appreciation to the Taif University, Saudi Arabia, for supporting this work through the project number (TU-DSPP-2024-14).

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 17 March 2024; accepted in revised form 15 November 2024. Available online 13 December 2024