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Techno-economic assessment of an integrated sewage treatment system for waste-to-ammonia and electricity generation†

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A techno-economic assessment was carried out for a novel system that combines anaerobic digestion, electrodialysis, electrochemical ammonia stripping, vacuum membrane distillation, and a direct ammonia-fed solid oxide fuel cell to generate electricity from sewage treatment. Traditional wastewater treatment systems focus primarily on removing contaminants with limited resource recovery opportunities. The current study presented an innovative wastewater treatment system designed to address the limitations of conventional plants. An assessment was performed to determine the scalability of the proposed system to effectively produce ammonia from municipal wastewater, which can be further used for electricity generation. The levelized costs of ammonia (LCOA) and electricity (LCOE) were determined along with the net present value, payback period, return on investment and benefit-cost ratio. Detailed evaluations of the cost and performance of each processing unit indicated that long-term cost savings can be achieved despite substantial initial capital investment. The proposed system can produce ammonia at 0.11 Mt per year, which can further generate around 254.58 GWh of electricity per year. The findings demonstrated that at a discount rate of 5% and assuming plant life to be 25 years, LCOA and LCOE were estimated at US$ 238.09 per ton of ammonia and US$ 0.16 per kWh of electricity, respectively. A sensitivity analysis was conducted by varying the discount rate (0–20%), which demonstrated that ammonia production was comparatively more financially stable at high discount rates under a certain threshold. The study provided a model for modern wastewater treatment plants aiming for energy neutrality and resource recovery, aligning with global sustainability goals. Future research can explore renewable energy integration with the assessed system to sustain long-term operations.

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Sustainability spotlight

The increasing global population and associated high water consumption patterns have led to an increased generation rate of domestic wastewater. Direct discharge of such wastewater to the sea or land is not ideal as it can cause environmental harm. On the other hand, conventional wastewater treatment systems are primarily designed for contaminant removal, neglecting the opportunities for resource recovery. Hence, the current research introduces a hypothetical integrated sewage treatment system that combines anaerobic digestion, electrodialysis and electrochemical ammonia air stripping followed by vacuum membrane distillation and a direct ammonia-fed solid oxide fuel cell to recover resources and/or generate electricity from domestic wastewater treatment. Techno-economic feasibility highlights the potential of the integrated treatment system to target energy neutrality and the circular economy. Therefore, the work aligns with the following UN sustainable development goals: SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), SDG 12 (responsible consumption and production), and SDG 13 (climate action).

1 Introduction

Water is generally needed for almost all activities carried out in day-to-day life. The rate of the overall global population is increasing, and so are the resource-intensive water consumption patterns. An average of 380 billion m^3 of municipal wastewater is discharged on an annual basis around the world. Projections estimate that this figure will reach 470 billion m^3 by the end of 2030 and 547 billion m^3 by 2050, which represents an increment of 24% and 51%, respectively, over the current municipal wastewater generation,[1] therefore emphasizing the alarming situation. This global concern is equally relevant at the regional level, particularly in arid and water-stressed countries. Currently, Qatar has one of the world's highest domestic water consumptions per capita, *i.e.*, 500 L per day.[2] The statistics in Fig. 1 show that 43% of potable water is consumed domestically, followed by agriculture.[3] This reveals that a substantial amount of water is discarded from domestic

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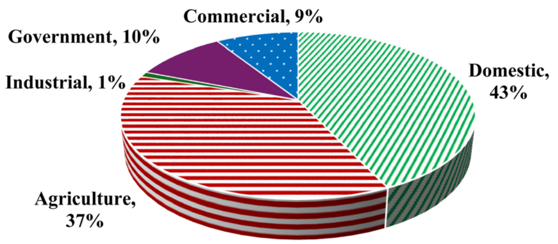


Fig. 1 Water consumption in different sectors of Qatar (data extracted from Ismail[3]).

households, which brings the need to treat municipal wastewater, also termed sewage.

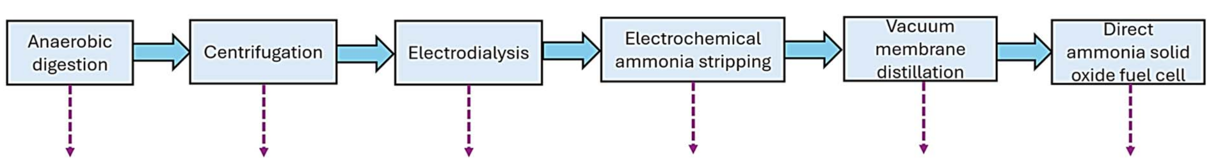
The average ammonia-nitrogen (NH_3–N) concentration in raw municipal wastewater typically reaches up to 40 mg L^{-1},[1] while an average concentration of 75 mg L^{-1} has been observed in Qatar's untreated effluent.[4] Considering the huge volume of municipal wastewater discharged daily, ammonia removal is essential to avoid environmental pollution.[5] It should also be noted that ammonia is a valuable component of fertilizers,[6] an excellent hydrogen carrier and used as a clean fuel.[7]

The more conventional types of municipal wastewater treatment at large operational plants focus on removing ammonia and other valuable by-products rather than recovering them. Recent studies have highlighted the need for an integrated treatment system to recover multiple resources from municipal wastewater streams while also remaining economically feasible for large-scale implementation with lower lifecycle impacts.[8,9] Addressing this need, the present study performs a techno-economic assessment (TEA) of a hypothetical novel integrated system that combines different forms of treatment approaches to simultaneously recover ammonia from domestic wastewater and use it as a source of electricity.

The anaerobic digestion (AD) of municipal wastewater can provide benefits such as low energy demand, digestate rich in nutrients, and biogas generation.[10] The resulting anaerobic digestate contains high levels of ammonium–nitrogen (up to 1400 mg L^{-1}) that can be further concentrated for producing fertilisers and energy.[11,12] Multiple techniques have been researched for ammonia recovery from digested wastewater. Electrodialysis (ED) is one of the mature electrochemical membrane-based technologies that separates and concentrates ions in wastewater. ED has been successfully used for NH_4^+ recovery from anaerobically digested sludge.[11,13] One of the studies claimed a concentration of NH_4^+–N reaching more than 10 000 mg L^{-1} for anaerobic digestate using electrodialysis.[14] However, additional stages are required to recover ammonia because other ions coexist with ammonium ions in the ED concentrate. In this regard, ammonia stripping is necessary to isolate ammonia and capture it for further applications.

Electrochemical ammonia stripping (EAS) is an innovative method to extract ammonia from effluent with high ammonium concentrations. Previously, EAS has been studied for ammonia recovery from source-separated urine, having a 93% efficiency[15] and liquid anaerobic digestate with around 90% efficiency.[12] However, acquired ammonia is in aqueous form. This means an individual process will be required to separate ammonia from water. Vacuum membrane distillation (VMD) can aid the separation by employing a porous hydrophobic membrane. Only vapour or gaseous species can cross through the membrane pores upon applying a vacuum.[16]

Ammonia is known to be a promising hydrogen carrier because of its high H_2 content (75% by volume) and low-pressure liquefaction storage, which leads to easier transportation. Ammonia-based fuel cells can provide cleaner energy solutions.[17] Direct ammonia solid-oxide fuel cells (SOFCs) are emerging as an efficient, carbon-free power generation



	Anaerobic digestion	Centrifugation	Electrodialysis	Electrochemical ammonia stripping	Vacuum membrane distillation	Direct ammonia solid oxide fuel cell
+	• Biogas production • Operates at high organic load rates with sludge volume reduction • Provides environmental benefits, i.e., decreased greenhouse emissions and pathogen control • Well-established	• Offers up to 100% separation efficiency • Excellent for dewatering hard-to-handle sludges • Ability to process large volumes of samples • Well-established technology	• Compact system design • Superior water recovery • Prolonged service life • Separation done without changing phases • Higher concentration of the targeted ion/s in the concentrate	• Promising results for recovering ammonium from high-concentration wastewaters • Zero carbon emissions • Achieves high-purity concentrate	• Lower operating temperatures than conventional distillation methods • High rejection of non-volatile solutes • High permeate flux • Smaller environmental footprint • Allows separation without chemical addition	• Carbon-free power generation • High energy conversion efficiency with higher power densities
-	• High capital expenditure requirements • Digestate handling requires care and further processing	• Energy-intensive process • Provision required for noise control	• High operational expenditure • Feed-water requires pre-treatment, i.e., in the case of domestic wastewater • Membrane fouling • Ion competition	• Presence of some toxic by-products (i.e., certain heavy metals) if other compounds are present in the feed • High operational expenditure needs • Membrane fouling	• Greater risk of membrane wetting • Requires specialized equipment (vacuum pumps, condensers) making its capital expenditure high • Vacuum maintenance can be challenging	• Longer start-up times due to high operating temperature • High capital cost • Requires operational optimization

Fig. 2 Advantages and disadvantages of the considered process in the integrated system.

technology. Operating at high temperatures (>650 °C), these fuel cells decompose ammonia to generate electricity at a net efficiency of over 50%.[18,19] Long-term durability tests on 1 kW-class SOFC stacks revealed excellent stability and 57% energy conversion efficiency,[20] hence indicating the potential of SOFCs. A summary of the pros and cons of the discussed technologies is enlisted in Fig. 2.

The current study hypothesized a treatment system that combined AD-ED-EAS-VMD-SOFC for municipal wastewater to provide energy and cost savings compared to conventional treatment systems. TEA is a methodology that evaluates the capital costs, operating expenses, and revenue streams associated with the product, process, or technology, which helps identify the key factors affecting its economic viability.[21]

Techno-economic feasibility of energy and phosphorus recovery from municipal sewage by incineration has been evaluated by Bagheri, Öhman,[22] in which co-combustion resulted in reasonable heat recovery costs, *i.e.*, around 20 to 32 US$ per MWh (19 to 30 € per MWh) and promising phosphorus recovery. In one of the research studies, the modification of conventional wastewater treatment plants from energy-consuming to energy-generation facilities with the utilization of residual biosolids, process modification and effluent thermal energy recovery was done to result in a net present value of US$ 177.36 million.[23] Likewise, process upgradation for mixed sludge treatment in terms of primary sludge thickening and post-aerobic digestion stages was introduced to reduce produced sludge and increase nutrient recovery. Cost analysis revealed that upgrade alternatives were cheaper than conventional plants, considering the different dynamics involved.[24]

TEA of membrane-based pre-concentration and post-treatment of municipal wastewater has also been performed by He, Fang *et al.*[25] for water-energy reclamation. The proposed combined membrane pre-concentration followed by reverse osmosis and anaerobic digestion was found to have an overall operating cost of 0.16 US$ per m^3 (CNY 1.132 per m^3). Techno-economic assessment has been done for electrodialysis treatment of municipal wastewater,[13] indicating lower capital and operational costs than traditional nitrification/denitrification and anammox technologies. Similarly, another research study evaluated the selling price of ammonium sulphate recovered from anaerobically digested domestic wastewater by air stripping as US$ 0.046 per kg. The estimated price was lower than the average selling price of ammonium sulphate in farms in the United States, highlighting its economic viability.[26]

As briefly discussed, previous studies have explored the techno-economics of energy and nutrient recovery from municipal wastewater treatment systems employing various processes. However, to the best of the authors' knowledge, no prior research focussed on the techno-economic feasibility of the integration of anaerobic digestion, electrodialysis, electrochemical ammonia stripping, vacuum membrane distillation, and ammonia fuel cells to acquire electricity from municipal wastewater. The recent shifts in policy, sustainability goals, and resource economics are encouraging the wastewater sector to explore advanced treatment strategies that move beyond compliance and towards value recovery. This is particularly relevant for ammonia, which is a viable hydrogen carrier and clean fuel. Furthermore, advances in electrochemical and membrane-based systems have reduced operational barriers and promised an efficient integration of resource recovery units.[27,28] Conventional systems may be economically feasible and well-established, yet they may result in a single purpose, *i.e.*, contaminant removal rather than recovery. Therefore, the studied approach not only offered a novel methodology to treat domestic wastewater but also assessed the energy and revenue generation from the system, which is a critical factor in building industry confidence for adoption.

The primary aim of the research was to conduct a comprehensive TEA of the proposed system. The specific objectives included determining the capital and operational expenditure associated with the system, calculating the levelized costs of the subsequent products produced, *i.e.*, ammonia and electricity, and lastly, evaluating the economic feasibility of the integrated approach to achieving sustainable resource recovery and energy production.

2 Methodology

2.1 System boundary

A system boundary was designed, as shown in Fig. 3. The municipal wastewater entering the system undergoes anaerobic digestion. The digestate from the anaerobic digestor was centrifuged. The supernatant of the digestate was further treated by electrodialysis to separate the ammonium ions and concentrate them. The concentrate solution from the ED was used as a feed for electrochemical ammonia stripping. The reaction leads to the production of ammonia but in aqueous form. Ammonia was separated from the aqueous solution using vacuum membrane distillation and then used to generate electricity through the solid oxide fuel cell. The economic feasibility of producing ammonia and generating electricity through the system was analyzed.

To ensure an uninterrupted operation, the individual units in the proposed system are functionally connected through pumps, valves, and pipelines, which facilitate the control of mass or volume flow from one process to the next. In addition to this, the system design also accounted for the labour essential to ensure safe, smooth and controlled operation. The team for each processing unit included a plant manager, engineer, supervisor, operator, maintenance supervisor and technician, as well as a safety officer. This staffing was done to ensure that the operational functionality was maintained while also supporting routine inspections, maintenance, and on-site troubleshooting.

It must also be noted that for the techno-economic analysis, the only by-product considered was biogas from the anaerobic digestion of sewage to generate electricity. However, the other by-products, such as the dilute resulting from electrodialysis and ammonia stripping units and the unrecovered ammonia in the reject of the vacuum membrane distillation unit, can be recirculated back to the electrodialysis unit for further ion recovery. This will enhance the overall resource recovery,

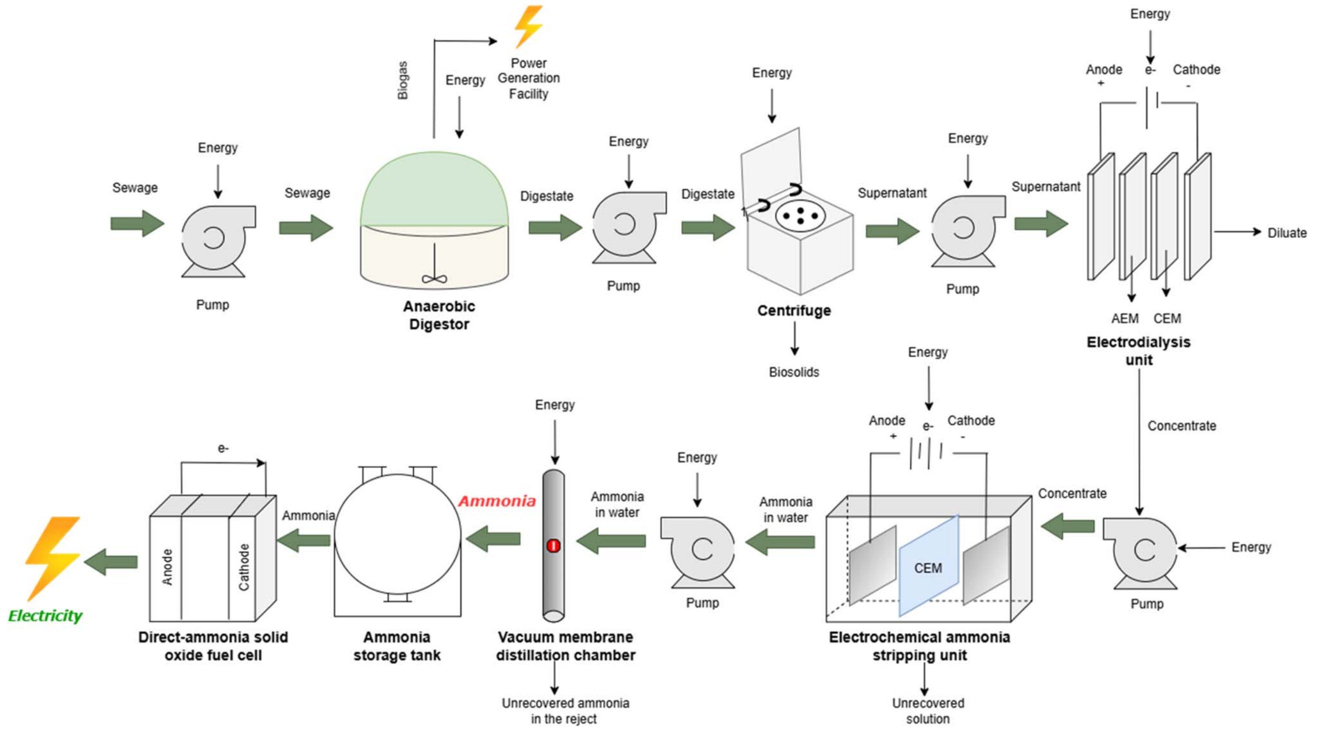


Fig. 3 System diagram for ammonia recovery and associated electricity production from wastewater treatment plant.

aligning with the principles of the circular economy. However, this is not included in the scope of the current investigation.

2.2 Data inventory

Data inventory was a crucial step in the analysis. The data were collected from the research articles and implemented projects. The data included the equipment cost for individual processes, which accounted for capital expenditures (CAPEX) and operational costs (OPEX). CAPEX represents the cost of the purchased equipment, installation, instrumentation, construction, piping, electric work, land and facility requirements, site development, engineering and supervision, and contingencies, which are one-time. OPEX sums up the annual operating costs. Operating costs include maintenance, energy, and labour costs. Also, the costs of the replaceable consumables are accounted for in operating costs.

All the necessary data were extracted and input into Excel spreadsheets. The cost data obtained had different working flow rates, so those were scaled up and down based on the current scenario. Also, some of the data were from past years, so the Chemical Engineering Plant Cost Index (CEPCI) was employed to convert them for 2024. The formula to calculate the equipment costs is given in eqn (1).[29]

$$\text{Equipment cost} = \text{Base cost} \times \left(\frac{\text{Design size}}{\text{Base size}}\right)^n \times \left(\frac{\text{CEPCI}_c}{\text{CEPCI}_b}\right) \quad (1)$$

The size here refers to the mass or volumetric flow rate. CEPCI_c is the index for the analysis year (taken as 2024), and CEPCI_b is for the base year (as quoted in the reference). The 'n' in the equation is the scaling exponent, which varies for different equipment. The scaling exponent for certain basic equipment is defined as a standard, but it can be taken as 0.6 for the other equipment according to the 'six-tenth' thumb rule for scale economies.[30] The scaling exponent for some of the components of the system are listed in Table 1.

The other key components of CAPEX were priced in correlation with the calculated purchased equipment cost.[31]

For the OPEX, the labourer's wage as per their position was taken, based on Qatar's reference [32] for eight working hours daily. The electricity cost was taken as 0.13 QR per kWh in Qatar,[33] consistent with all the processes considered in the system boundary.

Table 1 Scaling exponents for some equipment[29]

Equipment	Scaling exponent	Reference
Feed tank	0.7	29
Digestor	0.6	
Pump	0.6	
Centrifuge	0.6	
Reactor	0.6	
Ammonia storage tank	0.7	

2.3 Processing unit variables

The estimated costs associated with the individual processing units in the proposed system are enlisted in Table 2, while the

Table 2 Cost summary of the components and consumables used in the proposed hypothetical treatment and recovery system

Process	Component/Consumable	Description	Base cost	Base cost, US$ – indexed to 2024	Base flow	Base year	Reference
Anaerobic digestion	Feed tank	Stainless steel, 20 300 gallons, 14′ D × 18′ H	174 800 US$	253 980	842 tons per day	2010	29
	Anaerobic digestor	Stainless steel, a volume of about 2425 m^3	8 020 000 AU$	5 213 000	86.4 tons per day	2024	37
	Feed pump	2500 gal per min, a submersible rail mounted with 50 HP	231 488 US$	336 347	10 400 tons per day	2010	29
	Power generation facility	Biogas storage tank and power generator	1 020 000 AU$	663 000	86.4 tons per day	2024	37
	Chemicals	Sodium bicarbonate for pH adjustments (per ton)	1 AU$	0.65	—	2024	39
Centrifugation	Pump	2500 gal per min, a submersible rail mounted with 50 HP	231 488 US$	336 347	10 400 tons per day	2010	29
	Centrifuge	Capacity of 1000 m^3 of the effluent	114 875 US$	154 201	997.6 tons per day	2020	40
Electrodialysis	Secondary effluent pump	Capacity of 3 mega gallons per day	450 000 US$	646 794	9463.54 tons per day	2015	42
	Feed tank	Capacity 320 gallons per min	320 250 US$	460 302			
	Feed pump	Capacity of 1.5 mega gallons per day	480 000 US$	689 914			
	Treatment system	Capacity of 1.5 mega gallons per day	21,000 000 US$	30,183 728			
	Housekeeping	Clean-in-place system	100 000 US$	143 732			
	Acid feed system with storage	—	90 000 US$	129 359			
	Antiscalant feed system with storage	—	65 000 US$	93 426			
	Ammonium hydroxide feed system with storage	—	90 000 US$	129 359			
	Sodium hypochlorite feed system with storage	—	90 000 US$	129 359			
	pH adjustment	Carbon dioxide feed system	50 000 US$	71 866			
	Waste tank	Epoxy coated steel	848 769 US$	1 219 953			
	Tank roof adder	—	449 074 US$	645 463			
	Membranes	Anion and cation exchange membranes (lifetime:10 years)	1 036 800 US$	1 490 214			
Electrochemical ammonia stripping	Cation exchange membranes	FumaTech FKS50 (lifetime: 2 years)	7 US$	7	1 L per day	2024	45
	Anode	Titanium-based with 64 cm^2 geometric area (lifetime: 10 years)	157 US$	157			
	Cathode	Stainless steel mesh cathode with 64 cm^2 geometric area (lifetime: 10 years)	7 US$	7			
	Reactor (with the pump included)	Two-chamber parallel-plate reactor, acrylic-18 cm × 18 cm ×1.9 cm	162 US$	162			
	Sodium chloride	1.46 g L^{-1} required for electrolyte preparation	0.05 US$	0.05			

Table 2 (*Contd.*)

Process	Component/Consumable	Description	Base cost	Base cost, US$ – indexed to 2024	Base flow	Base year	Reference
Vacuum membrane distillation	Distillation setup	The entire module, including the vacuum pump, condenser and other auxiliaries	569 433 US$	764 370	320 m^3 per day	2020	46
	Membranes	280 m^2 geometric area (lifetime: 6 months)	20 160 US$	27 061			
Ammonia storage	Storage tank	Capacity of 28 000 gallons	196 000 US$	284 784	30.98 tons per day	2010	29
Direct ammonia solid oxide fuel cell	Complete stack	Active area of 80 cm^2 (includes an anode, a cathode, and an electrolyte)	31 444 US$	42 209	10 kW nominal power	2020	48
	High-temperature heat exchanger	90% efficiency	5467 US$	7334			
	Low-temperature heat exchanger	90% efficiency	12 408 US$	16 656			
	Decomposition chamber	Adiabatic	2207 US$	2963			
	Afterburner	Adiabatic	436 US$	586			
	Blower	90% efficiency	3915 US$	5255			
	Inverter	—	32 413 US$	43 509			

descriptions of each unit's configuration and function are provided in the following sub-sections.

2.3.1 Anaerobic digestor. The wet sewage in Qatar is generated at a rate of 300 000 m^3 per year,[34] which was considered the initial volumetric rate in the analysis. The initial process of the proposed system involved the anaerobic digestion of the sewage. Biogas was a useful by-product of AD. The digestor was assumed to operate at normal room temperature, *i.e.*, 25 °C,[35] and equipped with a stirrer having a mean electricity consumption of 5.9 kWh per ton of feedstock.[36]

It was reported that for a large-scale anaerobic digestion plant in Sydney dealing with 86.4 tons of sewage sludge per day, the average biogas generation reaches up to 8.90 m^3 per ton of sewage sludge. This yields approximately 7.61 kWh m^{-3} of biogas generated. As per the calculations, the biogas density was 0.80 kg m^{-3}. The density of sludge was 997.58 kg m^{-3}.[37] The levelized cost of generating electricity from biogas varies according to the feedstocks and ranges from US$ 50 per megawatt-hour (MWh) to US$ 190 per MWh. This averages 120 US$ per MWh.[38] The yearly maintenance cost was taken as 3% of the CAPEX.[39]

2.3.2 Centrifuge. A large-scale centrifuge (centrifuging approximately one megalitre per day of wastewater effluent) has a energy consumption of 1500 kWh per day, assuming that the centrifuge works for 10 hours a day for 1000 m^3 of the effluent.[40] The pump used for the centrifuge was assumed to be the same as an anaerobic digestor. The maintenance costs were considered 2% of the CAPEX each year.[40] The digestate, on average, has 1.7% of the solid fraction.[41] Hence, it is assumed to be negligible.

2.3.3 Electrodialysis unit. The cost data associated with each component for electrodialysis were obtained from an industrial report.[42] 10% of the capital expenditures were assumed to be the maintenance allowance for equipment breakdown and other overhead costs.[43] The membrane replacement and labour costs, as well as the chemical allowances, were accounted for in the operational and maintenance costs. The concentrate recovery from the electrodialysis unit was taken as 50%.[44] The specific power consumption of the secondary effluent pump, the pumping system, and the electrodialysis process itself was assumed to be 0.07 W/L, 1.11 W/L, and 0.03 W/L, respectively.[42]

2.3.4 Electrochemical ammonia stripping unit. For electrochemical ammonia stripping, 1.46 g L^{-1} of sodium chloride is required to increase the conductivity of the water. As stated in the research, the specific electric power consumption of EAS was about 2.29 W/L for the module and 0.076 W/L for the pumping.[45] The annual maintenance cost was assumed to be 3% of the CAPEX. The ammonia recovery from electrochemical ammonia stripping could reach up to 90% for anaerobic digestate.[12] However, the obtained ammonia would be in aqueous form.

2.3.5 Vacuum membrane distillation chamber. Vacuum membrane distillation is useful in removing ammonia from its aqueous solution. The equipment consists of a PTFE membrane, membrane cell, and peristaltic pump to transfer the incoming flow to the cell, as well as a vacuum pump on the permeate side, with a stirrer and heater. The costs considered for the analysis were in the form of purchased equipment costs and operating and variable costs taken from Shi, He *et al.*[46] It was reported in the same reference that the electricity requirement of the VMD process was 0.10 Wh L^{-1} and 49.68 MJ of heat is required per m^3 of the feed. Ammonia recovery could be up to 85% from the feed solution.[47]

2.3.6 Ammonia storage tank. The achieved ammonia by vacuum distillation was then presumably stored until it was needed to convert it into electricity. The maintenance cost for the tank was assumed to be 3% of the total CAPEX.

2.3.7 Direct ammonia solid oxide fuel cell. The stored ammonia was then used as a fuel in a direct ammonia-SOFC to generate electricity. The SOFC unit operates at 750 °C. The stack utilizes nickel-based anode-supported planar cells. At temperature over 650 °C, it is assumed that ammonia is almost fully decomposed. The operational and maintenance costs were taken as 18.7% of the total initial investment.[48] The formula to calculate the electric work from the SOFC is defined in eqn (2).[49]

$$\eta = \frac{\dot{W}_{\mathrm{out}}}{\dot{m}\mathrm{NH_3} \times \mathrm{LHV}} \quad (2)$$

η represents the energy conversion efficiency of the SOFC, which is approximately 52.1%.[48] The term $\dot{m}$ is the mass flow rate of ammonia coming into the system, and LHV is the low heating value of ammonia, which is 18.7 MJ kg^{-1}.[50] $\dot{W}_{\mathrm{out}}$ is the power output from the fuel cell. The price of electricity sold to the grid using the SOFC was taken as 0.24 US$ per kWh.[51]

2.4 Economic assessment

A comprehensive economic assessment was done to evaluate the feasibility of the novel system for green ammonia and electricity generation from sewage. For this purpose, levelized cost, net present value (NPV), return on investment (ROI), payback period (PBP), and benefit-cost ratio (BCR) were estimated for ammonia and electricity production using eqn (3)–(7).[32] In the equations, '*r*' is for the plant's lifetime, given in years.

$$\text{Levelized cost}\left(\frac{\$}{\text{product unit}}\right) = \frac{\text{CAPEX} + \left(\left(\sum_{1}^{t=r}\text{OPEX} - \text{byproducts sales}\right)(1+\text{discount rate})^{-r}\right)}{\sum_{1}^{t=r}\text{product yield}(1+\text{discount rate})^{-r}} \quad (3)$$

$$\text{Return on investment (\%per year)} = \frac{\text{Net cash flow}}{\text{Initial investment}} \quad (4)$$

$$\text{Net present value(\$)} = \sum_{1}^{t=r}\frac{\text{Net cash flow}}{(1+\text{discount rate})^{-r}} - \text{Initial investment} \quad (5)$$

$$\text{Payback period (years)} = \frac{\text{Initial investment}}{\text{Net cash flow}} \quad (6)$$

$$\text{Benefit} - \text{cost ratio} = \frac{\dfrac{\text{Net benefits}}{(1+\text{discount rate})^{r}}}{\dfrac{\text{CAPEX} + \sum_{1}^{t=r}\text{OPEX}}{(1+\text{discount rate})^{r}}} \quad (7)$$

The finances associated with processing units, until VMD, were considered to calculate the economic parameters associated with ammonia production, and the whole system was taken to determine the financial stability of electricity generation.

2.4.1 Assumptions. The plant's life was assumed to be 25 years. The annual operation time was taken as a nominal value of 8000 hours.[52] The discount rate was estimated at 5%.[53] Additionally, the market price of ammonia was taken as 390 US$ per ton.[54]

3 Results and discussion

3.1 Yields of ammonia and electricity

The mass flow rate entering the system was 300 000 m^3 per year (Qatar's scenario), which can be translated to 819.92 tons per day (Fig. 4). The flow was anaerobically digested in AD to produce biogas equivalent to 5.83 tons per day, considering the density and yield of the biogas per ton of sludge. The biogas could potentially generate power at a rate of 7.61 kWh m^{-3}. Therefore, the total power yield from the biogas in the current scenario was evaluated to be 55.58 MWh per day or 20.28 GWh per year, representing a significant energy offset potential from biological processing.

Post digestion, a total of 814.09 tons per day of the digestate was centrifuged, which separated the solid fraction, and the centrate/supernatant was processed in the ED unit. Two streams were generated from the ED unit in an equal proportion (50%), termed dilute and concentrate. The concentrate (saturated with ions), having a flow rate of around 407.05 tons per day, was then fed into the stripping unit, where 90% of the ammonium-rich stream was recovered. This stream was then passed through the vacuum membrane distillation chamber, where 85% of the ammonia was yielded from the stream. Hence, 311.52 tons per day of ammonia was produced as the result of the novel municipal wastewater treatment. By using eqn (2), the energy output was estimated at 31.82 MWh per day, in other words, the electricity could be produced at

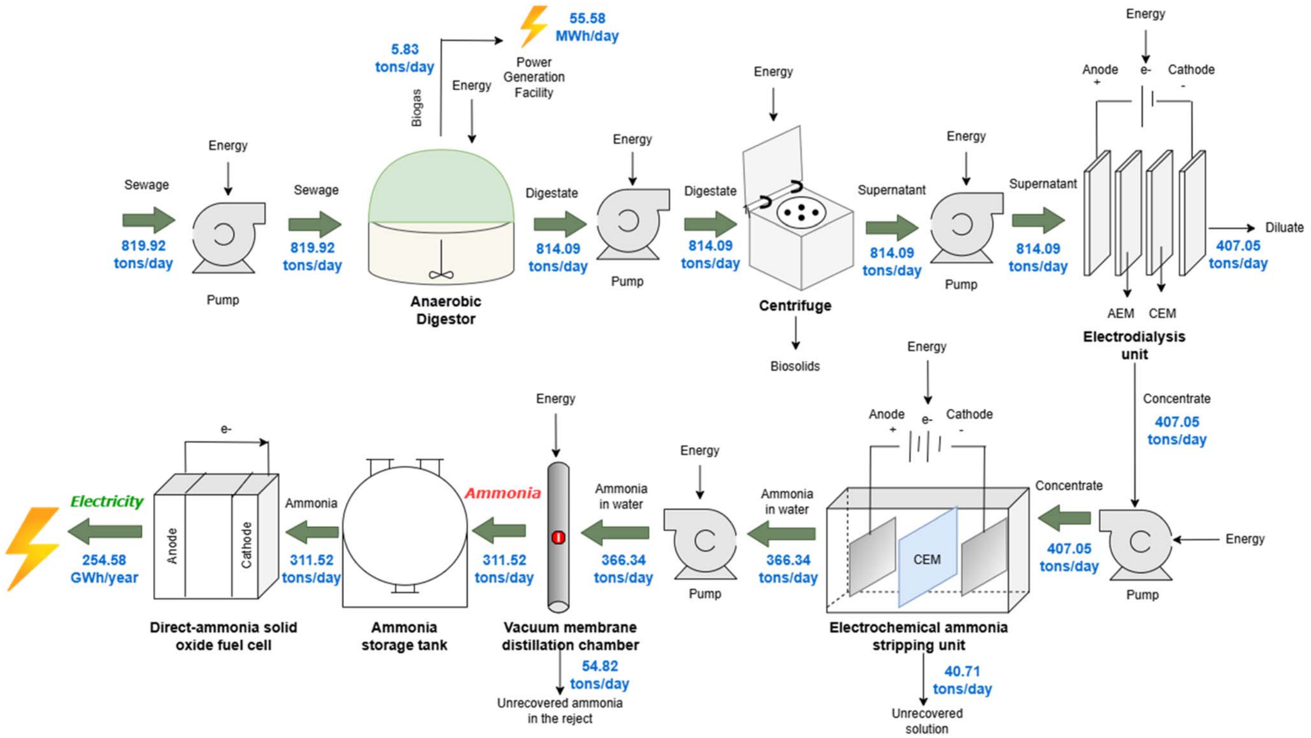


Fig. 4 Mass flow rates passing through different treatment units of the proposed system.

a rate of 254.58 GWh per year while taking 8000 functional hours.

The quantification of mass flow rates across each unit operation serves as a foundation element for the techno-economic assessment carried out in this study. These flow rates allow for the scaling of capital and operational costs using cost estimation methods, hence aiding in the economic modelling to assess the feasibility and scalability of the proposed integrated treatment solution.

3.2 Energy consumption of the proposed system

The electricity consumed by different processing components of the integrated system is presented in Fig. 5. The results are expressed both in GWh per year and as a percentage of the total

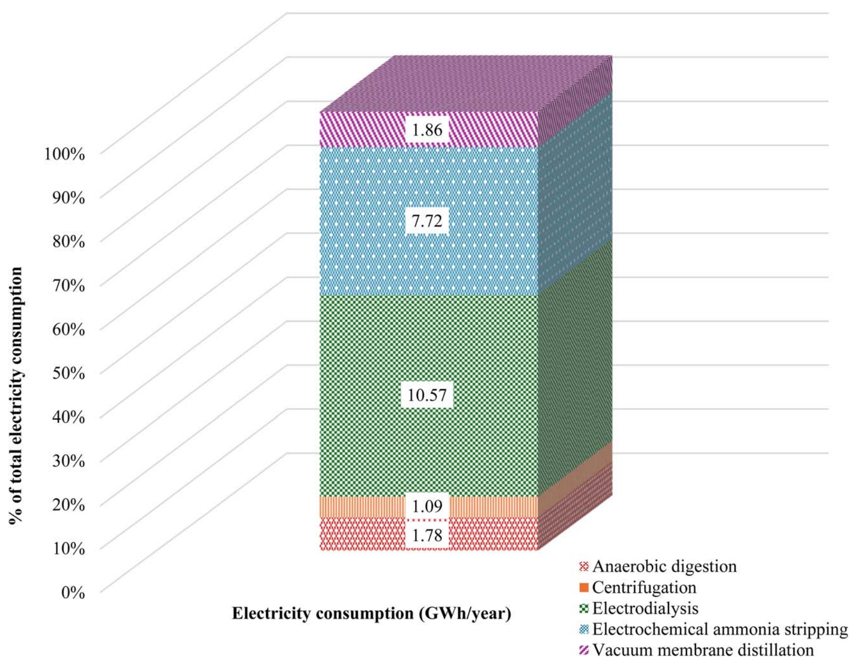


Fig. 5 Energy consumption breakdowns of system components.

system electricity demand. The total electricity demand of the system was calculated to be approximately 23.02 GWh per year.

Electrodialysis exhibited the highest energy consumption, *i.e.*, representing 45.9% of the total demand. This can be explained by the electricity required to drive the ion transport through the membranes, which requires continuous voltage application and contributes significantly to the energy intensity of the system. However, the process is essential for concentrating ammonium ions from the anaerobic digestate, enabling downstream recovery steps. The electrochemical ammonia stripping unit also consumed substantial energy, *i.e.*, 7.7 GWh per year, which is 33.5% of the total. Similar to electrodialysis, for a high-purity recovery, a continuous voltage is required to allow the movement of ions through the cation-exchange membranes. ED and EAS are followed by vacuum membrane distillation, which accounted for 8.1% of the overall energy required. The process requires energy to develop a vacuum and maintain thermal gradients for phase separation.

The other remaining units, such as the anaerobic digestor and centrifuge, had lower energy needs, consuming 7.7% and 4.7% of the total electricity of the whole system. The reason for these lower energy demands can be linked to the reliance on biological activity in the case of AD and mechanical separation for centrifugation, which are less energy-intensive compared to the membrane or electrochemical processes.

It must be noted that electricity consumption associated with an ammonia storage tank is considered negligible due to its passive functionality. Once the ammonia is separated, it is stored in a temperature-controlled tank, which requires minimal energy and, thus, has almost negligible impact on the final consumption.

It can be observed that the system consumed significant amounts of energy. However, the energy recovery potential of the system far exceeded its consumption, ensuring energy viability. The biogas produced from anaerobic digestion contributed approximately 20.28 GWh, while electricity generated from green ammonia *via* the SOFC adds an additional 254.58 GWh per year, resulting in a combined output of 274.86 GWh per year. The system demonstrated a net positive energy balance, affirming its self-sustainability and surplus energy generation potential.

These results highlight the importance of unit-level energy analysis to determine the hot spots for optimizing energy efficiency. One pathway for reducing long-term energy consumption is the incorporation of renewable energy sources, such as solar photovoltaic systems, which can supplement grid electricity. Additionally, the system itself generates energy in the form of biogas from anaerobic digestion, which could be looped internally to power high-energy demanding units such as ED and EAS.

3.3 Capital and operational expenditures of the whole system

An elaboration of the capital and operational expenditures of each treatment unit in the designed hypothetical system could be graphically viewed in Fig. 6. The total capital expenditure of the novel treatment system for electricity generation was estimated at approximately US$ 141.68 million, while the operational expenditure to be paid yearly was nearly US$ 32.02 million. Approximately 47% of the total CAPEX was associated with the anaerobic digestor due to the scale and infrastructure requirement of the digestion facility, which includes gas-tight reactors, pumps, and additionally a power generation facility for biogas. However, the OPEX associated with AD remained relatively low (US$ 3.73 million per year), given that the biological treatment process depends mainly on microbial activity and requires limited energy input and maintenance. The revenue generated from the biogas in the current study was estimated at US$ 2.43 million, calculated from the electricity generation from biogas.

In contrast, electrodialysis and electrochemical ammonia stripping units were identified as cost-intensive, particularly in

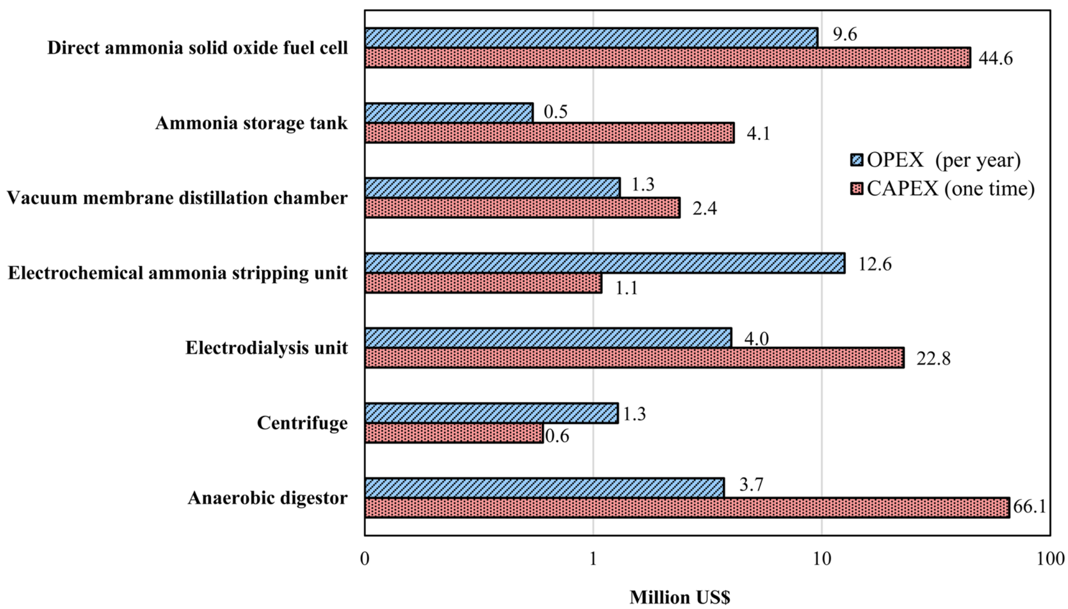


Fig. 6 CAPEX and OPEX breakdown for different units of the novel system.

terms of operational expenditure. The EAS unit recorded the highest OPEX, accounting for 38% of the OPEX of the integrated treatment and recovery system. The elevated operational costs are largely due to the high energy consumption (Fig. 5), replacement of membranes, anodes, cathodes, and the chemical requirements of the electrolytes to sustain efficient ion transport. The electrodialysis unit also had a substantial OPEX associated (12% of the overall OPEX per year) due to similar reasons.

The centrifugation unit displayed minimal capital investment, *i.e.*, US$ 0.6 million. Nevertheless, it had higher operational costs (US$ 1.28 million per year) than its CAPEX, mainly due to its energy demands. The vacuum membrane distillation chamber and ammonia storage tank represented lower-cost units. The reason is that there are fewer mechanical components, and physical (rather than chemical) separation is primarily performed in the VMD chamber, while simple mechanical design and passive function led to lower costs of the storage tank.

Lastly, the SOFC also contributed substantially to both capital and operating costs. These high costs result from the intricate nature and function of the cell and its mechanical complexity due to the different components used in the cell. SOFCs offer comparable efficiency and ensure clean energy production. However, their commercialization is still ongoing, making them susceptible to high investment and maintenance costs. Despite this, the electricity generated from SOFC operation can provide a valuable offset, potentially compensating for its elevated cost structure over time.

The results of the cost analysis reveal that both capital and operational expenditures are influenced by the energy intensity and technology maturity of the units employed in the integrated treatment system. This highlights the need for energy optimization across the units to improve the economic viability of the integrated system. Additionally, the high chemical (salt) requirements for the electrolytes can be fulfilled by utilizing the salt from the brine or from a similar source to further optimize the costs.

High capital expenditures are linked to anaerobic digestion and solid oxide fuel cells, but these are the main units for generating electricity *via* the treatment of wastewater, thus offsetting the high costs. In addition to this, certain units such as EAS, VMD, and SOFC are still undergoing commercialization, which, when fully commercialized, may reduce the costs even further.

Therefore, the results quantified the capital and operational cost requirements of integrating the mentioned technologies and provided an economic interplay between them, thus developing a foundation for an implementation. CAPEX and OPEX breakdowns allow for the identification of most resource-intensive components so as to develop strategies for enhancing cost-efficiency. This side of techno-economic assessment is often overlooked in the prior literature.

3.4 Levelized cost, net present value, return on investment, and payback period

The economic parameters were evaluated for ammonia and electricity generation, at a base discount rate of 5%. All the other necessary details and readings are provided in the ESI Data.† The discount rate basically refers to the interest rate used to determine the present value of future cash flows. Sensitivity analysis was also done by changing the discount rates from 0% to 20% to observe its effect on the levelized cost and net present value of the targeted products (Fig. 7). Sensitivity analysis is an important tool in techno-economics that gives a better picture of the economic outcomes of a project by changing the input parameters. It helps identify the economic risks to ensure robust decisions regarding the viability of technologies or systems. By changing the discount rates, as in the current study, it would allow a better understanding of the system's economic performance to market volatility, thus informing more resilient decision-making.

If the system only produces green ammonia with the assumptions made, the levelized cost (LCOA) equals approximately US$ 238.09 per ton and a net present value of US$ 101.49 million. A total of 311.52 tons per day of ammonia was expected to be produced, given the initial flow at capital and operational expense of US$ 92.97 million and US$ 22.91 million per year, respectively. The payback period was determined to be as short as 5.38 years, with an attractive return on investment of up to 18.58%. However, the breakeven point for ammonia synthesis occurred at a discount rate of 16.42% (Fig. 7b), beyond which the NPV would get negative. This means that there would be more expenditure than earnings, putting the system at a financial loss. Therefore, maintaining a discount rate below 16.42% is paramount.

Likewise, the levelized cost of electricity (LCOE) generated from solid oxide fuel cells after following a series of units from biological domestic sludge treatment to ammonia storage was calculated. It was found to be US$ 0.16 per kWh. The system was estimated to have a net present value of US$ 88.63 million and a 14.44% ROI. This led to the understanding that the project would likely be profitable and add significant value over its lifetime of 25 years. The payback period was approximated at nearly 6.93 years. However, exceeding a discount rate of 11.89% will result in an economic deficit for the system.

The calculated benefit-cost ratios of 1.76 for ammonia production and 1.64 for electricity generation at a 5% discount rate indicated that both pathways are economically viable. A BCR greater than 1 signified that the present value of economic benefits outweighed the present value of costs, meaning that the system is expected to give a positive return on investment and contribute to long-term financial sustainability. In other words, with every investment of US$ 1 in the project, there would be a return of US$ 1.76 for ammonia production and US$ 1.64 for electricity generation, respectively.

The levelized costs of ammonia and electricity exhibit a direct correlation with the discount rate (Fig. 7a). The LCOA increased from around US$ 213 per ton to US$ 345 per ton as the discount rate changed from 0% to 20%. A similar trend was observed for LCOE that increased from approximately US$ 0.14 to US$ 0.23 per kWh. This trend was expected, as higher discount rates reduce the present value of future revenues while keeping capital and operational costs fixed, thereby inflating the calculated unit cost of production.

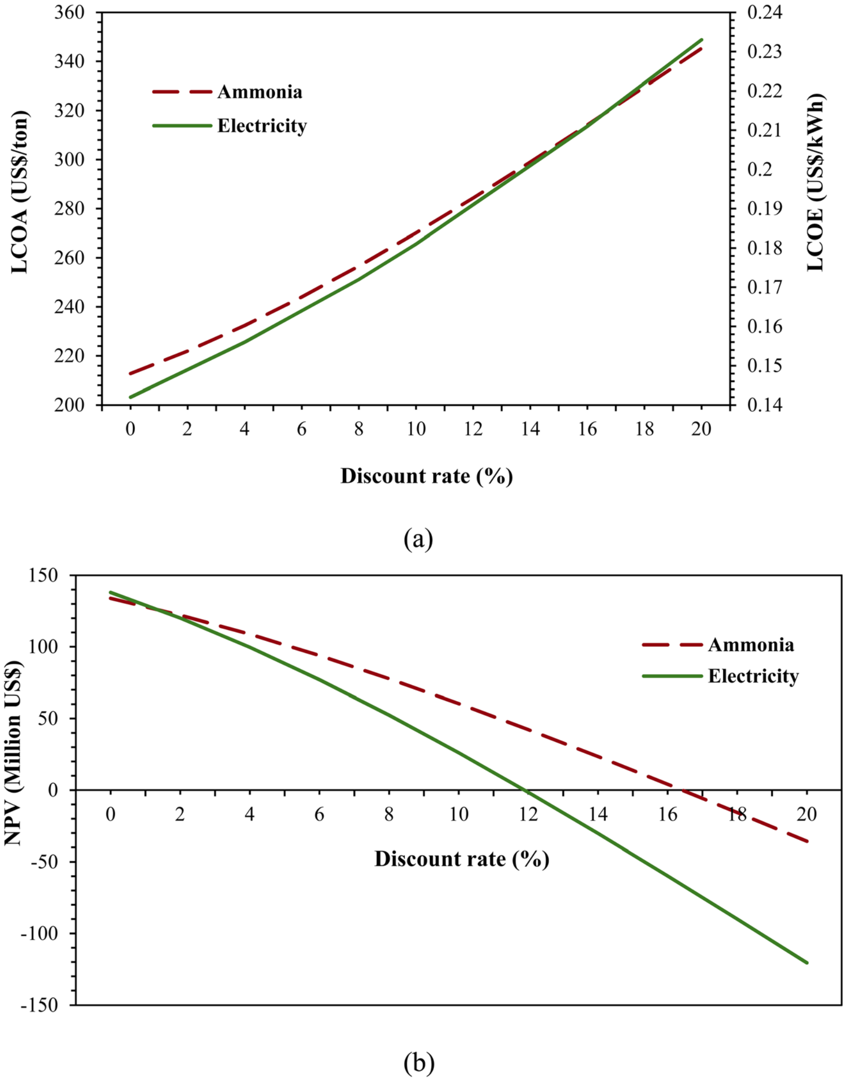


Fig. 7 Change in the (a) levelized costs and (b) net present value with differing discount rates.

However, on close observation, it was revealed that LCOE increases at a slightly faster rate than LCOA. Although the difference may seem minimal, it indicates that electricity production is more sensitive to financing assumptions. The primary reason is that electricity generation from ammonia using solid oxide fuel cells is highly capital-intensive, which amplifies the effect of discounting future revenue and inflates unit cost. Therefore, a longer cost recovery period becomes essential. On contrast, ammonia production has comparatively greater economic stability across varying discount conditions.

The discussion can be further strengthened by investigating the net present values (Fig. 7b). At a 0% discount rate, both ammonia and electricity yield positive NPVs of approximately US$ 130–140 million, hence indicating favourable project returns. As the discount rate increased, the net present values for both products declined. The NPV of electricity declined more steeply, crossing into negative values near the 12% discount rate and giving a deficit of US$ 120 million at 20%. However, the NPV for ammonia decreased more gradually and gave a break-even point at around 16–17%. Therefore, it represents better economic resilience. This suggested that ammonia production is better at withstanding economic fluctuation than electricity generation without jeopardizing investment returns.

Both ammonia and electricity are technically viable products from wastewater; ammonia offers more financially risk-tolerant benefits, particularly in regions with limited access to low-interest financing or where discount rates are subject to volatility. These insights hold significant implications for the overall objective of this study, which is to assess the techno-economic viability of the integrated treatment and resource recovery system and emphasise the discount rate sensitivity in long-term economically viable infrastructure planning.

3.5 Comparison of the obtained levelized costs with literature

3.5.1 LCOA. The cost of renewable ammonia, which was averaged to be US$ 720 per ton in 2022, is forecasted by IRENA to be US$ 480 per ton by 2030 and US$ 310 per ton by 2050.[55] The

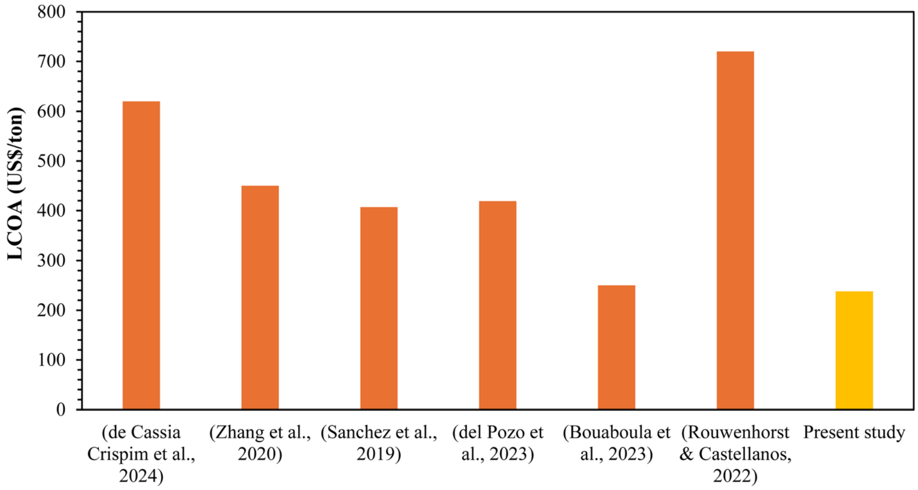


Fig. 8 Comparison of estimated LCOA with those in the previous studies.

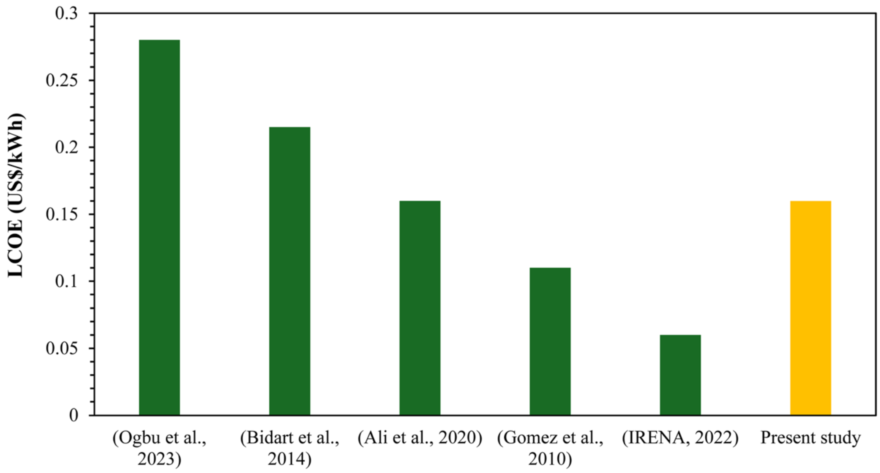


Fig. 9 Comparison of LCOE from the digestion of waste.

levelized cost of green ammonia obtained from wastewater sludge, biomass gasification, or coal-biomass co-gasification has been estimated previously[56–59] as shown in Fig. 8. The LCOA in the present study was lower than that identified in previous studies. However, it aligns with the levelized cost of green ammonia (predicted at US$ 250 per ton) produced in a plant solely powered by renewable energy sources as modelled in a study by Bouaboula, Ouikhalfan *et al.*[60]

3.5.2 LCOE. The weighted average LCOE of biomass-fired electricity generation is around US$ 0.04 per kWh in India and 0.05 US$ per kWh in China. However, this LCOE is a bit higher in Europe and America, up to US$ 0.085 per kWh, due to more advanced technology and stringent emission controls. Taking an average for the aforementioned countries, LCOE becomes 0.06 US$ per kWh.[61] Most previous studies also focused on the digestion of sewage or wastewater sludge to produce electricity and calculated LCOE.[62–65] The levelized cost of electricity evaluated in the present study was within the range of similar previous studies (Fig. 9).

4 Conclusions

The techno-economic evaluation of the system demonstrated a viable opportunity for generating environmentally friendly power from sewage treatment. By combining anaerobic digestion, centrifugation, electrodialysis, electrochemical ammonia stripping, vacuum membrane distillation, and SOFC technologies, the system recovered ammonia from municipal wastewater treatment that could be used for power generation. Although there may be a substantial upfront expenditure, the proposed system can offset these costs by producing useful by-products while promoting environmental sustainability.

The study's findings suggested that LCOA amounted to US$ 238.09 per ton, accompanied by an attractive NPV of US$ 101.49 million, assuming a discount rate of 5% and project lifetimes of 25 years. The power generated by the innovative wastewater treatment system had a levelized cost of electricity estimated at US$ 0.16 per kilowatt-hour. Both the products gave a BCR > 1 under the analyzed assumptions, confirming the economic viability of the project. Electricity production was found to be more sensitive to the change in discount rates, as demonstrated in sensitivity analysis. Hence, producing ammonia from the proposed hypothetical treatment system is more financially resilient. Therefore, the high benefit-cost ratios, positive net present value, and return on investment suggest that the system is not only financially viable but also scalable. The economic indicators reflect the potential for long-term cost recovery and profit generation, supporting the system as a sustainable business model. It offers attractive returns to the stakeholders, including municipalities and private investors and enhances its applicability in real-world investment-driven contexts.

The work contributes to the current state of the art by not only integrating multiple emerging technologies but also quantifying the capital and operational expenditure in depth for each processing unit and providing economic trade-offs, therefore advancing the transition from a linear wastewater treatment model to a multi-output circular model. Future research should prioritize optimizing system components to save capital expenses and investigate the integration of renewable energy sources to ensure the long-term sustainability of operations. The current study did not consider the regional, seasonal fluctuations in sewage generation; rather, an average sewage generation in Qatar was considered for analysis. Future assessments can incorporate the spatiotemporal flow variability in Qatar's sewage for more specific evaluations and operational resilience. Additionally, future work can include a detailed evaluation of managing and treating the secondary pollution resulting from residual by-products.

Data availability

The data supporting this article have been included as part of the ESI.†

Conflicts of interest

The authors declare no conflict of interest.

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