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# Ammonia air stripping for nitrogen recovery from reject water: A consequential life cycle comparison with nitrification–denitrification

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ABSTRACT

Nitrogen removal from wastewater is essential for preventing eutrophication and ecosystem degradation. Conventional nitrification–denitrification removes reactive nitrogen but does not recover it as a useful product, whereas nitrogen recovery can return recovered nitrogen to the fertilizer cycle. This study compares the life cycle environmental performance of ammonia air stripping and conventional nitrification–denitrification for nitrogen removal from reject water under Swedish conditions. A functional unit of 1 kg of reactive nitrogen removed was applied, with both technologies evaluated using a common reject-water basis and harmonized system boundaries.

Nitrification–denitrification resulted in a net climate impact of approximately 6.6 kg $CO_2$-eq $kg^{-1}$ N removed, mainly driven by direct process emissions, particularly $N_2O$, and methanol consumption. In contrast, ammonia air stripping resulted in a net climate impact of approximately −3.4 kg $CO_2$-eq $kg^{-1}$ N removed. Air stripping also showed lower burdens for human health and ecosystem quality, even when avoided impacts from marginal fertilizer production were excluded. For resource use, the two technologies had similar process-related impacts before fertilizer substitution; therefore, the net resource-use advantage of air stripping depended strongly on the avoided fertilizer production credit. Sensitivity analysis showed that the magnitude of the environmental advantage of air stripping was affected by the choice of marginal fertilizer, $N_2O$ emissions, and ammonia recovery efficiency, while the comparative ranking remained unchanged across the tested scenarios.

Overall, ammonia air stripping showed lower environmental burdens than nitrification–denitrification under the conditions evaluated, although its resource-use advantage remained sensitive to the assumed fertilizer substitution.

## 1. Introduction

Reject water generated during the dewatering of anaerobically digested sludge is a concentrated nitrogen-rich side stream of municipal wastewater treatment. Although it represents only a small fraction of the total wastewater flow, reject water can contain a substantial proportion of the nitrogen load entering the treatment plant, predominantly in the form of ammonium (Högstrand et al., 2023). In conventional wastewater treatment, reject water is typically returned to the main treatment line for further nitrogen removal. However, if the nitrogen it contains is not effectively removed or recovered, it can ultimately be discharged with treated effluent and contribute to nitrogen loading of receiving water bodies (Malovanyy et al., 2022). Excessive nitrogen loading can promote eutrophication through nutrient enrichment, excessive algal growth, oxygen depletion, and associated degradation of aquatic ecosystems. Consequently, effective nitrogen removal and recovery are important for reducing nitrogen loading and protecting water quality.

A range of technologies are available for nitrogen removal and recovery from wastewater, including biological processes, physicochemical separation, and hybrid approaches. Physicochemical options include air stripping, steam stripping, ion exchange, reverse osmosis, and struvite precipitation, while biological nitrogen removal remains the dominant approach in municipal wastewater treatment systems (Farghali et al., 2024). Among these technologies, conventional nitrification–denitrification is widely applied for nitrogen removal, whereas ammonia stripping represents a mature physicochemical option for nitrogen recovery, particularly from concentrated wastewater side streams (Liu et al., 2015).

The conventional biological nitrogen removal process consists of nitrification under aerobic conditions followed by denitrification under anoxic conditions (Mishra et al., 2022). However, this process is energy-intensive due to aeration and mixing requirements and requires

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a carbon source for microbial activity and biomass growth. The required carbon source can be supplied by biodegradable organic matter in the influent, while external carbon sources such as methanol may be added when the available biodegradable carbon is insufficient to achieve the required denitrification performance (Bachmann et al., 2024). A further limitation of denitrification is the potential emission of nitrous oxide ($N_2O$), a potent greenhouse gas with a global warming potential approximately 300 times higher than $CO_2$ (IPCC, 2013).

As an alternative, ammonia can also be recovered from wastewater using physicochemical processes such as air stripping. Air stripping removes ammonia by promoting the transfer of dissolved $NH_3$ from the liquid to the gas phase using an air stream. Although this process can achieve high ammonia recovery efficiency and enables the production of ammonium-based fertilizers such as ammonium sulfate, it requires energy for air circulation and pumping and may require chemical inputs such as sulfuric acid and CaO for scrubbing and recovery (van Zelm et al., 2020).

From a broader circular-bioeconomy perspective, wastewater and other residual streams can be regarded as potential sources of recoverable resources, supporting the transition toward more resource-efficient and circular production systems (Shurpali et al., 2025). Consequently, life cycle assessment (LCA) has increasingly been applied to evaluate the environmental performance of nitrogen removal and recovery technologies. Several studies have evaluated and compared physicochemical nitrogen recovery and biological nitrogen removal across different wastewater treatment contexts. These studies differ substantially in their objectives, functional units, feed streams, system boundaries, recovered products, and LCA modelling approaches, which can influence the comparability of their results (Table 1). For air stripping, Kar et al. (2023) assessed the environmental impacts of recovering ammonia from wastewater side streams and converting it into ammonium sulfate, comparing it with conventional ammonia production via the Haber-Bosch process. Similarly, van Zelm et al. (2020) compared ammonia stripping for ammonium sulfate recovery with the biological SHARON-Anammox process and reported potential environmental benefits associated with fertilizer recovery and the assumed displacement of conventional fertilizer production. In contrast, Saud et al. (2023) found that air stripping-based nitrogen recovery could increase climate change impacts relative to conventional sludge treatment due to electricity and chemical consumption. For biological nitrogen removal, Vineyard et al. (2021) highlighted that nitrification-denitrification processes are energy-intensive due to aeration and may contribute to greenhouse gas emissions, particularly nitrous oxide.

Although comparative LCAs of physicochemical and biological nitrogen management pathways have been reported, limited attention has been given to a direct comparison of ammonia stripping and conventional nitrification–denitrification for nitrogen removal from reject water using a common functional unit, harmonized system boundaries, and prospective Swedish marginal conditions. Consequently, the environmental trade-offs between these two nitrogen management strategies for concentrated municipal wastewater side streams remain insufficiently understood within this specific decision context.

Therefore, this study performs a comparative consequential LCA of ammonia recovery via air stripping and nitrogen removal by conventional nitrification-denitrification using reject water under Swedish conditions. The contribution of the study is not the development of ammonia recovery itself, but the harmonized comparison of two alternative nitrogen-management pathways that provide the same nitrogen-removal function. By applying a common functional unit, harmonized system boundaries, and consistent modelling assumptions for energy supply, chemical consumption, and direct emissions, the study provides a consistent comparison of the environmental trade-offs between physicochemical nitrogen recovery and biological nitrogen removal and supports decision-making on the management of nitrogen-rich

**Table 1**
Overview of LCA studies assessing nitrogen removal and recovery technologies in wastewater treatment.

| Study | Technology | Feed stream | Functional unit | System boundary | Product recovery | LCA approach |
|---|---|---|---|---|---|---|
| Gao et al. (2023) | Partial nitritation-anammox vs conventional nitrification-denitrification | Industrial wastewater | Treatment of 1 $m^3$ wastewater | WWTP influent to effluent, including energy, chemicals, sludge treatment, transport, and emissions | None | Not explicitly stated |
| Kar et al. (2023) | Air stripping vs conventional ammonium sulfate production via the Haber–Bosch process | Side stream from anaerobic sludge digestion | 1 kg ammonium sulfate | Gate-to-gate ammonium sulfate production, including ammonia recovery, energy and chemical inputs. | Ammonium sulfate | Not explicitly stated |
| Saud et al. (2023) | No nitrogen recovery vs air stripping for ammonia recovery vs biochar adsorption for nitrogen recovery | Reject water from sludge dewatering and condensate from sludge thermal drying | 870 kt/year rejected water + 45 kt/year condensate treated | Sludge treatment system, including chemical and energy input, nitrogen recovery, and fertilizer substitution | Ammonium sulfate (air stripping) and N-enriched biochar fertilizer | Not explicitly stated |
| van Zelm et al. (2020) | Air stripping vs SHARON-Anammox | Side stream anaerobic digestate | Treatment of 1 kg total dissolved nitrogen inflow | WWTP digestate side-stream treatment, including ammonia stripping and ammonium sulfate production | Ammonium sulfate | Attributional |
| Vineyard et al. (2021) | Do nothing vs nitrification–denitrification vs anammox vs electrodialysis for nitrogen recovery | Anaerobic digester side stream | 1 kg $NH_4^+$-N removed | Gate-to-gate side-stream nitrogen treatment (construction/disposal excluded); fertilizer substitution included for electrodialysis | Ammonium-based fertilizer (electrodialysis only) | Not explicitly stated |
| Högstrand et al. (2023) | NP Harvest membrane contactor vs struvite precipitation + ammonia stripping | Reject water from dewatered, anaerobically digested sludge | Treatment of 1 $m^3$ reject water | Chemical and energy inputs, direct emissions, nutrient product management, fertilizer substitution, and main-line WWTP impacts | Ammonium sulfate, P-rich product, and struvite | Attributional |
| This study | Air stripping vs conventional nitrification-denitrification | Reject water | 1 kg nitrogen removed | Nitrogen-removal processes, including chemical and energy use, direct emissions, and fertilizer substitution for air stripping | Ammonium sulfate for stripping and none for nitrification-denitrification | Consequential |

wastewater side streams.

## 2. Life cycle assessment methodology

Data on material and energy streams were compiled from the literature and validated using mass and energy balance approaches to ensure their accuracy and consistency. This study follows the LCA instructions and guidelines issued by ISO 14040 to ISO 14044 (Finkbeiner et al., 2006) and the International Reference Life Cycle Data (ILCD) Handbook (WOLF et al., 2010), encompassing four mandatory stages that are outlined in the subsequent subsections.

### 2.1. Goal and scope definition

The goal of this study is to evaluate and compare the environmental performance of two nitrogen removal technologies in wastewater treatment reject water: conventional biological nitrification–denitrification and ammonia air-stripping. The study aims to assess whether ammonia air-stripping can represent an environmentally preferable alternative to biological nitrogen removal from a life cycle perspective. To provide a common feed-stream basis for both technologies, the characteristics of the reject water were represented using average values calculated from the available Swedish reject-water data reported by Malovanyy et al. (2022). The resulting characteristics were pH 7.84, total N 1025 mg/L, $NH_4$–N 967 mg/L, and alkalinity 3539 mg $CaCO_3$/L.

The functional unit is defined as 1 kg of reactive nitrogen removed from the reject water. All input and output flows are normalized to this functional unit to ensure a consistent comparison between the two systems. A common reactive nitrogen removal efficiency of 80% was assumed for both technologies. Thus, achieving the functional unit of 1 kg of reactive nitrogen removed requires 1.25 kg of reactive nitrogen in the influent. This common removal efficiency was applied to ensure functional comparability of the two technologies with respect to nitrogen removal; it does not imply identical overall effluent quality, as other water-quality parameters were outside the scope of this study.

The system boundaries include only processes directly associated with nitrogen removal and recovery. In the nitrification-denitrification scenario, as shown in Fig. 1(a), the system includes electricity consumption, external carbon source addition (methanol), and direct process emissions associated with nitrogen removal. In the ammonia air-stripping scenario, as shown in Fig. 1(b), the system includes electricity and heat consumption, calcium oxide and sulfuric acid inputs, ammonia stripping and recovery, and ammonium sulfate production. For both scenarios, upstream processes that are common to the two systems, including wastewater collection, mainstream wastewater treatment, anaerobic digestion, and sludge treatment, are outside the system boundary. Downstream management of residual sludge, treated effluent, cleaning wastewater, scrubber purge, scaling residues, and other secondary residual streams are also excluded. Infrastructure and capital equipment are likewise excluded from both scenarios. These exclusions define a consistent gate-to-gate comparison focused on the operational nitrogen-removal function; however, the potential influence of downstream residual-stream management and valorization is recognized as a limitation of the assessment (section 4).

System expansion is applied to the stripping scenario to account for the production of ammonium sulfate. The recovered ammonium sulfate is assumed to substitute marginal mineral nitrogen fertilizer, and the corresponding avoided environmental burdens are credited to the system.

The study is conducted as a consequential life cycle assessment (CLCA) because it evaluates the prospective environmental consequences of replacing conventional biological nitrogen removal with ammonia air stripping for nitrogen removal and recovery from reject water in Swedish municipal wastewater treatment. The consequential model represents changes in background production associated with this substitution using marginal suppliers. The geographical scope is Sweden, and a 10-year prospective horizon is adopted to represent the anticipated period over which the technology could be implemented, and background energy and fertilizer supply could respond to the change. The 10-year horizon is therefore used to define the temporal scenario.

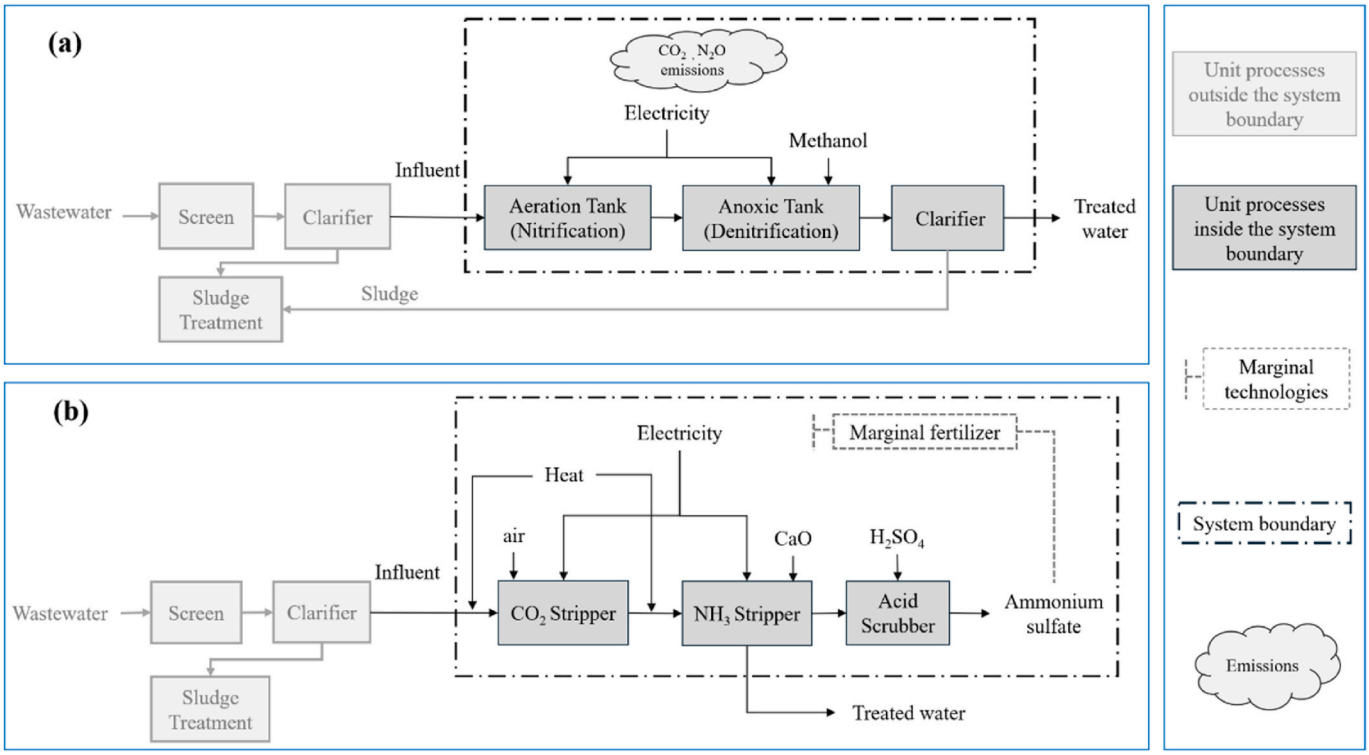


**Fig. 1.** System boundaries and process flow diagrams for **(a)** biological nitrification-denitrification and **(b)** ammonia air stripping.

### 2.2. Life cycle inventory

Foreground life cycle inventory (LCI) data were compiled from published literature. Background data, including information on energy carriers, chemicals, and materials, were obtained from the Ecoinvent database. A summary of the inventory data used across the scenarios is presented in Table 2, and further details are provided in the following sections. The corresponding background ecoinvent datasets and market/geographical specifications are provided in Table S1.

*Nitrification-denitrification*: The nitrification-denitrification scenario represents a conventional nitrogen removal process based on aerated and anoxic tanks, where wastewater is circulated using pumps and aerators. Electricity demand was assumed to be 3.20 kWh per kg N removed. Methanol addition is an established approach for enhanced denitrification in Swedish wastewater treatment (Carranza Muñoz et al., 2025; Nyberg et al., 1992). Methanol consumption was estimated based on the stoichiometric requirement for heterotrophic denitrification, corresponding to 2.44 kg methanol per kg $NO_3^-$–N removed. The associated direct $CO_2$ emission was estimated as 2.40 kg fossil $CO_2$ per kg N removed, following Vineyard et al. (2021). $CH_4$ emissions were considered negligible for this process. Fugitive $N_2O$ emissions were estimated as 0.00647 kg $N_2O$ per functional unit, based on the literature-derived emission factor reported by Vineyard et al. (2021), which compiled $N_2O$ emission data from multiple studies and meta-studies of full-scale wastewater treatment systems.

*Ammonia air-stripping*: The ammonia air-stripping system consists of two main phases: ammonia recovery and conversion to ammonium sulfate. Wastewater is first preheated to 55 °C and stripped of dissolved $CO_2$. The pH is then adjusted using lime, followed by further heating to 70 °C to enhance ammonia volatilization. In the stripping column, elevated temperature and alkaline conditions promote the transfer of $NH_3$ from the liquid to the gas phase. Heat from the high-temperature treated stream leaving the ammonia-stripping column was assumed to be recovered through a heat exchanger to preheat the incoming reject water; resulting in a net thermal-energy requirement of 0.40 $kWh_{th}$ per kg N removed.

The ammonia-rich gas is first neutralized and then contacted with sulfuric acid in a scrubbing column to produce ammonium sulfate according to $2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$. The product is stored at approximately 35 wt% to avoid crystallization. Citric acid is included for periodic cleaning of the stripping unit (Kar et al., 2023).

To minimize gaseous emissions to the environment, the system is equipped with a gas-lock containing a small amount of $H_2SO_4$. The gas-lock was assumed to capture residual ammonia; therefore, $NH_3$ emissions to the atmosphere were considered negligible, consistent with the underlying literature source (van Zelm et al., 2020).

**Table 2**
Life cycle inventory (LCI) data for the nitrification-denitrification and ammonia air-stripping, expressed per functional unit of 1 kg N removed from reject water.

| Item | Unit | Value |
|---|---|---|
| Nitrification-denitrification based on (Vineyard et al., 2021) | | |
| Electricity | $kWh_{el}$ | 3.2 |
| Methanol | kg | 2.44 |
| $CO_2$ emission (fossil) | kg | 2.40 |
| $N_2O$ emission | kg | 0.00647 |
| Stripping based on (van Zelm et al., 2020) | | |
| Electricity | $kWh_{el}$ | 1.21 |
| Heat | $kWh_{th}$ | 0.40 |
| Citric acid | kg | 0.015 |
| Calcium (CaO) – 95% purity | kg | 0.29 |
| Sulfuric acid | kg | 3.50 |
| $CO_2$ (biogenic) emission | kg | 10.52 |
| Ammonium sulfate (product) | kg | 4.714 |

### 2.3. Selection of marginal technologies and products

This study evaluates the prospective substitution of conventional biological nitrogen removal with ammonia air stripping for nitrogen removal and recovery from concentrated reject water at Swedish municipal wastewater treatment plants. The implementation of ammonia air stripping is assumed to affect three background markets: electricity, heat, and mineral nitrogen fertilizer.

Sweden has an official roadmap targeting a fossil-free electricity system by 2040, with electricity demand projected to increase substantially toward 2050. The current electricity mix is dominated by low-carbon sources, primarily hydropower, nuclear power, and wind power, while fossil fuels account for a minor share of total generation. Long-term energy system analyses indicate that future increases in electricity demand will require additional low-carbon generation capacity. Based on this prospective capacity-expansion context, onshore wind power was selected as the marginal electricity supplier for the Swedish scenario, consistent with its identification as a cost-effective option for new generation capacity (Kan et al., 2020). This represents the assumed marginal response to the additional electricity demand associated with the treatment technologies rather than a prediction that wind power will supply all future incremental electricity demand. This assumption is consistent with consequential LCA methodology, which identifies marginal technologies based on long-term capacity expansion rather than the current average mix (Weidema et al., 1999).

Heat supply in Sweden is largely provided through district-heating systems, with biomass and wood-based combined heat and power contributing substantially to heat production and fossil fuels playing a comparatively minor role. Based on the prospective development of the Swedish energy system, wood-based district heating was selected as the marginal heat supplier for the scenario (Swedish Energy Agency, 2023). This represents the assumed marginal response to the additional heat demand associated with ammonia air-stripping.

For fertilizer substitution, ammonium nitrate was selected as the reference marginal mineral nitrogen fertilizer based on its relevance as a mineral nitrogen fertilizer in the Swedish and broader European market and its use in previous LCA studies of recovered nitrogen products (Ebrahimian et al., 2026; Ebrahimian and Mohammadi, 2023; Khoshnevisan et al., 2020). The recovered ammonium sulfate was assumed to displace an equivalent amount of nitrogen supplied as ammonium nitrate. System expansion was therefore applied to represent the avoided production of ammonium nitrate, and the associated environmental burdens were credited to the air-stripping system. Because the identity of the marginal fertilizer is uncertain, alternative fertilizer-substitution assumptions were evaluated through sensitivity analysis.

### 2.4. Sensitivity analysis

A sensitivity analysis was conducted using the ReCiPe 2016 Endpoint Single Score indicator to assess the influence of alternative assumptions regarding the marginal fertilizer displaced by recovered ammonium sulfate. In this analysis, urea, ammonium sulfate, ammonium nitrate (baseline), and calcium ammonium nitrate (CAN) were considered as alternative marginal substitution scenarios to evaluate how the choice of displaced fertilizer affects the overall environmental results. The quantities of these fertilizers were calculated based on an equivalent nitrogen content to that contained in the recovered ammonium sulfate. Accordingly, 4.714 kg of ammonium sulfate (equivalent to 1 kg N) was assumed to substitute 2.17 kg urea, 2.86 kg ammonium nitrate, or 3.70 kg CAN.

Sensitivity analysis was also conducted to assess the influence of $N_2O$ emissions and ammonia recovery efficiency. The $N_2O$ emission for nitrification–denitrification was varied by ±20%, while ammonia recovery in the stripping process was reduced by 20% relative to the baseline.

### 2.5. Life cycle impact assessment (LCIA)

The LCA model was implemented in SimaPro version 10.3.0.1. Background processes for electricity, heat, methanol, sulfuric acid, calcium oxide, citric acid, and fertilizer production were obtained from the ecoinvent database version 3.11 using the consequential system model.

Environmental impacts were assessed using ReCiPe 2016 Hierarchist (H) V1.13 at both midpoint and endpoint levels. Primary results were reported as characterized midpoint and endpoint indicators without applying user-defined normalization or weighting. For the sensitivity analysis, the ReCiPe 2016 Single Score indicator available in SimaPro was additionally used as an aggregated damage indicator. The Single Score results were used only for sensitivity analysis and were not used as the basis for the primary comparison.

Negative values indicate avoided potential environmental burdens associated with the relevant substitution or recovery credit and are referred to as environmental savings or benefits for simplicity. Positive values represent potential environmental burdens. The net environmental effect was calculated as the sum of the burdens and avoided burdens associated with each scenario. Consequently, lower net impacts indicate lower overall potential environmental burdens under the assumptions of the assessment.

## 3. Results and discussion

Results are presented at both midpoint (impact category) and endpoint (area of protection) levels; however, the discussion focuses primarily on climate change and the three endpoint damage categories, i.e., human health, ecosystem, and resources, to provide a concise interpretation of the results. The detailed midpoint contribution results are provided in Tables S2 and S3, while the corresponding endpoint results are reported in Tables S4 and S5.

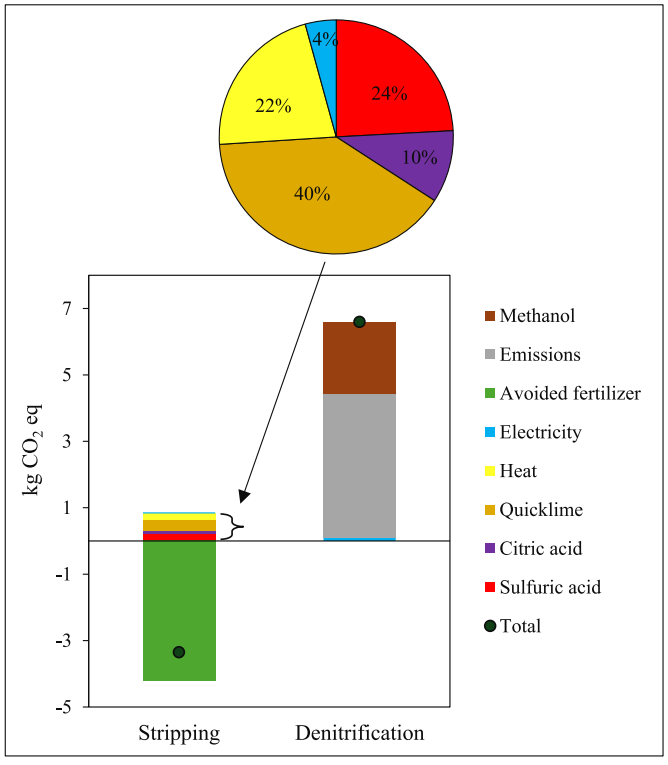


**Fig. 2.** Contribution of stripping and nitrification-denitrification to the climate change impact category.

### 3.1. Climate change

Fig. 2 compares the climate change impacts associated with ammonia air-stripping and conventional nitrification-denitrification, expressed as kg $CO_2$-eq per kg N removed.

The results indicate a substantial difference between the two technologies. The nitrification-denitrification system generates a net climate change impact of approximately 6.6 kg $CO_2$-eq $kg^{-1}$ N removed, whereas the air-stripping system achieves a net impact of approximately −3.4 kg $CO_2$-eq $kg^{-1}$ N removed. The negative net value for air stripping results from the environmental credit assigned to the recovered ammonium sulfate through the assumed displacement of marginal mineral fertilizer. Under this consequential LCA framework, the avoided emissions associated with fertilizer substitution exceed the emissions generated by the stripping process, resulting in a negative net climate change impact.

Importantly, the lower climate impact of air stripping is not solely attributable to the fertilizer substitution credit. Before accounting for the avoided emissions from ammonium sulfate substitution, the air-stripping process has a climate change impact of approximately 0.86 kg $CO_2$-eq $kg^{-1}$ N removed, compared with 6.6 kg $CO_2$-eq $kg^{-1}$ N removed for nitrification–denitrification. Thus, air stripping has lower direct process-related climate impacts under the assumptions of the assessment, while the negative net result is obtained only after accounting for the avoided fertilizer production.

For the nitrification-denitrification scenario, direct process emissions constitute the largest contribution to the impact of overall climate change, followed by methanol consumption. The dominance of process emissions is expected, as biological nitrogen removal is associated with the release of greenhouse gases, particularly nitrous oxide ($N_2O$), which has a high global warming potential. Methanol production and consumption further increase the carbon footprint due to upstream fossil energy requirements. In contrast, electricity consumption contributes only marginally to the total impact.

The air-stripping scenario exhibits a different environmental profile. The largest environmental burdens arise from quicklime production, followed by the consumption of sulfuric acid and heat demand. These process-related burdens are outweighed by the environmental credit associated with ammonium sulfate recovery. By substituting marginal mineral nitrogen fertilizer, the recovered ammonium sulfate avoids emissions that would otherwise occur during fertilizer manufacturing. As a result, the stripping system achieves an overall negative net climate change impact, indicating that the avoided potential emissions associated with fertilizer substitution exceed the emissions from the stripping process under the assumptions of the assessment.

These findings are consistent with previous studies highlighting the potential environmental advantages of ammonia recovery over conventional nitrogen removal. Kar et al. (2023) reported that ammonium sulfate produced through wastewater ammonia air-stripping generated greenhouse gas emissions approximately six times lower than conventionally produced ammonium sulfate via the Haber–Bosch route. Their study showed that the environmental benefits of fertilizer recovery can substantially offset the impacts associated with energy and chemical consumption during the stripping process.

Similar conclusions have been reported for alternative biological nitrogen removal pathways such as partial nitritation-anammox (PN/A), where life cycle assessments of full-scale systems indicate a reduction in greenhouse gas emissions compared to conventional nitrification-denitrification, primarily due to lower energy demand and reduced nitrous oxide formation (Gao et al., 2023). However, unlike recovery-based technologies such as ammonia air stripping, PN/A systems primarily achieve environmental benefits through process optimization rather than resource recovery. This highlights that while advanced biological processes can mitigate emissions from conventional treatment, technologies enabling direct nutrient recovery may provide additional climate benefits through avoided fertilizer production.

### 3.2. Human health impacts

Fig. 3 compares the human health impacts of ammonia air stripping and conventional nitrification-denitrification, expressed in disability-adjusted life years (DALY) per functional unit. The results reveal a substantial difference between the two treatment strategies. The nitrification-denitrification system results in a net human health burden of approximately $1.0 \times 10^{-5}$ DALY, whereas the air-stripping system shows a negative modelled impact of approximately $-4.6 \times 10^{-6}$ DALY. This indicates that the environmental benefits associated with nutrient recovery outweigh the environmental burdens generated during operation.

For the nitrification-denitrification scenario, direct process emissions represent the largest contribution to human health impacts, followed by methanol consumption. The dominance of emissions reflects the release of pollutants associated with biological nitrogen conversion processes and their upstream impacts on human health. Methanol production further contributes through fossil energy consumption and emissions occurring during its manufacture. Electricity consumption contributes only a minor fraction of the total impact.

In contrast, the air-stripping system exhibits a markedly different profile. Sulfuric acid production is the largest source of environmental burden, followed by heat demand and quicklime consumption. Nevertheless, these impacts are outweighed by the substantial environmental credit associated with ammonium sulfate recovery. By substituting marginal nitrogen fertilizer, recovered ammonium sulfate avoids emissions and resource use that would otherwise contribute to human health damage. Consequently, the overall human health impact of the stripping process becomes negative, indicating an avoided potential human-health damage. These results indicate that nutrient recovery may provide environmental benefits beyond climate change mitigation through the assumed displacement of marginal fertilizer production.

### 3.3. Ecosystem impacts

Fig. 4 presents the ecosystem impacts of the two nitrogen management strategies, expressed as potential species loss. Similar to the human health category, the air-stripping system exhibits a net environmental benefit, while the nitrification-denitrification process results in a positive ecosystem burden. The total ecosystem impact of denitrification is approximately $5.4 \times 10^{-8}$ species·yr, whereas air stripping achieves a net impact of approximately $-2.5 \times 10^{-8}$ species·yr.

For the nitrification-denitrification system, process emissions constitute the dominant contributor to ecosystem damage, with methanol consumption representing the second-largest source. The contribution from electricity consumption is negligible. These results suggest that emissions generated during biological nitrogen removal are a major driver of ecological impacts, likely due to their influence on air quality, climate-related stressors, and associated ecological effects throughout the life cycle.

The air-stripping system again derives its environmental advantage primarily from the recovery of ammonium sulfate. Although sulfuric acid production, quicklime use, citric acid consumption, heat demand, and electricity use contribute positively to ecosystem impacts, these burdens are substantially outweighed by the avoided impacts associated with fertilizer substitution. The negative net result indicates that, under the assumed fertilizer substitution, the avoided potential environmental

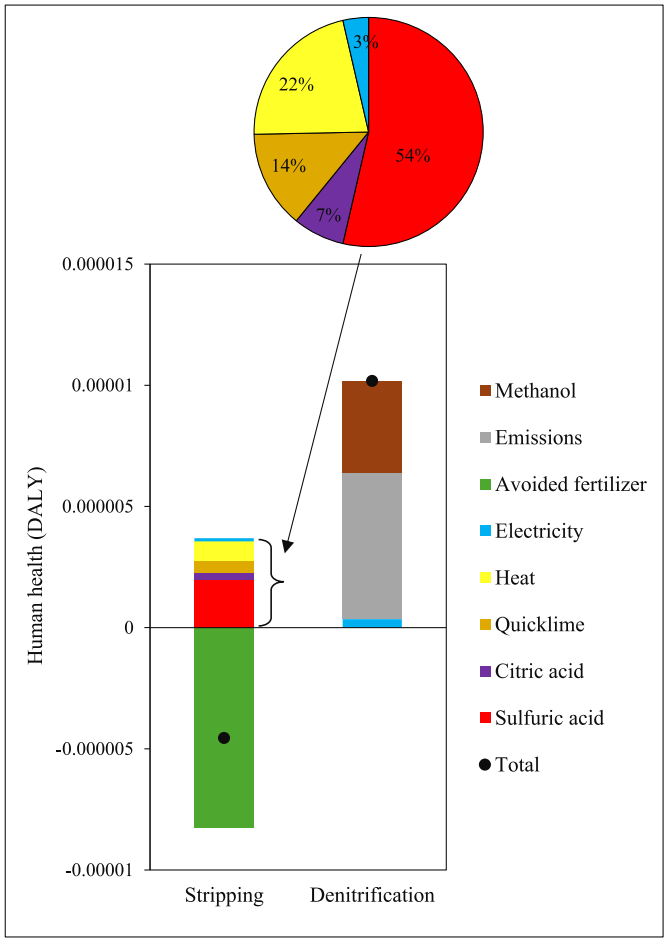


**Fig. 3.** Contribution of stripping and nitrification-denitrification to the human health damage category.

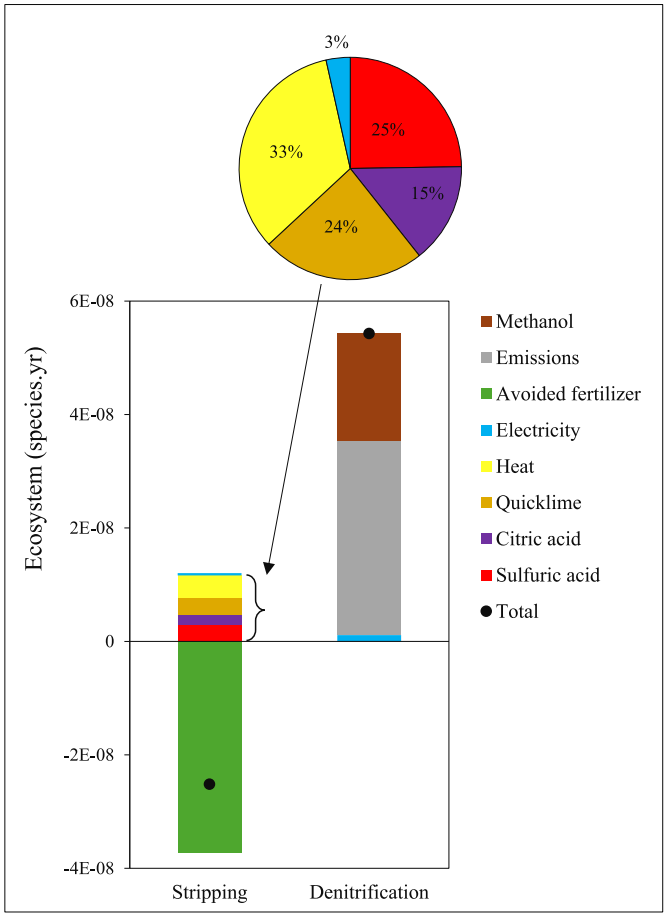


**Fig. 4.** Contribution of stripping and nitrification-denitrification to the ecosystem damage category.

burdens associated with marginal fertilizer production exceed the operational burdens of the stripping process.

### 3.4. Resource use impacts

Fig. 5 compares resource use impacts for ammonia air stripping and nitrification–denitrification, expressed in USD2013. Both systems require energy and process chemicals, which contribute to their resource use impacts. Before accounting for the avoided production of marginal fertilizer, the resource use impacts of the two technologies are similar, indicating that the process-related resource requirements of air stripping do not inherently provide a clear advantage over nitrification–denitrification.

The nitrification–denitrification system has a resource use impact of 0.022 USD2013, mainly associated with the continuous consumption of methanol as an external carbon source, followed by electricity consumption. These inputs reflect the ongoing material and energy requirements of biological nitrogen removal. Ammonia air stripping also requires substantial inputs of chemicals and thermal energy, resulting in a resource use impact of 0.023 USD2013 before fertilizer substitution. However, it additionally produces recoverable ammonium sulfate that can substitute marginal mineral fertilizer.

Consequently, the substantially lower net resource impact of air stripping (−0.01 USD2013) is primarily attributable to the avoided production of marginal fertilizer rather than to lower resource requirements within the stripping process itself. Under the full fertilizer-substitution assumption applied in this study, the fertilizer credit more than offsets the resource burdens associated with the chemicals, heat, and electricity required for air stripping, resulting in a negative net impact. Thus, the resource-use advantage of air stripping is strongly dependent on the assumed extent of effective displacement of marginal fertilizer production.

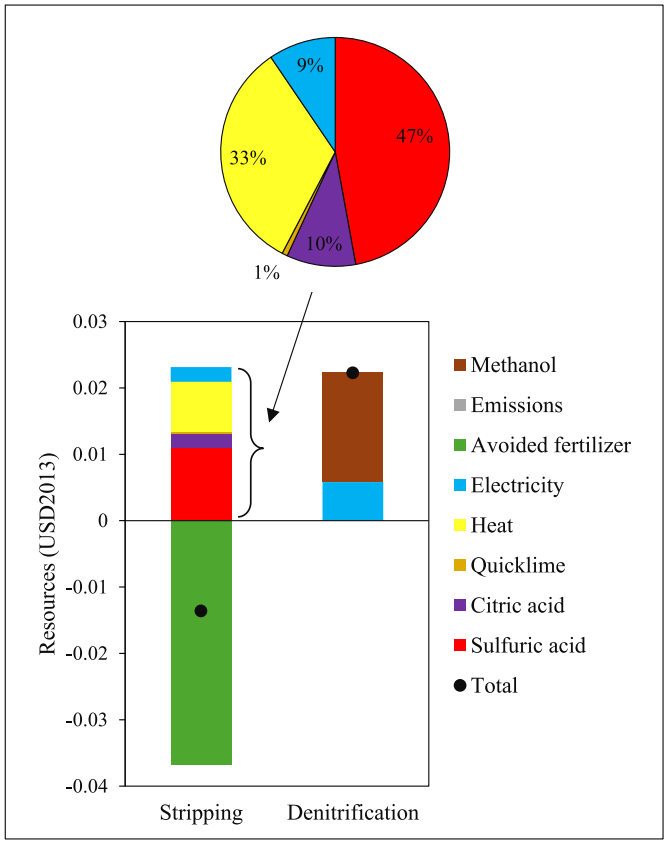


**Fig. 5.** Contribution of stripping and nitrification-denitrification to the resource damage category.

These findings are consistent with broader sustainability assessments of wastewater treatment systems showing that nutrient-recovery technologies can achieve improved overall sustainability through nutrient recovery and system-level offsets, even when they require substantial operational inputs (Johannesdottir et al., 2021).

### 3.5. Sensitivity analysis

A sensitivity analysis was conducted to evaluate the influence of the fertilizer substitution assumption on the environmental performance of ammonia stripping, as this parameter had the largest influence on the comparative results and represents a key uncertainty associated with the environmental credit assigned to nitrogen recovery.

The results, presented in Fig. 6, are based on the single-score damage assessment results and compare the baseline assumption, in which recovered ammonium sulfate substitutes marginal ammonium nitrate (AN), with alternative scenarios where ammonium sulfate (AS), calcium ammonium nitrate (CAN), and urea are assumed to be the marginal nitrogen fertilizer displaced by the recovered product. These scenarios were included to assess the robustness of the results with respect to uncertainty in the marginal fertilizer market and the choice of substituted nitrogen fertilizer.

The results demonstrate that the choice of substituted fertilizer has a significant influence on the magnitude of the environmental credits obtained through system expansion. However, the overall conclusions of the study remained unchanged across all scenarios. In all fertilizer substitution scenarios, ammonia stripping resulted in substantially lower environmental impacts than conventional nitrification-denitrification, indicating that the superiority of the stripping technology is robust with respect to assumptions regarding the displaced fertilizer.

Among the fertilizers considered, the substitution of ammonium sulfate resulted in the largest environmental benefit, followed by urea and calcium ammonium nitrate. Ammonium nitrate substitution yielded the lowest environmental credit among the fertilizer recovery scenarios. These differences are attributable to variations in the environmental burdens associated with the production of the respective fertilizers. Fertilizers with higher production-related impacts generate larger avoided burdens when displaced by recovered ammonium sulfate.

The single score results further indicate that the environmental benefits associated with fertilizer substitution are primarily driven by improvements in Human Health and Ecosystems damage categories, while the contribution to the Resources category is comparatively smaller. In contrast, the denitrification scenario exhibited positive impacts across all damage categories, with Human Health and Ecosystems representing the dominant contributors to the overall environmental burden.

In addition, sensitivity analyses were conducted for $N_2O$ emissions and ammonia recovery efficiency. $N_2O$ emissions from nitrification–denitrification were varied by ±20%, while ammonia recovery in the stripping process was reduced by 20% relative to the baseline. These variations affected the magnitude of the environmental impacts but did not change the comparative ranking of the two technologies. Even under the most conservative scenarios, including the lowest fertilizer-substitution credit and 20% lower ammonia recovery, air stripping maintained a substantial environmental advantage over nitrification–denitrification. Overall, the results indicate that the comparative advantage of air stripping is robust to the tested variations in $N_2O$ emissions, ammonia recovery efficiency, and marginal fertilizer substitution.

## 4. Future directions

The present study evaluates the environmental impacts associated with nitrogen removal and recovery at the treatment stage, using a common functional unit and system boundary for comparison. Future

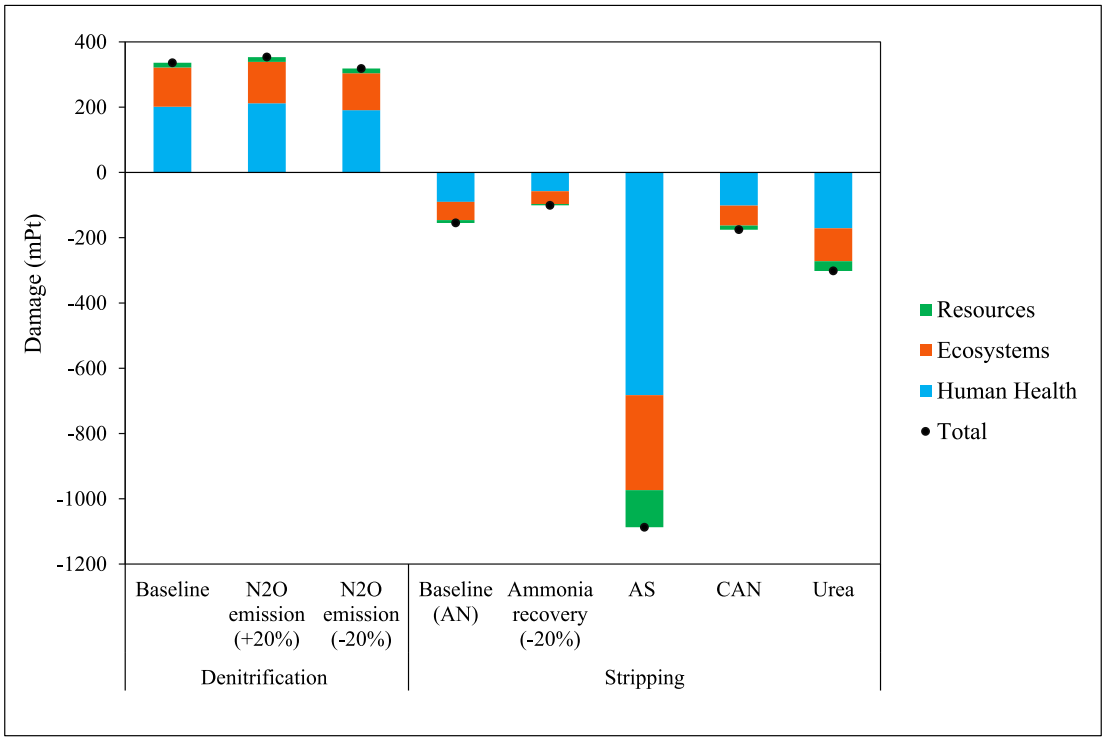


**Fig. 6.** Sensitivity analysis of single-score environmental impacts considering ±20% variation in $N_2O$ emissions, 20% reduction in ammonia recovery efficiency, and alternative marginal fertilizers (AS, CAN, and urea) compared with the baseline AN substitution.

research could extend this perspective by incorporating downstream management of residual streams and treated effluents. For nitrification–denitrification, this could include the treatment and potential valorization of excess biomass, while for ammonia stripping, the management and potential reuse of nitrogen-depleted effluent and chemical residues could be considered. Including these pathways would provide a more comprehensive assessment of the environmental trade-offs associated with the two nitrogen-management strategies. Previous research has shown that the management and valorization of residual streams can influence the environmental performance and credits of resource-recovery systems (Chen et al., 2019; Ghiasirad et al., 2025).

Future assessments could also examine the quality and downstream use of recovered ammonium sulfate when assigning environmental credits. The environmental benefit of recovered products depends not only on their nutrient content but also on product quality, treatment requirements, intended use, and their ability to substitute conventional products (Peng et al., 2023). A more detailed consideration of these factors could further refine the estimation of avoided fertilizer production.

Further work could investigate operational factors that may affect the performance of ammonia stripping under varying process conditions. In particular, fouling and cleaning requirements, chemical handling and storage, and variability in reject-water characteristics could be considered, as these may influence pH adjustment, ammonia recovery, energy demand, and chemical consumption.

Finally, the uncertainty analysis could be extended using probabilistic approaches, such as Monte Carlo simulation, to quantify the combined uncertainty associated with key process parameters and inventory assumptions. This would provide a broader characterization of the range of possible environmental outcomes and further support the robustness of comparisons between nitrogen removal and recovery technologies. Such approaches are consistent with recommendations for quantitative uncertainty analysis in assessments of emerging resource-recovery systems (Osman et al., 2024).

## 5. Conclusions

This study compared the environmental performance of ammonia air stripping and conventional nitrification–denitrification for nitrogen removal from reject water. Under the conditions evaluated, air stripping showed lower environmental burdens for human health and ecosystem quality than nitrification–denitrification. Importantly, this advantage remained when the avoided impacts associated with mineral fertilizer substitution were excluded, indicating that it was primarily associated with the lower process-related burdens of air stripping rather than with fertilizer recovery credits.

For resource use, the two technologies showed similar endpoint impacts before accounting for fertilizer substitution, with values of approximately 0.023 USD2013 for air stripping and 0.022 USD2013 for nitrification–denitrification. In this category, the environmental advantage of air stripping was therefore strongly influenced by the recovery of nitrogen as ammonium sulfate and its assumed substitution of marginal mineral fertilizer. Under the full fertilizer-substitution assumption applied in this study, the avoided production impacts offset the resource burdens of air stripping and resulted in a negative net modelled impact.

Overall, under the conditions and assumptions evaluated, ammonia air stripping showed lower net environmental burdens than nitrification–denitrification for the assessed nitrogen-removal function. The sensitivity analysis confirmed that this comparative advantage was maintained across the scenarios evaluated, although the magnitude of the difference varied with the underlying assumptions.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2026.100532.

## Data availability

Data will be made available on request.

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