Life cycle assessment of side stream removal and recovery of nitrogen from wastewater treatment plants

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Abstract
In the light of a circular economy, the Nijhuis Ammonia Recovery system (AECO-NAR) was developed to not only remove nitrogen from wastewater streams, but also produce ammonium sulfate (AS), used as fertilizer, in a single plant. The goal of this paper was to quantify the environmental impacts of side stream ammonia recovery with the AECO-NAR system and compares them with the impacts of side stream nitrogen removal combined SHARON (partly nitrification)-anammox plant. For this, an environmental life cycle assessment was performed with a functional unit (FU) of the treatment of 1 kg of total dissolved nitrogen inflow. Since AS obtained by the AECO-NAR is a by-product of the ammonia removal process, allocation was based on system expansion. Foreground inventory data were obtained from a full-scale plant. ReCiPe2016 was used to determine human health and biodiversity impacts. Results show that due to the production of AS in an integrated water treatment and production system, the AECO-NAR avoids impacts of current AS production, leading to negative impact scores. Impacts per FU decrease with increasing inflow concentrations of ammonia. Main improvement options are the use of renewable energy and the replacement of the cleaning chemical citric acid with a sustainable alternative. Total impacts of the AECO-NAR system diminish when comparing the system to the biological SHARON-Anammox system, due to production of AS fertilizer product. Due to the fertilizer production step being integrated in the side stream treatment, the complete system is beneficial over ammonia recovery and wastewater treatment as separate systems.

KEYWORDS
allocation, ammonia, ammonium sulfate, circular economy, fertilizer, nutrient recovery

1 | INTRODUCTION

(International policies currently aim to advance a circular economy (CE), including efforts to take the bio-based economy a step further by focusing on recycling and reuse of products and materials to minimize waste and resource use (e.g., EC, 2015, 2019; Rijksoverheid, 2019). As part of the European Union action plan toward a CE, nutrient recycling and water-efficiency measures are addressed (EC, 2015). Globally, an increase in wastewater emissions of nitrogen (N) is predicted, at least a doubling from 2000 to 2050 (Van Drecht, Bouwman, Harrison, & Knoop, 2009). Nutrient over-enrichment, that is, eutrophication, may lead to aquatic ecosystem degradation due to algal blooms, the growth of macrophytes, and aquatic hypoxia and anoxia (as summarized by Van Drecht et al., 2009).

Several countries have set nitrogen discharge limits applicable to wastewater treatment plants (WWTPs), such as the ones by the European Water Framework Directive (2000/60/EC) that calls for the implementation of the Urban Waste Water Directive (92/271/EEC) and sets discharge...
levels of 10–15 mg N/L for European WWTPs. Next to eutrophication, energy use related impacts are of concern since wastewater treatment plants (WWTPs) are large energy consumers (Di Fraia, Massarotti, & Vanoli, 2018; EPA, 2013).

Rodriguez-Garcia et al. (2014) showed the potential for nitrogen removal from the supernatant resulting from the anaerobic digestion of sludge, also called side stream, which substantially decreased eutrophication impacts, while also slightly reducing other environmental impacts. Among investigated side stream technologies are more common technologies such as nitritation-anammox (Rodriguez-Garcia et al., 2014; Schaubroeck et al., 2015), SHARON-Anammox (Hauck, Maalcke-Luesken, Jetten, & Huijbregts, 2016; Lin, Guo, Shah, & Stuckey, 2016), nitrification/denitrification (Lin et al., 2016; Rodriguez-Garcia et al., 2014), and struvite crystallization (Rodriguez-Garcia et al., 2014). But there are also promising new technologies such as ion-exchange (Lin et al., 2016) and cyanobacterial removal (Quiroz-Arita et al., 2019).

Various authors (e.g., Foley, de Haas, Hartley, & Lant, 2010; Hauck et al., 2016; Lederer & Rechberger, 2010; Lin et al., 2016; Rodriguez-Garcia et al., 2011; Vidal, Poch, Marti, & Rodriguez-Roda, 2002) highlighted the trade-off between more nitrogen removal on the one hand and higher energy demand, and related greenhouse gas emissions, on the other hand when comparing different types of wastewater treatment. Higher energy and chemical demands generally lead to higher costs. Hall, Priestley, and Muster (2018) investigated the environmental and economic impacts of wastewater treatment systems and showed a possible win-win situation for costs and impacts. Resource recovery is an important factor to achieve such win-win situations. Ye et al. (2018) reviewed ammonium recovery systems, indicating benefits of using recovered ammonium to supplement fertilizer production and save the expenses required in the conventional manufacturing of fertilizer, the so-called Haber–Bosch (H–B) process. However, no system was included that contains the actual production of fertilizer.

In the light of a circular economy, the Nijhuis Ammonia Recovery system (AECO-NAR) was developed to not only remove nitrogen from the side stream anaerobic digestate supernatant, but also create a valuable product. The system combines ammonium removal and nitrogen-fertilizer production in a single plant. AECO-NAR is a novel chemical recovery technology developed in response to the current biological techniques and their existing obstacles when implemented in a full-scale, such as the slow growth rate and sensitivity of the Anammox bacteria to dissolved oxygen (Eini, 2012). The chemical removal of nutrients from wastewater has its own challenges, such as CO₂ dosage and expected climate change impacts related to the elevated use and consumption of chemicals and energy. However, due to the recovery of ammonium sulfate (AS), it is hypothesized that the AECO-NAR system will overall cause less environmental impacts. This stems from the avoidance of electricity and chemicals used for the production of AS by the mainstream Haber–Bosch process.

The goal of this research was to quantify the environmental impacts of side stream ammonia recovery with the AECO-NAR system and to compare these impacts with the impacts of side stream nitrogen removal combined SHARON (Stable High rate Ammonia Removal Over Nitrite)-anammox plant. For this, an environmental life cycle assessment was performed on the AECO-NAR’s plant located in the east of the Netherlands at Groot Zevert Vergisting in Beltrum. This is, to our knowledge, the first time the environmental impacts of this system are investigated.

2 | METHODOLOGY

2.1 | System description

Figure 1 shows the system boundaries of the AECO-NAR system, which is categorized into two main phases:

Phase A: Where high nutrient loaded digestate supernatant inflows are fed into a CO₂ stripping tank and an ammonia stripping column.

Phase B: After the stripping process, ammonium that is left goes to a neutralization column, where pH is controlled at +/−6. Subsequently, the flow is sent to the scrubber column where the ammonia removed reacts with H₂SO₄ and fertilizer (NH₄)₂SO₄ can be obtained with ammonium concentrations up to 38%.

Calcium (CaO) is used as an ion exchanger that prepares the solution for the ammonia removal step allowing up to 80% removal. When lower removal efficiencies (60–70%) are sufficient, the system can operate without the addition of calcium. A Combined Heat and Power gas engine (CHP) provides most of the electricity and heat for the system. Those engines are commonly implemented at digesters and are part of most WWTPs’ designs. The advantage of the CHP is that the AECO-NAR system can be fully fed with residual heat from the process itself. Moreover, the AECO-NAR’s electricity demand is constant and very little dependent on the NH₄-N concentration in digestate. To prevent emission to the environment a gas-lock (filled with a small amount of H₂SO₄) is installed at the exhaust of the AECO-NAR. Therefore, what is emitted to the air is mostly moist and a small percentage of CO₂.

At the moment, there is a full-scale AECO-NAR plant installed in the United Kingdom and a plant running in the Netherlands, where improvements and tests are constantly made.

1 The term AECO is used by Nijhuis Technologies to indicate technologies they developed that recover products from wastewater and sludge.
FIGURE 1 AECO-NAR's system boundaries: Phase A represents the ammonia removal, while phase B represents the AS production. Phase B is methodologically equivalent to the H-B process (Source: Nijhuis Water Technology)

2.2 Life cycle assessment

Life Cycle Assessment (LCA) is a tool that quantifies the environmental impacts associated with a product or service (Consoli et al., 1993). It reviews the complete life cycle of the product or service in several steps. We performed an LCA based on the guidelines described in the ISO 14040–44 standards (ISO, 2006). The functional unit (FU) was defined as the treatment of one kg of total dissolved nitrogen inflow (kg N_{\text{total,in}}). We chose this FU because the specific function of the AECO-NAR system is to remove and reuse nitrogen. Since the AS obtained by the AECO-NAR is a by-product of the ammonia removal process and its local commercialization and consumption are expected, allocation was based on system expansion. That is, first, an LCA of the entire side stream AECO-NAR process, including wastewater treatment and AS production process, was performed. Subsequently, to arrive at the impacts of the wastewater treatment only, the environmental impacts of the mainstream AS production processes (Haber–Bosch) were subtracted from the AECO-NAR’s impact. This allows a fair comparison of the outcomes with other side stream treatments. As the full AECO-NAR system is an integrated system, it is not possible to separate the impacts of the digestate treatment from the impacts of the AS production.

Since we chose an attributional LCA, the ammonium sulfate replaced is the market mix. According to the European nitrogen assessment, 88% of the ammonium sulfate is a by-product of caprolactam and 12% comes from other processes, such as Haber–Bosch but also nickel and copper production processes (Leip & Prud’homme, 2011).

Construction materials used for infrastructure involved in facilities were not included in the system boundaries due to data immaturity and an expected small difference with SHARON-Annamox facilities.

An inventory of the energy and material inputs and outputs of the AECO-NAR was done based on the data collected from the AECO-NAR’s plant located in the east of the Netherlands at Groot Zevert Vergisting in Beltrum. A digestate flow capacity of 270 m$^3$/day and 2.5 kg of NH$_4$-N concentration per m$^3$ of digestate and 80% of ammonia removal efficiency was taken. All the parameters of the AECO-NAR were modeled according to the FU (kg N_{\text{total,in}}) and can be found in Table 1. Background data on chemicals and energy were taken from ecoinvent v3.3, “allocation at point of substitution—unit processes” database (Wernet et al., 2016).

The ammonium sulfate, current market share, was modeled as 88% by-product of caprolactam, 4.6% from nickel mine operation (ecoinvent data), 0.2% smelting and refining of nickel ore (ecoinvent data), and the remaining 7.2% from Haber–Bosch process. For this, the ammonium sulfate production processes in SimaPro, including energy and materials only, were adapted to include the production of sulfuric acid and ammonia (see Supporting Information for all data used). For the allocation of impacts of ammonium sulfate as a by-product from caprolactam, plastics Europe was followed (Boustead, 2005), where the burdens associated with the production of the ammonia and sulfuric acid used in the production of ammonium sulfate were assigned to the ammonium sulfate by-product.

A transport distance of 150 km was included as part of the H–B process, which represents the average distance that the AS has to travel, via truck, from the Rotterdam Port to a consumer located in the center of the country. The Rotterdam port was used as a baseline location in the Netherlands due to its trading relevance (Shi & Xing, 2015). Because of the smaller quantities of the AS produced with the AECO-NAR system, transport is estimated to be a maximum of 50 km.

The ReCiPe2016 LCIA method (H) v1.1 on endpoint level was used to quantify the environmental impacts of the AECO-NAR system (Huijbregts et al., 2016). All calculations were performed with the software SimaPro v8.5 (Pré consultants, 2017).
TABLE 1  Foreground inventory data for the AECO-NAR system per functional unit of 1 kg of total dissolved nitrogen inflow

| Parameters                          | AECO-NAR | Unit     | Model | Unit/Functional unit                                      |
|-------------------------------------|----------|----------|-------|----------------------------------------------------------|
| **Influent**                        |          |          |       |                                                         |
| Digestate inflow                    | 270      | m³/day   | 1     | kg N_{total, in}                                         |
| NH₄⁺ concentration in digestate     | 2.5      | kg/m³    | 1     | kg N_{total, in}                                         |
| **Effluent**                        |          |          |       |                                                         |
| N\_{total, out}                     | 0.5      | kg/m³    | 0.2   | kg N_{total,out}/kg N_{total, in}                        |
| P\_{total, out}                     |          |          | 0.02  | kg P_{total,out}/kg N_{total, in}                        |
| **Ammonium sulfate**                |          |          |       |                                                         |
| N removed                           | 2.0      | kg/m³    | 0.8   | kg N_{removed}/kg N_{total, in}                          |
| **Chemical consumption**            |          |          |       |                                                         |
| Citric acid (C₆H₈O₇)               | 8.22     | kg/day   | 0.012 | kg of C₆H₈O₇/kg N_{total, in}                             |
| Calcium (CaO)—95% purity           | 0.58     | kg/m³    | 0.232 | kg/kg N_{total, in}                                     |
| Tap water                           | 0.19     | kg/m³    | 0.076 | kg/kg N_{total, in}                                     |
| Sulfuric acid (H₂SO₄)               | 7.0      | kg/m³    | 2.80  | kg of H₂SO₄/kg N_{total, in}                              |
| Energy consumption (CHP)            | 19.1     | kW/m³    | 7.62  | kW/m³/kg N_{total, in}                                   |
| Power (installed power + power factor) | 27.2   | kW      | 10.88 | kW/kg N_{total, in}                                     |
| Heat (if residual heat is not available) | 214    | kWh     | 0.317 | kWh/kg N_{total, in}                                     |
| Total electricity used              | 652.8    | kWh/day  | 0.967 | kWh/kg N_{total, in}                                     |
| **Emissions**                       |          |          |       |                                                         |
| CO₂ as CO₂/HCO₃                     | 8.6      | kg/m³    | 3.44  | kg of CO₂/HCO₃/kg N_{total, in}                           |
| CO₂ in effluent                     | 5.16     | kg/m³    | 2.064 | kg CO₂/kg N_{total, in}                                  |
| CO₂ removed                         | 3.44     | kg/m³    | 2.76  | kg CO₂/kg N_{total, in}                                  |
| CO₂ as CaCO₃                        | 0.069    | kg/m³    | 0.028 | kg CaCO₃/kg N_{total, in}                                |
| CO₂ in exhaust                      | 0.305    | kg/m³    | 0.122 | kg CO₂/m³/kg N_{total, in}                               |

2.3 | Comparison with biological removal

The two-step SHARON-Anammmox sidestream removal system configured at the Rotterdam Dokhaven WWTP was chosen as the system to be compared with the AECO-NAR. For this, data from Hauck et al. (2016) was used, where an LCA of the WWTP is performed using the same FU as in our study. Foreground inventory data can be found in Table S1 in the Supporting Information.

2.4 | Scenario analyses

To assess the robustness of the results three sensitivity analyses were performed:

1. **Availability residual heat**: On average, the amount of heat from the CHP is 500 kW, while 200 kW is needed to heat the system. However, to test the extra impacts when residual heat would not be available, we calculated the damage impacts in case extra heat would need to be produced from natural gas (European market mix).

2. **Varying influent concentrations**: Influent concentrations may vary over the year as well as per location, depending on nitrogen deposition and nitrogen addition to the soil, for example, in agricultural areas. Because these influent characteristics could have implications for the choice of ammonia side stream removal technologies, the effect of NH₄⁻N inflow concentration on the environmental impact of the AECO-NAR and the SHARON-Anammmox system was investigated. For this, all the chemical and electricity consumption of the AECO-NAR were adapted to a 0.5 kg variance, starting from 1 to 3.5 kg of NH₄⁻N concentration per m³ of digestate inflow. The inventory data are in Table S2 in the Supporting Information.

3. **Replacement of fertilizer**: As a default, the ammonium sulfate produced with the AECO-NAR system was assumed to replace the market mix. However, since ammonium sulfate will be produced as a by-product of various processes, the fertilizer sulfate produced via AECO-NAR will most likely replace the Haber–Bosch produced product only. Therefore, we tested the impacts by replacing this only, as well as a maximum impact scenario where no impacts were allocated to the fertilizer produced as a by-product in the caprolactam production process.
3 | RESULTS

To get an idea of the contribution to environmental impacts of each part of the system, Figure 2 shows the impacts of the full AECO-NAR system, including both the wastewater treatment and the ammonium sulfate production per kg $N_{\text{total}}$. It can be seen that for human health as well as ecosystem impacts, sulfuric acid production contributes to a large extent. This is because of particulate matter formation and acidification, respectively. Next to that, the direct phosphorus emissions in the wastewater causing eutrophication contribute most to ecosystem damage.

To be able to compare the system with other wastewater treatment technologies, the impacts were determined including avoided impacts of the ammonium sulfate production. Figure 3 shows the comparison of the AECO-NAR system and the SHARON-Anammox system.

Due to the production of ammonium sulfate in an integrated water treatment and production system, the AECO-NAR avoids impacts of current ammonium sulfate production, resulting in negative impacts. These results are caused by the avoidance of liquid ammonia production, which mainly causes impacts on global warming, ozone formation, acidification, water consumption, and fine particulate matter formation. For human health, net negative impacts were estimated for the AECO-NAR system, while anammox has positive impacts, mainly caused by global warming. For ecosystem damage, net positive impacts were estimated due to the phosphorous emissions, which are similar for the anammox system. Overall, the AECO-NAR system causes less damage to ecosystems. When residual heat was assumed not to be available from the CHP, human health and ecosystem impacts increased by 1.5% only.

Figure 4 shows the decrease in environmental impacts for increasing concentrations of ammonia. This is mainly caused by a decrease in energy consumption for 80% removal of low ammonium concentrations versus high ammonium concentrations. All impacts decrease for increasing concentrations, per FU of 1 kg of total dissolved nitrogen inflow, but global warming the most with 50%.

Figure 5 shows the results of the scenario analysis performed to check the results with changing assumption of replacement of the produced ammonium sulfate of current used fertilizer. It can be seen that in the likely scenario that the ammonium sulfate produced with AECO-NAR only
replaces the virgin ammonium sulfate produced with Haber–Bosch, the avoided impacts are 1.7 times larger for human health impacts and slightly larger for ecosystem impacts. In case no impacts from caprolactam production are allocated to the by-product ammonium sulfate, the impacts of AECO-NAR are 3.5 (human health) and 2.2 (ecosystems) times larger than the impacts of SHARON-Anammox treatment.

4 | DISCUSSION

4.1 | Uncertainties and limitations

In several cases, estimations were necessary for this study that could lead to uncertainties. First, due to the AECO-NAR’s system infrastructure data immaturity, not yet accountable by the time this study was performed, we had to limit the impact analysis by excluding the hydraulic and civil materials involved at the plant construction. Although in several cases the influence of major infrastructure to environmental impacts was shown to be negligible (e.g., Hauck et al., 2016; Morelli et al., 2018; Rahman, Eckelman, Onnis-Hayden, & Gu, 2018), some studies showed a contribution of 20–40% to overall environmental impact (Ortiz, Raluy, Serra, & Uche, 2007; Remy & Jekel, 2008). Next to that, improved levels of wastewater treatment and nutrient removal, such as the AECO-NAR system, are usually accompanied by improvements in the plant design and physical infrastructure. Consequently, the production and consumption of materials needed for the improvement can cause an increased environmental burden (Foley et al., 2010). However, the same counts for the SHARON-Anammox system, being at early-stage development, making the difference in the systems related to infrastructure small.

Second, emissions and energy inputs were determined as accurately as possible, based on various measurements done for the AECO-NAR system. Logically, these data could change over time, not the least because the design of the system is constantly being fine-tuned and the emissions...
might also vary. In a near future, once the AECO-NAR design achieves a final format, we recommend new emissions measurements for a longer period of time in order to include seasonal and concentration variations and provide a less uncertain average.

Third, both the AECO-NAR system and the SHARON-Anammox are technologies that can be implemented as side streams on a WWTP. Although Rodriguez-Garcia et al. (2014) showed that, compared to the impacts of a full WWTP, the environmental impacts of side stream supernatant resulting from the anaerobic digestion of sludge are small, we chose to focus on this part only for two reasons: (a) the main goal of this work was to specifically compare a biological side stream removal technology with a new chemical side stream recovery technology; and (b) the impacts of the mainstream WWTP will stay the same for both technologies. Our results are therefore not comparable to other studies investigating full WWTPs, but are comparable to LCA investigating specific side stream technologies.

4.2 | Interpretation of contribution analysis

The main contributors to the AECO-NAR impacts are the sulfuric acid needed to produce the fertilizer and the direct phosphorus emissions. Background data used on sulfuric acid production were from ecoinvent and judged to be of low uncertainty according to the pedigree matrix approach (Althaus et al., 2007). Production of this chemical contributes mainly to acidifying, fine dust, and global warming emissions, and to a lesser extent to water consumption, contributing to 84% of the impacts on human health and 27% of the impacts on ecosystems. However, if the wastewater treatment and ammonia production was not integrated in one system, the impacts of ammonia sulfate production would be much larger, since the ammonia stream would not be reused, and the ammonium sulfate would need to be transported from further away to its application site. The comparison with the combined SHARON-Anammox plant shows that, due to the fertilizer production step being integrated in the WWTP, the complete system is beneficial over ammonia recovery and wastewater treatment as separate systems.

Direct phosphorus emissions in the wastewater flow contribute for 63% to the total ecosystem damage, showing the importance of removing pollutants from the wastewater. Here, we assumed the same amount of total phosphorus emissions as when using the SHARON-Anammox system, since both systems focus on ammonia recovery only. These results show that technologies combining nitrogen and phosphorus removal, such as struvite crystallization (see e.g., Rodriguez-Garcia et al., 2014) could be beneficial, and it would be interesting to see the possibilities of recovering both nutrients from the water flow.
Electricity use and citric acid, used as cleaning agent, both contribute a large share to the total human health and ecosystem impacts. Regarding electricity use, the AECO-NAR system becomes more efficient with increasing concentrations of nitrogen in the influent. This means that the system is especially useful in areas with nitrogen-rich wastewater, such as agricultural areas and digestate from digesters. In the future, electricity sources will also become more and more renewable which might reduce the impact of electricity use on several categories. Citric acid, even though used in small amounts once in a while to clean the system, clearly contributes to the overall results (see Figure 2). The large contribution of citric acid in the production step was also found by Golsteijn et al. (2015), which stresses the need to look into potentially more sustainable alternatives (e.g., lemon juice from sustainable sources).

4.3 | Allocation and functional unit choices

As argued by Vadenbo, Hellweg, and Astrup (2017), when it comes to allocation procedures, it is important to systematically determine and communicate substitution processes. Here, we assumed that the ammonium sulfate produced with the AECO-NAR system replaces the market mix, as is commonly done in attributional assessments. Since most of the ammonium sulfate originates from caprolactam production, a choice needed to be made on how to allocate the impacts of this production process to ammonium sulfate. As argued by Boustead (2005), a relatively high mass of ammonium sulfate is produced compared to caprolactam. A simple mass partition would therefore assign most of the burdens to ammonium sulfate. Since the primary aim of the process is caprolactam production, and there are considerably simpler routes available for the production of ammonium sulfate, it would not be fair to allow most of the burdens to be assigned to ammonium sulfate. Therefore the choice was made to only assign the production of the ammonia and sulfuric acid used in the production of ammonium sulfate to the fertilizer. Our results showed that these impacts already are considerable, making the AECO-NAR an efficient process. Allocating parts of the energy consumption, for example, also to the fertilizer, would only increase the advances shown for the AECO-NAR process and were therefore not tested here. When allocating no impacts to the by-product (as the process will always be in place to create caprolactam and thus ammonium sulfate, independent of the need for it), however, we showed that the ecosystem impacts of the AECO-NAR system were more than two times larger than the impacts of the SHARON-Anammox system and the impacts on human health were even four times larger. However, because of the current market potential and thereby profit of the fertilizer, this is currently not a recommended way of allocating the impacts.

Next to the logical choice to replace the ammonium sulfate market mix, it could also be argued that in practice only the newly produced fertilizer would be replaced, as ammonium sulfate will be continued to be produced as a by-product, regardless of the potential market. Therefore, we tested this assumption and results showed the increase in environmental benefits with the AECO-NAR system compared to the SHARON-Anammox system.

For wastewater treatment in general an FU of 1 m³ water treated is chosen. However, as the specific function of the AECO-NAR system is to remove and reuse nitrogen, an FU of the treatment of one kg of total dissolved nitrogen inflow (kg N_{total,in}) was chosen. Another option would have been to look at the final product and to choose an amount of fertilizer produced, as for example, done by Pradel and Aissani (2019) for phosphorous removal. However, in that case, only part of the wastewater treatment can be allocated to the fertilizer production, as part needs to be allocated to the flow of clean wastewater out of the system. This will lead to another allocation problem. Moreover, due to the integrated nature of the AECO-NAR, that is, with the function to clean water but the side benefit to reuse ammonia, it is more appropriate to focus on the wastewater treatment. Pradel and Aissani (2019) found that fertilizer produced with their technology was less environmentally friendly over the production via the conventional way. This, while it should be seen as an extra benefit to produce fertilizer from wastewater streams and not as the main aim to produce fertilizers in this way.

5 | CONCLUSIONS

Ye et al. (2018) already showed that ammonium recovery from wastewater reduces the costs, energy, and environmental footprint associated with this removal process, and additionally ensures that the final product can be used to supplement fertilizer production and save the expense required in the industrial Haber–Bosch process. This paper shows the actual benefits of an integrated removal, recovery, and fertilizer production system in terms of environmental costs. Main improvement options are the use of renewable energy and the replacement of the cleaning chemical citric acid with a sustainable alternative. Looking more broadly to technological developments, the focus should be put on recovery of multiple substance flows from the wastewater. The total impacts of the AECO-NAR system diminish when comparing the system to the biological SHARON-Anammox system, due to ammonium sulfate production. Due to the fertilizer production step being integrated in the WWTP, the complete system is beneficial over ammonia recovery and wastewater treatment as separate systems.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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