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# Constructed wetlands and duckweed ponds as a treatment step in liquid manure handling — A life cycle assessment

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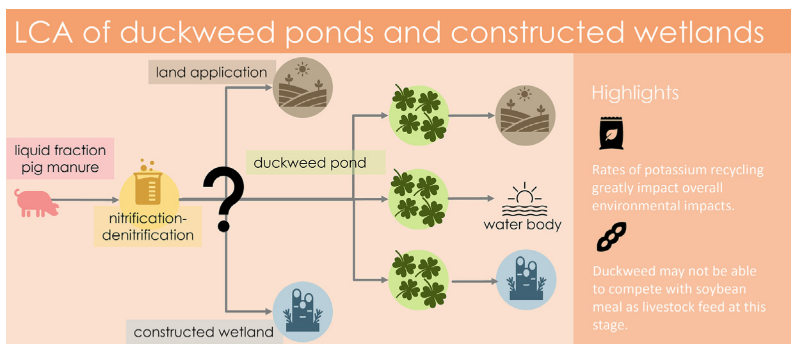
## HIGHLIGHTS

- Life cycle assessment on tertiary treatment of liquid fraction pig manure
- Assessment of different combinations of duckweed ponds and constructed wetlands
- Rates of potassium recycling greatly impact overall environmental impacts.
- Duckweed may not be able to compete with soybean meal as livestock feed.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Life cycle assessment (LCA) was applied to evaluate duckweed ponds and constructed wetlands as polishing steps in pig manure liquid fraction treatment. Using nitrification-denitrification (NDN) of the liquid fraction as the starting point, the LCA compared direct land application of the NDN effluent with different combinations of duckweed ponds, constructed wetlands and discharge into natural waterbodies.

Duckweed ponds and constructed wetlands are viewed as a viable tertiary treatment option and potential remedy for nutrient imbalances in areas of intense livestock farming, such as in Belgium. As the effluent stays in the duckweed pond, settling and microbial degradation reduce the remaining phosphorous and nitrogen concentrations. Combined with duckweed and/or wetland plants that take up nutrients in their plant body, this approach can reduce over-fertilisation and prevent excessive nitrogen losses to aquatic environments. In addition, duckweed could serve as an alternative livestock feed and replace imports of protein destined for animal consumption.

The environmental performance of the overall treatment systems studied was found to depend greatly on assumptions about the possible avoidance of potassium fertiliser production through the field application of effluents. If it is assumed that the potassium contained in the effluent replaces mineral fertiliser, direct field application of the NDN effluent performed best. If the application of NDN effluent does not lead to mineral fertiliser savings or if the replaced K fertiliser is of low grade, duckweed ponds seem to be a viable additional step in the manure treatment chain.

Consequently, whenever background concentrations of N and/or P in fields allow for effluent application and potassium fertiliser substitution, direct application should be favoured over further treatment. If direct land application of the NDN effluent is not an option, the focus should be on long residence times in duckweed ponds to allow for maximum nutrient uptake and feed production.

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## 1. Introduction

The agricultural landscape in Flanders, Belgium is characterised by high pig densities, and the accruing amounts of pig manure exceed the safe uptake capacities of arable land available locally (Landmaatschappij, 2021). This imbalance harms aquatic and terrestrial ecosystems and has resulted in a requirement for manure processing. One example of this kind of processing technique is solid-liquid manure separation, which divides the manure into a P-rich solid and an N- and K-rich liquid fraction. Given its low water content and high nutrient concentration, the solid fraction can be transported to distant P-deficient fields at a reasonable cost. However, the high water content of the liquid fraction renders its transport problematic and uneconomical. The liquid fraction can instead be subjected to additional treatments such as nitrification-denitrification (NDN), where most of the nitrogen is converted into harmless $N_2$ gas. Despite these efforts and given the high background concentrations in some Flemish agricultural soils, application of the remaining effluents may still exceed local application targets. In such cases, further polishing of the NDN effluent is needed to safeguard ecosystems adjacent to agricultural land. Apart from regional dependencies on foreign manure demand, Flemish farmers are dependent on large transcontinental imports of feed protein to sustain high livestock densities. These protein feeds contribute to environmental degradation in the areas where they are cultivated.

Constructed wetlands (Boets et al., 2011; Meers et al., 2008) and duckweed ponds (Devlamynck et al., 2021a, 2021b) can, when incorporated in the manure treatment chain, have the potential to mitigate these problems. Both installations serve as settling ponds, and through sedimentation and microbial nitrification-denitrification lower the remaining concentrations of phosphorous and nitrogen. Furthermore, by taking up nutrients into their plant biomass, duckweed and reeds refine the NDN effluent of pig manure and facilitate its safer disposal. In addition, duckweed may serve as a protein-rich livestock feed and as a natural link in pig production cycles (Devlamynck et al., 2020).

Two life cycle assessments (LCA) related to duckweed and constructed wetlands have been published. The most recent LCA assessed the environmental impacts of duckweed production on municipal wastewater and its use in biorefinery processes to produce energy and fertiliser (Calicioglu et al., 2021), while the other considered constructed wetlands as a polishing step in the treatment of pig manure in Mediterranean conditions (Bayo et al., 2012). However, no study has analysed these technologies as tools for cleaning the NDN effluent from the liquid fraction of pig manure produced in areas of intensive pig production, or analysed the combination of the two technologies to achieve acceptable water quality and compared their treatments with direct land application of the NDN effluent. In addition, the benefits of the produced duckweed as a feed source have never been included in LCA studies. Therefore, studies including all these effects are needed to assess the environmental impacts of such systems.

The purpose of this study was to assess the potential environmental benefits of deploying duckweed production and constructed wetlands for the treatment of wastewater from liquid fraction pig manure after NDN under the conditions found in Belgium. Different combinations of duckweed ponds and/or constructed wetlands were generated and the hypothetical effects of variations in residence time were examined. The inventory for this LCA was based on pilot-scale duckweed growth experiments and literature research.

## 2. Material & methods

### 2.1. Goal & scope

The goal of this LCA study was to assess the environmental implications associated with different liquid-fraction manure polishing pathways following nitrification-denitrification (NDN) as a secondary treatment step. The functional unit in all cases was the treatment of 1000 kg liquid fraction pig manure after separation. The different pathways were five combinations of land application, duckweed ponds, constructed wetlands and discharge into natural waterbodies (Fig. 1).

All the treatment chains start after the mechanical separation of raw pig manure and with the separated liquid fraction entering the system. Management of the solid fraction is common for all scenarios and is hence cut off from the system boundary. The entire amount or parts of the liquid fraction undergo NDN. After NDN, the effluent is field applied (Scenario 1 in Fig. 1 — grey), fed to a constructed wetland (Scenario 2 — yellow) or mixed with rainwater and the untreated liquid fraction and fed to a duckweed pond, from which the effluent is led to a constructed wetland (Scenario 3 — red), field applied (Scenario 4 — blue) or discharged into natural waterbodies (Scenario 5 — green). For each scenario, two possible 'realities' were assumed: either the potassium contained in the NDN effluent replaces the provision of mineral K fertiliser on the Belgian market or it does not (striped boxes in Fig. 1).

### 2.2. Inventory

The data underlying this study was derived from experiments, literature data, mass balancing and ecoinvent processes (v.3.7.1 consequential (Moreno Ruiz et al., 2020a)). Table 1 provides an overview of the inventory, while the supplementary information (SI) contains more detailed descriptions.

The liquid fraction is rich in nitrogen (N) and potassium (K), and has a higher N/P ratio than raw manure. While this allows for higher application rates compared with raw manure, nitrogen loads are still too high for the area available. For that reason, biological nitrogen removal (nitrification-denitrification) is used to convert parts of the ammonium-N into harmless $N_2$ gas.

#### 2.2.1. NDN treatment

NDN treatment (i.e. nitrification-denitrification of the liquid fraction) is the most common manure treatment technology in Flanders, with 95 installations in operation in 2020 (D'Haene and Vannecke, 2020). The inventory for the NDN treatment includes infrastructure (Corbala-Robles et al., 2018), direct emissions, and sludge and effluent disposal. The nitrogen mass balance of the NDN treatment was performed using STOAT (Henze et al., 2015), which models activated sludge systems and represents the treatment of the liquid fraction of pig manure through a nitrification-denitrification pathway.

The excess sludge is stored, transported and field-applied on P-deficient farmland in France. The biological effluent is either applied to arable agricultural land in Flanders (Scenario 1) or subjected to further treatments (Scenarios 2–5) (V.U. Vlaamse Landmaatschappij, 2015). Storage and field emissions were included in both cases.

#### 2.2.2. Duckweed pond

The inventory of the duckweed pond treatment includes pond construction and operation (Calicioglu et al., 2021), effluent and sludge disposal, and duckweed production. The mass balance was primarily based on data derived from laboratory and pilot-scale experiments conducted by the Provincial Research and Advice Centre for Agriculture and Horticulture (Inagro) in Belgium. Inagro assessed the ability of duckweed to serve as a polishing step in pig manure treatment. The experiments included indoor and outdoor trials and focused on water quality parameters as well as duckweed composition and, hence, its nutritional value. Descriptions of these studies can be found in Devlamynck et al. (2020, 2021a, 2021b) as well as in the SI.

After NDN, the biological effluent is mixed with untreated liquid manure and rainwater to obtain N and P ratios and concentrations (N: 2.8–350 mg/l, P: 0.4–11 mg/l) optimal for duckweed growth (Elias Landolt and Kandeler, 1987). To represent different treatment and production strategies, three different residence times of the biological effluent in the ponds and their influence on the overall environmental performance of the system were explored:

(i) Short: The residence time is kept sufficiently short so that duckweed grows under optimal nutrient supply, i.e. nutrient concentrations of N and P are always between 90 % and 100 % of the optimum (optimum growth conditions retrieved from Elias Landolt and Kandeler

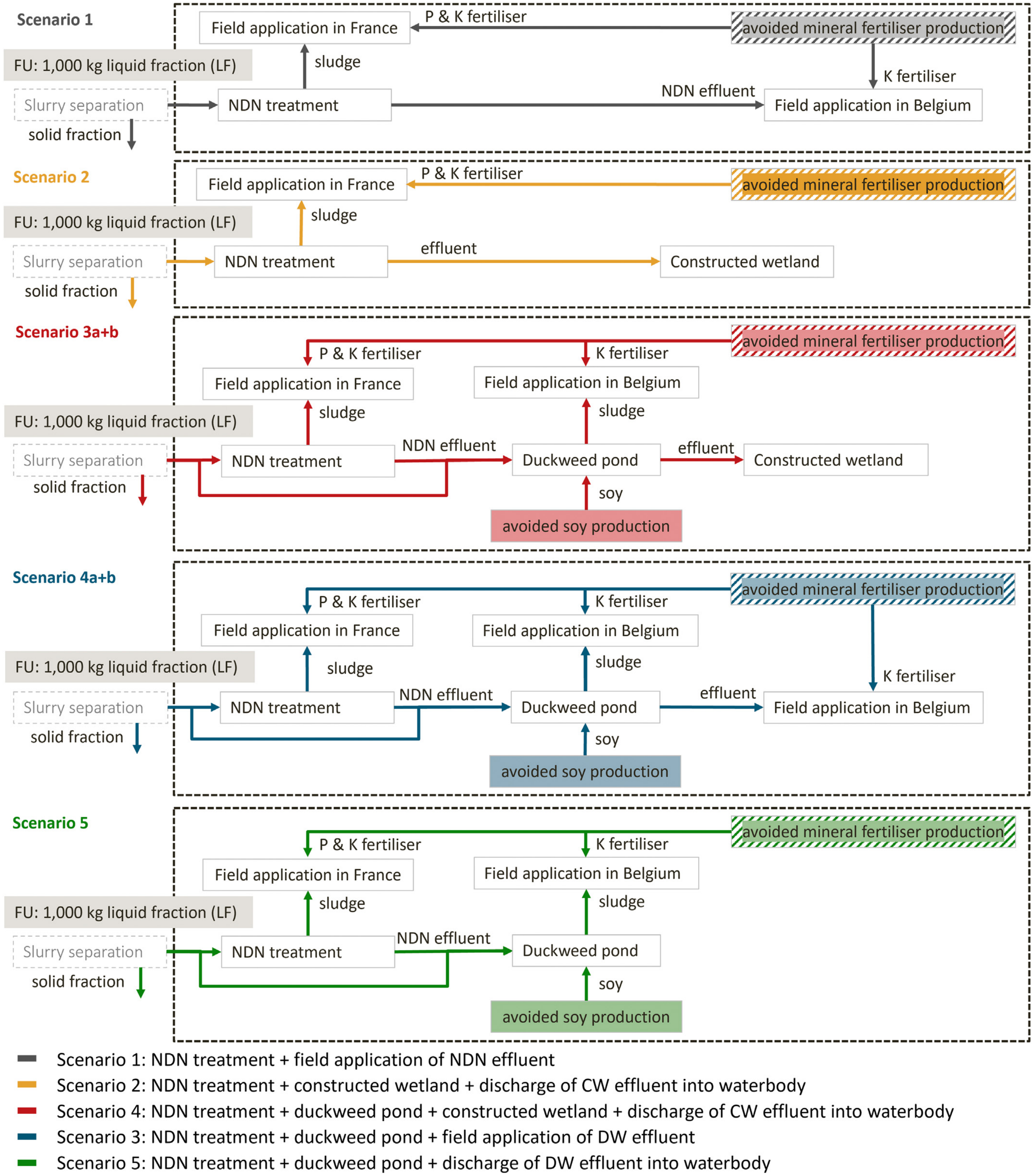


**Fig. 1.** Structure of treatment systems and scenarios under study. Boxes indicate activities in the foreground system. Arrows indicate exchanges. Boxes of avoided processes in colour. Striped box: assuming either avoidance or no effect. CW: constructed wetland, DW: duckweed pond, FU: functional unit (grey background), LF: liquid fraction, NDN: nitrification-denitrification (i.e. biological treatment).

(1987)). This requires a smaller area and facilitates faster treatment, but the 'recycling' rates of N and P are lower than for ii and iii. This treatment path is represented by Scenarios 3a and 4a.

(ii) Intermediate: The effluent is kept in the pond until it is 50 % below the optimum N and P concentrations. This results in an intermediate residence time of around 16 days. This treatment path is represented by Scenarios 3b and 4b.

(iii) Long: The mixture is kept in the duckweed pond until the lower optimum concentration of either N or P is reached. This requires a longer residence time and therefore a larger area, but greater amounts of

**Table 1**
Inventory for the treatment of liquid fraction pig manure for the baseline scenarios. Values refer to the functional unit of 1 $m^3$ liquid fraction entering the system.

| | 1 \| NDN + F | 2 \| NDN + CW | 3a \| NDN + DW (short) + CW | 3b \| NDN + DW (medium) + CW | 4a \| NDN + DW (short) + F | 4b \| NDN + DW (medium) + F | 5 \| NDN + DW (long) |
|---|---|---|---|---|---|---|---|
| | • Nitrification-denitrification treatment | | | | | | |
| | • Field application of the NDN effluent | • Treatment of the NDN effluent in a constructed wetland | • Treatment of the NDN effluent in a duckweed pond for 4 days • Treatment of DW effluent in constructed wetlands | • Treatment of the NDN effluent in a duckweed pond for 19 days • Treatment of DW effluent in constructed wetlands | • Treatment of the NDN effluent in a duckweed pond for 4 days • Field application of DW effluent | • Treatment of the NDN effluent in a duckweed pond for 19 days • Field application of DW effluent | • Treatment of the NDN effluent in a duckweed pond for 31 days • Discharge of DW effluent into natural waterbody |
| **INVENTORY** | | | | | | | |
| NITRIFICATION-DENITRIFICATION TREATMENT | | | | | | | |
| *Infrastructure* | Derived from Corbala-Robles et al. (2018) & see SI Table A1 | | | | | | |
| *Storage emissions* | | | | | | | |
| Ammonia [kg] | 0.01 | 0.01 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
| Methane [kg] | 0.33 | 0.33 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 |
| *Field application - sludge* | | | | | | | |
| Transportation to France [kg ∗ km] | 60 ∗ 250 | 60 ∗ 250 | 54 ∗ 250 | 54 ∗ 250 | 54 ∗ 250 | 54 ∗ 250 | 54 ∗ 250 |
| Field application [kg] | 60 | 60 | 54 | 54 | 54 | 54 | 54 |
| Avoidance of P fertiliser [kg] | −0.23 | −0.23 | −0.207 | −0.207 | −0.207 | −0.207 | −0.207 |
| Avoidance of K fertiliser [kg] | −0.17 | −0.17 | −0.153 | −0.153 | −0.153 | −0.153 | −0.153 |
| *Field application - effluent* | | | | | | | |
| Spreading to field [$m^3$] | 0.75 | | – | – | – | – | – |
| Avoidance of K fertiliser [kg] | −4.3 | | – | – | – | – | – |
| Ammonia emissions [kg] | 0.0002 | | – | – | – | – | – |
| $N_2O$ emissions [kg] | 0.0023 | | – | – | – | – | – |
| Nitrate leaching [kg] | 0.12 | | – | – | – | – | – |
| Phosphate leaching [kg] | 0.0001 | | – | – | – | – | – |
| DUCKWEED POND | | | | | | | |
| *Infrastructure* | – | – | Derived from Calicioglu et al. (2021) & see SI Table A6 | | | | |
| Electricity consumption for harvesting [kWh] | – | – | 0.04 | 0.90 | 0.04 | 0.90 | 3.30 |
| *Field application - sludge* | | | | | | | |
| Field application [m3] | – | – | 0.31 | 0.153 | 0.31 | 0.153 | 0.254 |
| Avoidance of K fertiliser [kg] | – | – | −0.26 | −1.3 | −0.26 | −1.3 | −2.2 |
| Ammonia emissions [kg] | – | – | 0.002 | 0.009 | 0.002 | 0.009 | 0.015 |
| $N_2O$ emissions [kg] | – | – | 0.0009 | 0.005 | 0.0009 | 0.005 | 0.008 |
| Nitrate leaching [kg] | – | – | 0.01 | 0.065 | 0.01 | 0.065 | 0.1 |
| Phosphate leaching [kg] | – | – | 2.66E−05 | 0.0001 | 2.66E−05 | 0.0001 | 0.0002 |
| Avoidance of protein feed [kg] | – | – | 0.1 | 0.5 | 0.1 | 0.5 | 0.9 |
| *Field application - effluent* | | | | | | | |
| Spreading to field [$m^3$] | – | – | – | – | 9.4 | 9.4 | – |
| Avoidance of K fertiliser [kg] | – | – | – | – | −3.3 | −2.3 | – |
| Ammonia emissions [kg] | – | – | – | – | 0.02 | 0.006 | – |
| $N_2O$ emissions [kg] | – | – | – | – | 0.009 | 0.004 | – |
| Nitrate leaching [kg] | – | – | – | – | 0.13 | 0.06 | – |
| Phosphate leaching [kg] | – | – | – | – | 0.0002 | 9.49E-05 | – |
| CONSTRUCTED WETLAND | | | | | | | |
| Infrastructure | – | Corbella et al. (2017), Scenario S1 & see SI Table A10 | | | | | – |

plant-available N and P are taken up by the duckweed. Following the treatment, concentrations of N and P are low enough for direct discharge into natural waterbodies and no additional treatment in a constructed wetland is needed. This treatment path is represented by Scenario 5 in Fig. 1.

The sludge from the duckweed ponds was assumed to be applied on fields in Belgium because the water content is too high for longer transport distances.

#### 2.2.3. Constructed wetland

The inventory for the constructed wetland treatment step includes construction and operation (Corbella et al., 2017). The nutrient mass balance was based on Meers et al. (2008), and was also used to calculate gaseous emissions.

### 2.3. Credits & consequential modelling

Apart from modelling the foreground wastewater treatment chains themselves, their implications and direct consequences in the background system were modelled through system expansion (Fig. 1).

When applying the sludge to agricultural fields in France, credits for the avoidance of mineral P and K fertiliser were included. When applying sludge or effluent to agricultural fields in Belgium, no credits were given for P fertiliser avoidance as fields are typically over-fertilised (Lagerwerf et al., 2019). Regarding the avoidance of K fertiliser, two scenarios were considered: one scenario in which the avoidance of K fertiliser is included (as in the case of sludge field application in France), and one scenario in which the effluent application had no substituting effect. While in Flanders recommendations regarding the spreading of effluents are typically based on the K requirements of receiving crops (Lemmens et al., 2007; V.U. Vlaamse Landmaatschappij, 2015), it was deemed critical to assume default replacement. Based on its protein content, the harvested duckweed is assumed to replace the marginal protein provider on the market, i.e. soybean meal.

### 2.4. Life cycle impact assessment

A consequential LCA perspective was applied and the ecoinvent v3.7.1 database (Moreno Ruiz et al., 2020b) in openLCA v1.10.3 (*https://openlca.org*) was used. For the impact assessment calculations, the Environmental Footprint 3.0 methodology (Fazio et al., 2018) was used. When interpreting the results, the recommendations of the Product Environmental Footprint Method were followed to the maximum extent possible, and included normalisation and weighting (European Commission, 2021). Normalisation provides dimensionless point values, which replace the different units of each impact category. Normalised impact results reflect the contribution of the system per functional unit to the average environmental impact of one global citizen during one year (EC-JRC, 2012). Weighting follows normalisation and scales the impact in each category according to its relevance. When combined, normalisation and weighting allow for a rating of impact categories (from greatest to least concern) and scenarios (least and most favourable alternative).

Hotspot analysis allowed identification of the life cycle stages, processes and elementary flows of greatest concern, and two alternative scenarios were created to explore the robustness of results.

In the alternative scenarios, different ecoinvent processes for K fertiliser provision and their effects on overall results were tested.

## 3. Results

This section consists of three parts: (i) the presentation of normalised and weighted environmental impact results, (ii) an overview of the impact contributions of a single life cycle stage, processes and elementary flows, and (iii) an assessment of the alternative assumptions in the scenario analysis. These alternative assumptions concern different ecoinvent processes for commercial sources of K fertiliser.

(i) Normalised and weighted environmental impacts

If it was assumed that mineral K fertiliser is avoided by the application of K contained in the biological effluents, some scenarios indicated net environmental benefits while others indicated net environmental damage potential.

Where no avoidance of K fertiliser was assumed, all scenarios resulted in net environmental impacts. In the case of avoidance, Scenario 1 (biological treatment + field application) indicated the greatest environmental benefits and Scenario 2 (biological treatment + constructed wetland) the highest overall weighted environmental burdens (Fig. 2). Of the scenarios including a duckweed pond treatment step, Scenario 4b (biological treatment + duckweed pond (intermediate residence time) + field application) indicated the greatest environmental benefits, and Scenario 3a (biological treatment + duckweed pond (short residence time) + constructed wetland) the highest weighted environmental impacts.

The normalised and weighted results suggested that the impact categories of freshwater ecotoxicity (beneficial impacts), climate change (harmful impacts) and minerals and metals resource use potential (mixed impacts) are of greatest importance in the studied treatment system. Mixed denotes that the environmental impact in this category was negative in some scenarios and positive in others.

It appeared that a longer residence time outcompetes a shorter residence time, as Scenarios 3b and 4b performed better than their respective counterparts in Scenarios 3a and 4a. Introducing a duckweed pond between the NDN treatment and a constructed wetland seemed to be favourable compared with leading the NDN effluent directly into a constructed wetland, as Scenarios 3 and 4 performed better than Scenario 2. Furthermore, it seemed to be more beneficial to apply the duckweed pond effluent to fields than to lead it into constructed wetlands, as Scenario 4 performed better than Scenario 3. Scenario 5 resulted in small environmental benefits due to the high K content of the duckweed pond sludge after a long sedimentation period. However, as the duckweed effluent is led to natural waterbodies, substantial amounts of K are still lost compared with its field application (Scenarios 4a + 4b). Consequently Scenario 5 performed better than Scenarios 3a and 3b, but worse than Scenarios 4a and 4b.

When no credits were given for the avoidance of K fertiliser, climate change and minerals and metals resource use potential were still of great importance, while freshwater ecotoxicity potential no longer appeared to be particularly relevant. Furthermore, the ranking of the treatment chains changed considerably: the differences between results decreased and no treatment path suggested net damage savings. Scenario 5 (NDN + DW (long)) suggested the lowest and Scenario 1 (NDN + F) the greatest environmental impacts (Fig. 2). The differences were mostly caused by variations in minerals and metals resource use and climate change potential. The NDN treatment still contributed greatly to both categories. Regarding climate change, the differences between the scenarios were mostly caused by variations in field application rates and the avoidance of soy production. The greater the nutrient application rates on agricultural fields in the form of sludge and effluent and thus the higher the emissions, the greater the impacts on climate change. Avoiding or reducing field application of nutrients through sludge and effluent by introducing duckweed ponds or constructed wetlands translated into lower climate burdens. Apart from field application, the results were determined by the replacement of soy production. The longer the residence time, the greater the production of duckweed per effluent volume, resulting in greater soy replacement rates, which positively influenced climate change potential.

From an environmental point of view, it is more important to avoid spreading surplus nutrients on fields than it is to produce small amounts of protein feed, grown on the low N effluent coming out of the NDN treatment. Therefore, Scenario 3a (NDN + duckweed pond (DW) (short residence) + constructed wetland (CW)) performed better than Scenario

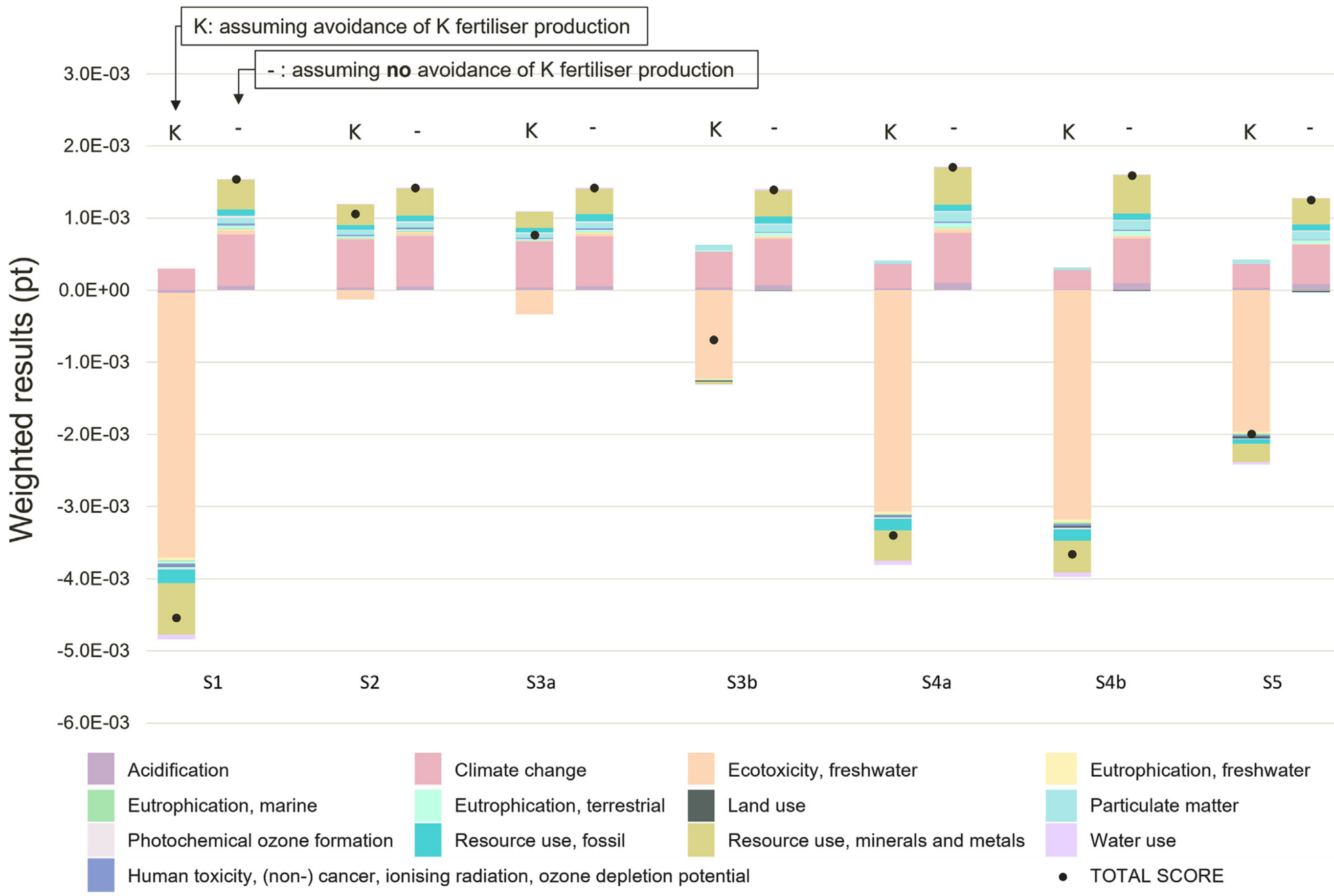


**Fig. 2.** Normalised and weighted environmental impacts per functional unit of treating 1000 kg of liquid fraction pig manure assuming K fertiliser is either substituted (K) or not (−). S1: nitrification-denitrification (NDN) + field application of NDN effluent; S2: NDN + constructed wetland (CW) + discharge to waterbody; S3: NDN + duckweed pond (DW) + CW : S4: NDN + DW + field application of DW effluent; S5: NDN + DW (long residence time) + discharge to waterbody; a: short residence time; b: intermediate residence time.

4b (NDN + DW (intermediate residence) + field application). In Scenario 3a the effluent is led to a constructed wetland instead of being field applied, while the shorter residence time in Scenario 3a compared with Scenario 4b resulted in lower duckweed yields. In Scenario 4b compared with Scenario 2 (NDN + CW + discharge to waterbody), enough nutrients have been extracted and enough duckweed produced to allow for field application instead of an additional constructed wetland treatment.

Despite the ranking, it should be noted that the differences between scenarios were small, and this ranking should therefore be interpreted with caution.

(ii) Impact contributions of life cycle stages, processes and elementary flows

The contributions of individual life cycle stages can be found in Fig. 3. Contributions to climate change potential were mostly caused by emissions resulting from NDN sludge disposal and fugitive emissions resulting from the NDN treatment ($N_2O$ emissions) (Fig. 3a). In the scenarios including K fertiliser avoidance, differences in net climate change impacts between scenarios mostly resulted from varying degrees of effluent and/or sludge land application (larger quantities result in greater savings of mineral fertiliser), which partially offset the harmful effects of NDN treatment. Using duckweed as an alternative protein source in livestock feed mitigated some of the adverse climate effects, but was insufficient to make the treatment climate neutral or even climate positive.

From Fig. 3b it is evident that the observed net benefits in terms of freshwater ecotoxicity potential stemmed from the land application of sludge or effluent from the NDN or duckweed treatment step and the associated avoidance of K mineral fertiliser production. The chosen default ecoinvent process 'market for inorganic potassium fertiliser, as K2O | BE' is associated with large emissions of sulfur into freshwater bodies. Sulfur is by far the single greatest elementary flow contributing to freshwater ecotoxicity in this analysis. Thus, avoiding K fertiliser production and consequently the release of sulfur results in great environmental reliefs. The more mineral K fertiliser is replaced, the greater the environmental benefits. In accordance with their respective K content, effluent land application resulted in greater benefits than sludge land application, and applying effluents from the NDN treatment resulted in greater benefits than from the duckweed pond treatment (as Scenario 1 performed better than Scenarios 4a and 4b under K fertiliser avoidance).

With regards to minerals and metals resource use potential, it was found that great environmental savings could be achieved through the field application of sludge and effluent, provided that the K supplied to the crops results in the avoidance of mineral K fertiliser production (Fig. 3c). Overall, the minerals and metals resource use potential in this study was mostly determined by copper extraction or the avoidance of it. In the ecoinvent database, a decrease in fertiliser production results in a decrease in building construction and consequently decreased extraction of copper. Savings in copper extraction greatly contribute to the favourable impact of reduced K fertiliser production and reliefs in resource use potential. These benefits, however, are reduced because of resource consumption related to infrastructure and operation of the NDN treatment plant, which similarly demands copper. Depending on the amount of K fertiliser avoided and related savings, overall impacts are either net negative (greater K fertiliser avoidance) or net positive (lower K fertiliser avoidance). If it was assumed

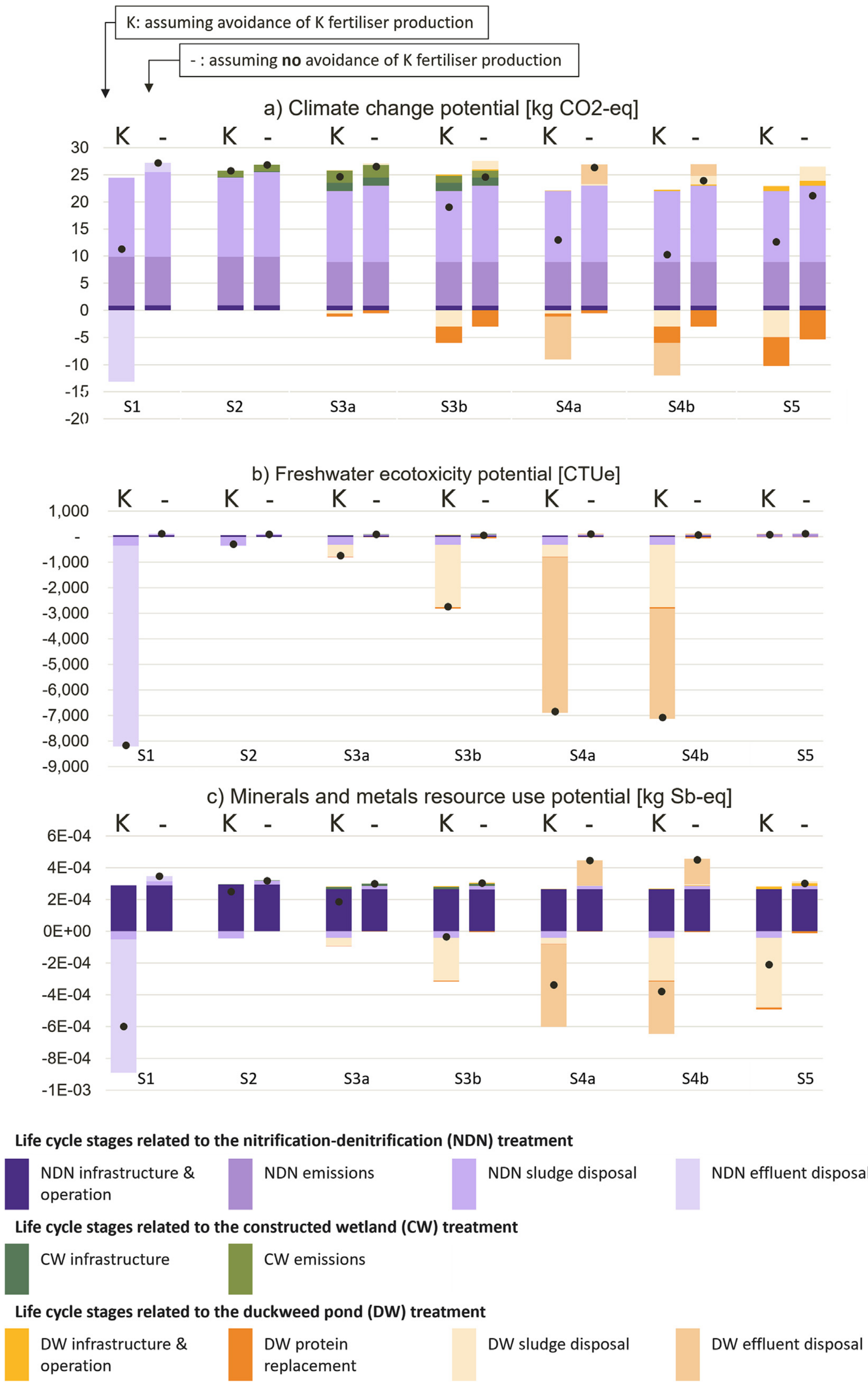


**Fig. 3.** Environmental impacts and contribution analysis of life cycle stages per functional unit of 1000 kg liquid fraction pig manure per studied scenario — on the assumption that K fertiliser is either avoided (K) or not (−). S1: nitrification-denitrification (NDN) + field application of NDN effluent; S2: NDN + constructed wetland (CW) + discharge to water body; S3: NDN + duckweed pond (DW) + CW: S4: NDN + DW + field application of DW effluent; S5: NDN + DW (long residence time) + discharge to waterbody; a: short residence time; b: intermediate residence time.

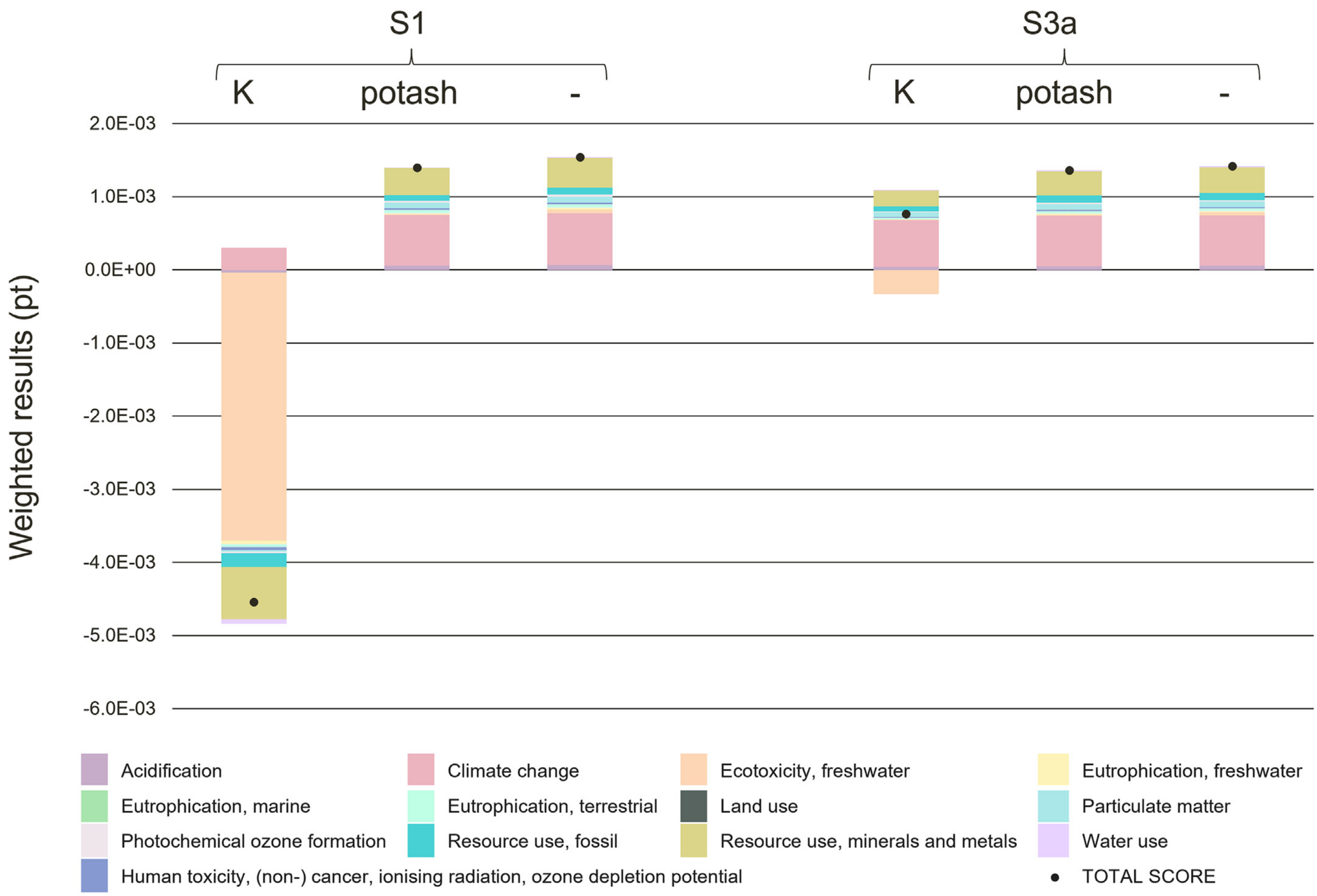


**Fig. 4.** Examples of weighted results for Scenario 1 (nitrification-denitrification and land application of the NDN effluent) as the best performing scenario in the baseline, and Scenario 3a (NDN + DW (short residence time) + CW as the best performing scenario that included a duckweed pond.

that no K fertiliser was avoided, the scenarios performed relatively similarly except for Scenarios 4a and 4b, which performed noticeably worse than all other scenarios. These higher environmental impacts are related to the application of the duckweed pond effluent to agricultural fields via the irrigation infrastructure. In the ecoinvent database, such an infrastructure requires copper, which as stated above greatly contributes to mineral and metals resource use.

The assumption that duckweed would replace other sources of protein feed, in the present case soy, did not seem to lead to noticeable environmental impact reductions. While visible with regards to climate change potential, feed impact-related savings were always overshadowed by other processes mentioned above, such as fertiliser avoidance, direct emissions and building construction.

Given the role of K fertiliser, the robustness of results related to it were examined further.

(iii) Scenario analysis: test of the robustness of results

a) Assessing different ecoinvent processes for K fertiliser

To explore further the response of the case study system to assumptions related to K fertiliser, two alternative ecoinvent processes for K fertiliser to the K fertiliser used in the first model (ecoinvent: market for inorganic potassium fertiliser, as $K_2O$ | BE) were examined; 1: the global market for organo-mineral K (ecoinvent processes: market for organo-mineral potassium fertiliser, as $K_2O$ | GLO) and 2: potash fertiliser (ecoinvent process: market for potash salt | RER). Detailed information about these two alternatives can be found in the SI.

The organo-mineral fertiliser showed higher contributions to freshwater ecotoxicity than the mineral K fertiliser on the Belgian market (Fig. S4, SI). Potash resulted in lower contributions to freshwater ecotoxicity, but in other categories its impacts exceeded those of both mineral and organo-mineral fertiliser (e.g. marine eutrophication, ionising radiation). However, when looking at the weighted results, the potash in the ecoinvent database was less environmentally harmful than mineral and organo-mineral K fertiliser (Fig. S5, SI). Consequently, the potential environmental savings from replacing it were smaller and, assuming either no K fertiliser replacement or potash fertiliser replacement, led to the same relative results (Fig. 4). The ranking of scenarios did not change, and Scenario 5 with a duckweed pond and long residence time appeared to have the lowest environmental damage potential. Fig. 4 provides an example of the effect of selecting potash instead of K fertiliser for the scenario with the greatest environmental benefits as a result of replacing K fertiliser (Scenario 1) and the scenario with highest environmental burden among the duckweed treatment scenarios (Scenario 3a). Obviously, the greater the influence of K fertiliser avoidance, the greater the change in overall impacts when changing assumptions regarding K fertiliser. Consequently, the presented results not only depended on the assumption of whether K fertiliser was avoided, but also of which type of K fertiliser would be substituted and how such a substitution was modelled.

## 4. Discussion

Constructed wetlands were initially designed as a nature-based solution for polishing municipal wastewater, and most previous LCA studies involving constructed wetlands have focused on such constellations (for example

Corbella et al. (2017), Fuchs et al. (2011) and Resende et al. (2019)). Constructed wetlands have only recently been tested in combination with animal manure treatment systems. To the authors' knowledge, only one LCA study has assessed constructed wetlands as part of an animal manure treatment system (Bayo et al., 2012). As in the current study, their study concerned a region of intense pig production (Murcia in Spain) and concluded that direct field application was environmentally more favourable than a constructed wetland treatment. They did not include an NDN treatment step, but instead assumed that the liquid fraction entered the wetland without prior treatment. Despite many similarities, it should be noted that in their study, despite stated over-fertilisation, credits were given not only for K, but for N and P as well. Furthermore, they assumed fertiliser credits after the constructed wetland treatment, while the present study assumed the effluent to be clean enough to be discharged into natural waterbodies. In terms of climate change potential, the two studies came to opposing conclusions: their study suggests that constructed wetland treatments perform better than direct application, while in the present study the constructed wetland resulted in greater impacts than direct field application. This discrepancy might be due to the present study not including fertiliser credits after the constructed wetland treatment and the avoided field emissions from the untreated liquid fraction being greater than those from the NDN effluent. Another important difference is that they did not include freshwater ecotoxicity in their study.

As with constructed wetlands, the environmental implications of duckweed production and its utilisation have only been assessed in a few studies, and only one LCA study on municipal wastewater-derived duckweed was found. The LCA compared a conventional bioethanol refinery process with a duckweed-based biorefinery (Calicioglu et al., 2021). In the duckweed scenario, credits were given for the avoidance of conventional wastewater treatment, and the duckweed was used to produce biomethane, bioethanol and fertiliser. Given the different goals and scopes of their study and the present study, a direct comparison is not feasible. However, they found that the duckweed biorefinery was more environmentally harmful than the conventional refinery process, and the present study also found that duckweed-related benefits were not sufficient to compensate for additional environmental burdens created by the implementation of the duckweed production and processing system.

Another study compared the environmental impacts of NDN treatment of pig manure plus solid fraction composting with direct land application of untreated manure under Flemish conditions (Corbala-Robles et al., 2018). They concluded that the NDN treatment performed better than no treatment, mostly due to the avoidance of emissions during storage and field application. Given that manure separation does not alleviate nutrient pressure on Flemish ecosystems sufficiently, this comparison was excluded. As mentioned above, NDN treatments are not always sufficient, and additional polishing might be needed locally. However, including an NDN-only scenario revealed the importance of environmental impacts related to K fertiliser production.

Choosing potash instead of further beneficiated K fertiliser completely changed the results and highlighted the sensitivities of modelling choices, especially those of ecoinvent processes. Potash is less processed than K fertiliser, and thus less toxic in its production. However, due to less beneficiation, potash is less pure than K fertiliser and might contain harmful impurities, which would only become apparent when including land application and related leaching. However, land application of the different forms of K fertiliser was not included in the system boundaries of this study, and differences were not reflected in the present LCA. Such a comparison might provide clarity with regard to the trade-offs between environmental impacts during production and impacts related to impurity and leaching in the field. It appears that no LCA study on K mining, fertiliser production or field application has to date been conducted. Information was only found on company websites and in the descriptions of the ecoinvent processes.

It is apparent that assumptions related to the replacement of K fertiliser are critical. In the present study, it was assumed that either 0 % or 100 % of K contained in the effluent and sludge would replace mineral fertiliser. If replacement occurs, replacement rates are likely to be somewhere between these two extremes. Furthermore, the present study found that freshwater ecotoxicity was the impact category of greatest concern in relation to K fertiliser replacement. However, weighting factors for freshwater ecotoxity impacts are noted to be rather uncertain (Annex 3–4 of the Product Environmental Footprint guidelines), especially when it comes to inorganic compounds (Sala et al., 2022). This means that the apparently high importance of the freshwater ecotoxicity impacts is also very uncertain. If freshwater ecotoxicity were given less weight, then the significance of avoided mineral K fertiliser would decrease and the environmental impacts of the scenarios would be more similar. This dependency hints at a reliance on the LCA methodology applied and a need for further improving characterisation and weighting factors. Despite these uncertainties, when designing systems for handling the effluent from NDN systems, it is important to consider ways that ensure recycling of K contained in the effluent.

Even though duckweed production and constructed wetlands were assumed to prevent K recycling, they may still be useful for preventing local nutrient overloads. However, it might be advisable to ensure K recycling in the duckweed ponds and/or constructed wetlands. In the present system, duckweed growth is limited by the availability of N and P, while K is available in abundance. If more of the K were to be absorbed, higher concentrations of N and P would be needed. It could thus be considered that duckweed ponds should not be used as polishing step, but introduced earlier in the management chain instead, i.e. following manure separation. Avoiding the nitrification-denitrification step has potential for greenhouse gas emission savings, and a much higher production of duckweed, but would also require much larger ponds and pond areas. Future (LCA) studies could evaluate the environmental implications of utilising duckweed ponds as an alternative to NDN treatments. Another option could be to reintroduce the duckweed effluent into livestock housing systems as scrubber water, which is used to remove ammonia from the stable air.

In the past, K fertiliser and its use efficiency have been discussed less than those of nitrogen and phosphorous. One reason could be that K causes little environmental damage when emitted to the aquatic environment (unlike N and P), its production is not associated with great energy consumption, and it is not a seriously limited resource. Potassium is not currently labelled a critical raw material by the European Union (unlike P). With the Russian Federation's invasion of Ukraine, however this view has started to change, since the European Union is highly dependent on Russia and Belarus, which together provide around 50 % of the EU's potash imports (Georgitzikis and D'Elia, 2022; OECD, 2022). In Flanders, nutrient balance studies for the agricultural sector are currently limited to N and P, however as shortages due to the political situation are confronted with increasing demands for mineral K fertiliser (Departement Landbouw en Visserij, 2022), future studies might include K mass flows. It could be worthwhile including K fertiliser implications, especially those related to ecotoxicity, in future (LCA) studies whenever K recycling is affected by manure treatment systems.

As K recovery appears to be essential for the sustainability of this solution, research on K recovery from secondary sources seems important and could be examined further in future studies.

Another critical assumption made in this study was to base the soybean meal replacement by duckweed on their protein content. It is known that protein content alone is insufficient for predicting growth performances of livestock, and parameters such as amino acid profile, fibre content, anti-nutritional factors and N or protein digestibility also play important roles and should not be disregarded when changing feed formulations. For instance, the nitrogen digestibility and lysin content of duckweed are lower than those of soybean meal (https://www.feedipedia.org/). Since soy feed appeared to perform better than duckweed feed, this would not change the relative results in this study. However, the zinc and fibre content in duckweed is higher than in soybean meal, which could be beneficial in view of the EU's ban on zinc oxide as a feed additive from 2022 (EU, 2017). Zinc oxide prevents diarrhoea in weaned pigs, but poses risks when released to the environment as a component of field-applied manure and due to zinc's contribution to the occurrence of antibiotic-resistant genes (Bonetti et al., 2021). In terms of diarrhoea prevention, no alternative to zinc oxide has as yet been established (Bonetti et al., 2021; Satessa et al.,

2020) and the inclusion of substitution effects in the present model was not feasible. Among possible solutions are the inclusion of high-fibre ingredients and natural sources of zinc into the pigs' diet, both found in duckweed (Devlamynck et al., 2021a; Li et al., 2020). Studies on feeding strategies for piglets could investigate the effects of duckweed-supplemented feed beyond its replacement of protein, and such effects could then be implemented in future LCA studies. Potassium is not a concern or limiting factor in pig feed (Cromwell, 2022). Thus, accounting for the replacement of dietary potassium would not reflect realistic practices and was therefore omitted.

The current paper considers ways of treating manure in areas of high animal densities. Perhaps it is worth remembering that these problems are mainly created by animal densities being too high for simple land application of animal manure. From the farm-centred perspective taken in this paper, treating and redistributing the manure might be a logical solution to the problem of over-fertilisation, thus the question is how to do this in the least damaging manner. From a wider, cross-country perspective, redistributing livestock production and equalising densities should be a consideration.

## 5. Conclusions

The present LCA indicated that additional treatment steps for NDN effluent, such as duckweed ponds and constructed wetlands, could be problematic as they prevent potassium recycling. The fact that duckweed was assumed to replace soy had a small influence on the overall results.

Preventing potassium fertiliser recycling has large ecotoxicity impacts due to the mining and beneficiation of mineral K fertilisers that have to take place. However, if no replacement of potassium fertiliser takes place in response to the land application of the effluent, duckweed ponds as a polishing step would result in smaller environmental impacts than direct land application or additional treatment through constructed wetlands without duckweed. Nevertheless, this does not change the fact that both systems serve as potassium sinks and prevent its further agricultural application. This study highlights clearly the importance of considering potassium. Due to the potentially large impacts of the production of potassium fertilisers, it is suggested that potassium be considered on a par with P and N in studies of nutrient recycling technologies.

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## CRediT authorship contribution statement

**Miriam Beyers:** Conceptualization, Methodology, Visualization, Writing – original draft. **Rahul Ravi:** Conceptualization, Methodology, Writing – review & editing. **Reindert Devlamynck:** Data curation, Writing – review & editing. **Erik Meers:** Conceptualization, Funding acquisition, Writing – review & editing. **Lars Stoumann Jensen:** Conceptualization, Funding acquisition, Writing – review & editing. **Sander Bruun:** Conceptualization, Methodology, Funding acquisition, Writing – review & editing.

## Data availability

Data will be made available on request.

## 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

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