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Life cycle assessment of nutrient recovery from wastewater – current methodological practices

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Abstract: Life cycle assessment (LCA) is an established methodology to assess the potential environmental impacts of products and processes. We reviewed 49 recent LCA studies (2010-2019) on wastewater nutrient recovery to synthesise some current methodological practices. Their scopes, variations, nutrient recovery accounting, uncertainty and sensitivity management, and future opportunities are discussed. There are many opportunities to improve the current practice such as assessing a broader scope of environmental impacts, improving model and inventory transparency, communicating uncertainties and understanding model sensitivities. While this study focuses on nutrient recovery from wastewater, a lot of the insights are also relevant to other water-related LCA.

Keywords: Life cycle assessment; nutrient recovery; wastewater; environmental impacts; review

Introduction

Many technologies exist for recovering nutrients such as phosphorus and nitrogen from wastewater. The challenge of transitioning to resource-efficient urban water systems is often not the availability of technology for resource recovery, but the lack of planning and design methodology to identify and deploy the most sustainable solution in a given context (Guest et al., 2009). Life cycle assessment (LCA) provides a methodology to quantify potential environmental impacts (benefits or burdens) from implementing nutrient recovery strategies and in some cases, provide insights of potential trade-offs between different environmental impacts (Hellweg and Canals, 2014) and/or economic performance (when evaluating with cost assessment).

This study reviewed 49 recent LCA studies (2010-2019) on nutrient recovery from wastewater (Figure 1). The objective is to provide an updated overview of the current methodological practices from these LCA studies across different countries and scales. This can contribute to global perspectives for planning and implementation of next-generation resource recovery, wastewater treatment and sanitation infrastructure. This review complements with some recent reviews on the methodological aspects of LCA for nutrient recovery – struvite precipitation (Sena and Hicks, 2018), life cycle inventory practices for major nutrient flows in wastewater and sludge management systems (Heimersson et al., 2016).

Material and Methods

This study targeted process-based LCA studies on nutrient recovery from wastewater published in peer-reviewed academic journals between 2010 and 2019. A literature search was conducted to find these studies using Scopus. In the first stage, different combinations of keywords such as resource recovery, nutrient recovery, LCA and water were used to identify applicable studies. In the second stage, the reference lists of these applicable studies and the citations on these studies were checked to identify more applicable studies. This process was repeated on the newly found applicable studies.

After the literature search, a systematic review was conducted on the selected studies. The review was structured according to four aspects – goal and scope definition, inventory analysis, impact assessment, and interpretation (Table 1).

Results and Discussion

Most of the selected LCA studies are either i) comparing a system with nutrient recovery approach(es) (in some cases, also integrated with other resource recovery approaches) to a reference system without recovery, or ii) comparing multiple recovery alternatives for a given system. These studies cover nutrient recovery opportunities from their early stage of development to more full-scale applications. Assessing a technology at its early development stage with LCA can provide an opportunity to identify environmental impacts that can be potential barriers for its full-scale implementation (Fang et al., 2016) and to gain insight on technical factors that require further research and development (Kavvada et al., 2017).

Most studies evaluated i) sewage sludge management strategies for nutrient recovery, ii) recovery through struvite precipitation, iii) urine source separation integrated with nutrient recovery, or iv) alternative wastewater treatment methods to enhance nutrient recovery (Figure 2). A range of environmental impact categories were assessed, with the most-evaluated categories being global warming potential (44), eutrophication potential (36), acidification potential (33), ecotoxicity (27), human toxicity (26) and photochemical ozone formation (24).

How to account for the environmental benefits from the recovered nitrogen and phosphorus differs considerably among these studies (e.g., type of synthetic fertiliser being substituted, bioavailability of recovered material). In some cases, the underlying assumptions for fertiliser offset are neither documented nor well-justified. This can be a major source of uncertainty if the contribution from fertiliser offset is significant relative to the overall environmental impact of the assessed system.

Assessing only a few of the environmental impact categories and/or with a limited system boundary may be insufficient to make informed decisions for implementing nutrient recovery strategies. The “best” option based on a limited set of environmental impact categories may not necessarily be the “best” option for the overall environmental impacts. For instance, some studies only looked at the carbon footprint of nutrient recovery without acknowledging the potential negative impacts from for example, ecotoxicity, human toxicity or emissions from storage.

Like any model-based analysis, uncertainty presents in LCA. Increasingly, studies used Monte Carlo simulation to examine uncertainty propagation. Sensitivity analysis is commonly conducted to identify key influencing parameters on LCA results. This is particularly important where the technology evaluated is still in its early stage of development. In this regard, sensitivity analysis can highlight areas for further research to address these uncertainties. For the research area of nutrient recovery LCA, the practice of uncertainty analysis remains limited.

In general, nutrient recovery can reduce the overall life-cycle environmental footprints of wastewater treatment systems. One prominent benefit is the reduction of greenhouse gas emissions mostly from substituting synthetic fertiliser, despite potential burdens of ecotoxicity and human toxicity. Minimising chemical inputs in nutrient recovery processes is an important factor to enhance the environmental performance of recovery processes. Urine source separation is consistently shown to improve the environmental performance of nutrient recovery strategies.

Conclusions

As LCA is becoming a popular approach to provide environmental information for decision making in water sector, it is important to understand the current status in terms of the application trend, variations, good practices and shortcomings. There are many opportunities to improve the current practice such as assessing a broader scope of environmental impacts, improving model and inventory transparency, standardising fertiliser offset accounting, communicating uncertainties and understanding model sensitivities. There are also future opportunities to apply LCA to assess emerging nutrient recovery technologies and integrated resource recovery systems, and to use LCA from a product perspective instead of a process perspective to assess recovered nutrient products. While this study focuses on nutrient recovery from wastewater, a lot of the insights are also relevant to other water-related LCA.

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Figures and Tables

Table 1 Overview of methodological aspects reviewed.

Category	About
Goal and scope definition	Country
	System size
	Number of options compared
	Functional unit
	Type of recovered nutrient products
Inventory analysis	Fertiliser offset accounting
	Heavy metals, organic pollutants and pathogens accounting
Impact assessment	Number and type of impact categories assessed
Interpretation	Uncertainty analysis
	Sensitivity analysis

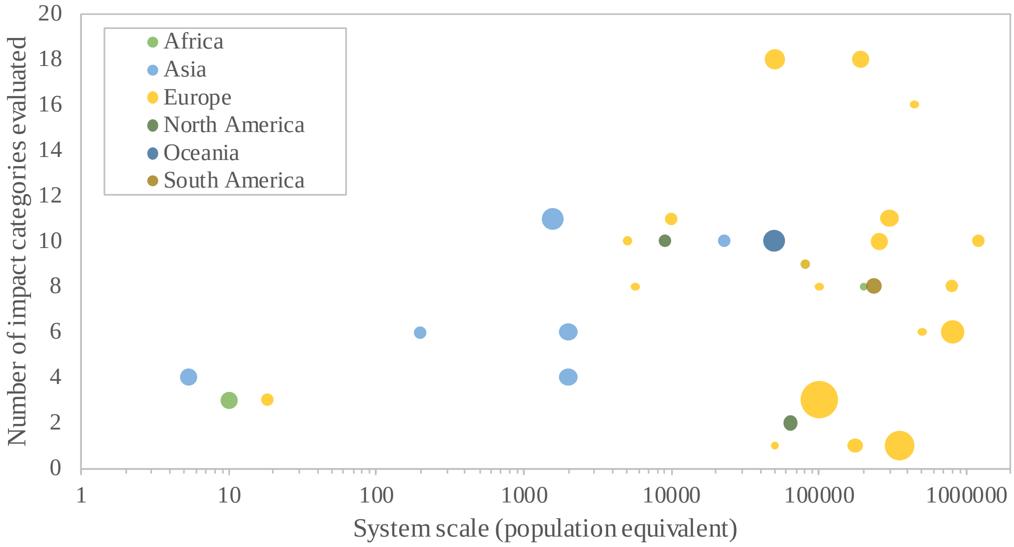

Figure 1 Scope of 32 nutrient recovery LCA studies reviewed in terms of i) system scale, ii) number of impact categories evaluated, iii) number of nutrient recovery strategies compared in each study, and iv) studied regions. Each circle is a study, and its size corresponds to the number of strategies compared in that study (from 1 to 18 resource recovery strategies). The other 17 studies are not shown in this figure because system sizes were not specified. For a few studies that only specify volumetric system scales, 200 litres wastewater treated per person per day was assumed to estimate the population equivalent values.

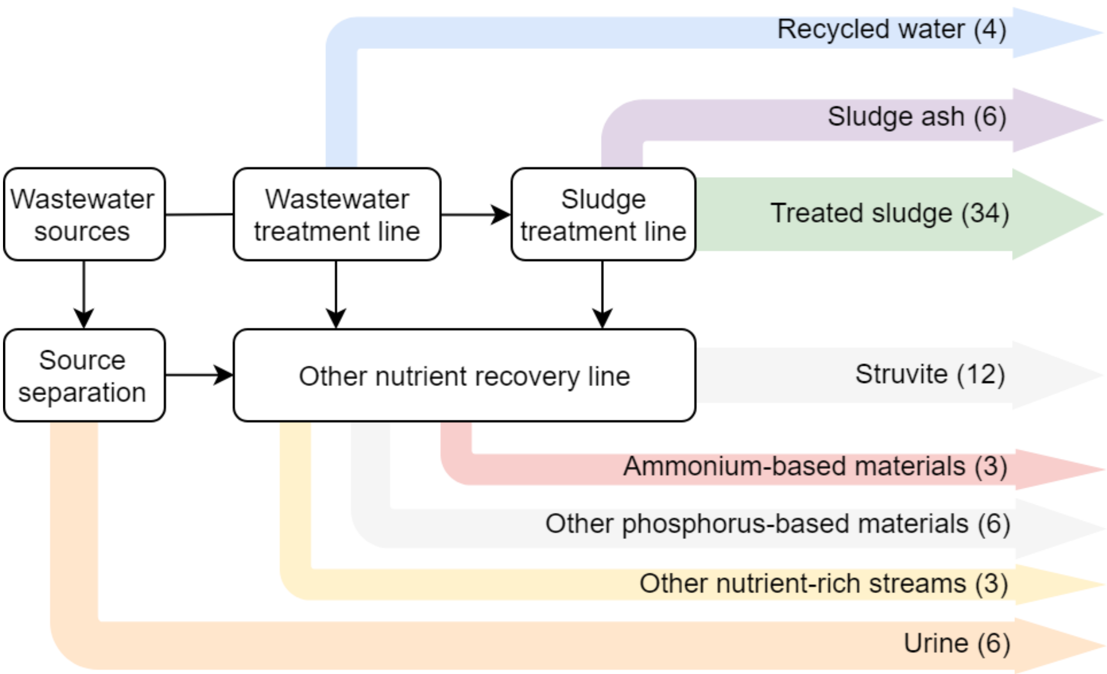

Figure 2 Categories of recovered nutrient products for agricultural land applications evaluated by LCA studies reviewed. For each category, the number of studies is shown in brackets. The total number is more than the total number of studies reviewed because some studies evaluated multiple categories in a single study.