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Life Cycle Assessment of a Retrofit Wastewater Nutrient Recovery System in Metro Manila

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The increase in water pollution from nutrients like phosphorus and nitrogen has prompted the Philippine government to issue stringent regulatory standards for wastewater effluent quality. Hence, two alternatives are being proposed to be integrated in the current wastewater treatment plant in the Philippines: biological nutrient removal and nutrient recovery systems. Biological nutrient removal technologies (BNRT) utilize microorganisms to minimize the nutrient content in the effluent streams to the standard limit while leaving high nutrient concentrations to the sludge that is typically transported as waste to landfill. The nutrient recovery system aims to recover phosphorus and nitrogen in the form of struvite ($NH_4MgPO4{\cdot}6H_2O$) fertiliser from sludge through chemical precipitation. The two proposed systems have been studied in other settings but their effectiveness has not been studied in the Metro Manila setting. There is a need to systematically assess the environmental effects brought about by the proposed systems in Metro Manila, whether beneficial or adverse, in the context of agriculture, food and energy consumption, and wastewater. A holistic evaluation of the environmental benefits and burdens was done using Life Cycle Assessment (LCA) framework considering a cradle-to-grave approach of three scenarios: 1) current wastewater treatment system scenario; 2) biological nutrient recovery technology; and 3) nutrient recovery system. The environmental impact assessment was done using IMPACT2002+ methodology with the following impact indicators: human health, ecosystem quality, climate change and resources. The life cycle assessment of the scenarios shows the potential of the proposed retrofit wastewater systems for Metro Manila that extends to a more sustainable approach in dealing with issues such as water pollution, climate change, resource depletion and even food security. Moreover, a baseline understanding of the food-water-energy-nutrient nexus in the Philippines was established which can be the basis for future life cycle sustainability assessment studies.

1. Introduction

Fertilisers contain nutrients such as phosphorus and nitrogen that are needed in order to improve the growth of agricultural and aquatic plants. However, increased availability of nutrients in the water bodies leads to eutrophication (Chislock et al., 2013). The adverse impact caused by eutrophication has recently prompted the Philippine government to strictly control nutrient loads in the effluent streams of all wastewater treatment plants (WTP) throughout the country. Among the changes is the addition of parameters to be monitored and controlled including ammonia-N (NH_3-N), nitrate-N (NO_3-N) and phosphates. The current scenario of WTPs in the Philippines does not involve any nutrient removal technologies yet. Thus, industries are evaluating the integration of biological nutrient removal technologies (BNRT) in the current scenario. A BNRT in WTPs is typically composed of microorganisms, grouped into anaerobic, anoxic, and aerobic zones, which reduce the nitrogen and phosphorus content before discharge as effluent (The Cadmus Group, 2009). Efforts are also being done to utilize wastewater as a resource via recovery of phosphorus from the wastewater sludge as struvite fertiliser (Ashley et al., 2011). Phosphorus can be recovered from untreated wastewater inflow, sewage sludge, effluent side stream from sludge dewatering, and ash from sludge incineration (Linderholm et al., 2012). However, the operation could introduce additional use of energy, produce emissions, and generate

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waste, among others (Blanco et al., 2016). More efficient phosphorus removal could also increase infrastructure resources and chemical consumption while operational energy and direct GHG emissions were not affected (Foley et al., 2010). A life cycle study on phosphorus recovery showed that using sludge leaching with an acid could recover 50 % of P from wastewater sludge; however, the process utilizes more chemicals in order to remove the heavy metals (Remy et al., 2016). An enhanced biological phosphorus removal and recovery (EBP2R) system with downstream photobioreactor (PBR) was found to reduce the impact by 15 % for global warming and 9 % for marine eutrophication compared to the conventional wastewater treatment system (Fang et al., 2016). Therefore, there is a need to objectively evaluate the potential of a nutrient recovery system to retrofit the current wastewater treatment systems in the Philippines.

Life Cycle Assessment (LCA) is a quantitative approach for addressing the environmental impacts and potential environmental impacts of a certain product or system throughout its life cycle. LCA would cover a cradle-to-grave approach that is from raw material acquisition, production, utilization, end-of-life, waste treatment, recycling and disposal (International Organization for Standardization, 2006). Assessments of the food systems will also estimate the indirect effects of climate change and increasing world population to food security (Soussana, 2014). Consumption and lifestyle patterns have significant effects on the environmental assessments constituting agriculture sectors and WTPs. An LCA study on food consumption in Europe was evaluated showed that meat and dairy products have the highest environmental burdens in most of the impact categories (Notarnicola et al., 2017). A study by Cordell et al. (2011) focused on the life cycle costing of phosphorus recovery considering different cases in different countries. It should be noted that different countries, having different contexts such as economic growth, adapt different nutrient recovery systems. Hence, there is a need to investigate the most appropriate system on a localized basis that can be identified systematically (Cordell et al., 2011).

This study will focus on the life cycle assessment of a wastewater nutrient recovery system in Metro Manila, Philippines in the context of agriculture, food consumption and wastewater to initially establish the concept of food-water-energy-nutrient nexus. Three scenarios were considered: 1) current wastewater treatment system scenario; 2) retrofit to biological nutrient recovery technology; and 3) retrofit nutrient recovery system. To our knowledge, this is the first life-cycle assessment of the food supply in any location in the Philippines. We are also not aware of any life-cycle assessment for wastewater treatment systems in the Philippines. By comparing wastewater treatment alternatives and demonstrating that environmental compliance with some parameters may result in trade-offs in others, we provide guidance to decision makers in the selection of waste treatment systems.

2. Life Cycle Assessment Methodology

Life Cycle Assessment is used to evaluate the potential to retrofit the conventional wastewater treatment systems in the Philippines in order to comply with the new regulations and to address environmental concerns. Through a consequential approach, the challenges in achieving accuracy in LCA results will be minimized. System or product improvements will be compared in terms of consequences brought about by the changes in the business as usual or baseline scenario (Weidema et al., 2018).

The first stage involves construction of a system composed of different unit processes which represent quantitative flows. The system boundaries of the LCA model for each of the scenarios are shown in Figure 1. In order to represent the Food-Energy-Water-Nutrient nexus, the following process or activity blocks are included in the system boundaries: 1) Fertiliser; 2) Agriculture; 3) Food Consumption and; 4) Wastewater Treatment.

The geographical boundary in this study includes one identified sewage treatment plant (STP) located in Metro Manila where it serves a population of 80,000 people. The functional unit used was 12,779 x10^3 kg of food consumed by the population served by the STP (Philippine Statistics Authority, 2017).

The second stage is the inventory analysis which considers the inputs and outputs for every unit process. The inventory analysis was processed through the LCA software SimaPro 8.3. Allocations for processes with multiple products were based on the total mass of each stream.

The impact assessment phase covers the identification of impact categories such as global warming potential and acidification that is linked with the environmental flow. The impacts were characterized using IMPACT 2002+. The impact categories evaluated are 1) human health (carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion and respiratory organics); 2) ecosystem quality (aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutrification and land occupation, aquatic acidification, aquatic eutrophication; 3) global warming and; 4) resources (non-renewable energy and mineral extraction) (Jolliet et al., 2003).

3. Life Cycle Inventory

The first approach for the inventory analysis was to establish a “food basket” that contains the information on the representative food commodity which is assumed to be consumed by each person. The food basket is scaled-up to constitute the total consumption of the population served by the STP (Notarnicola et al., 2017). The food basket considered includes rice, corn, fruits (banana, pineapple and papaya), vegetables (tomato, cabbage, carrot, onion and eggplant), root crops (cassava and potato), pork, beef, and chicken. The calculated average food consumption of food basket for 80,000 people is 12,779.52 x10^3 kg·y^{-1} (Philippine Statistics Authority, 2017).

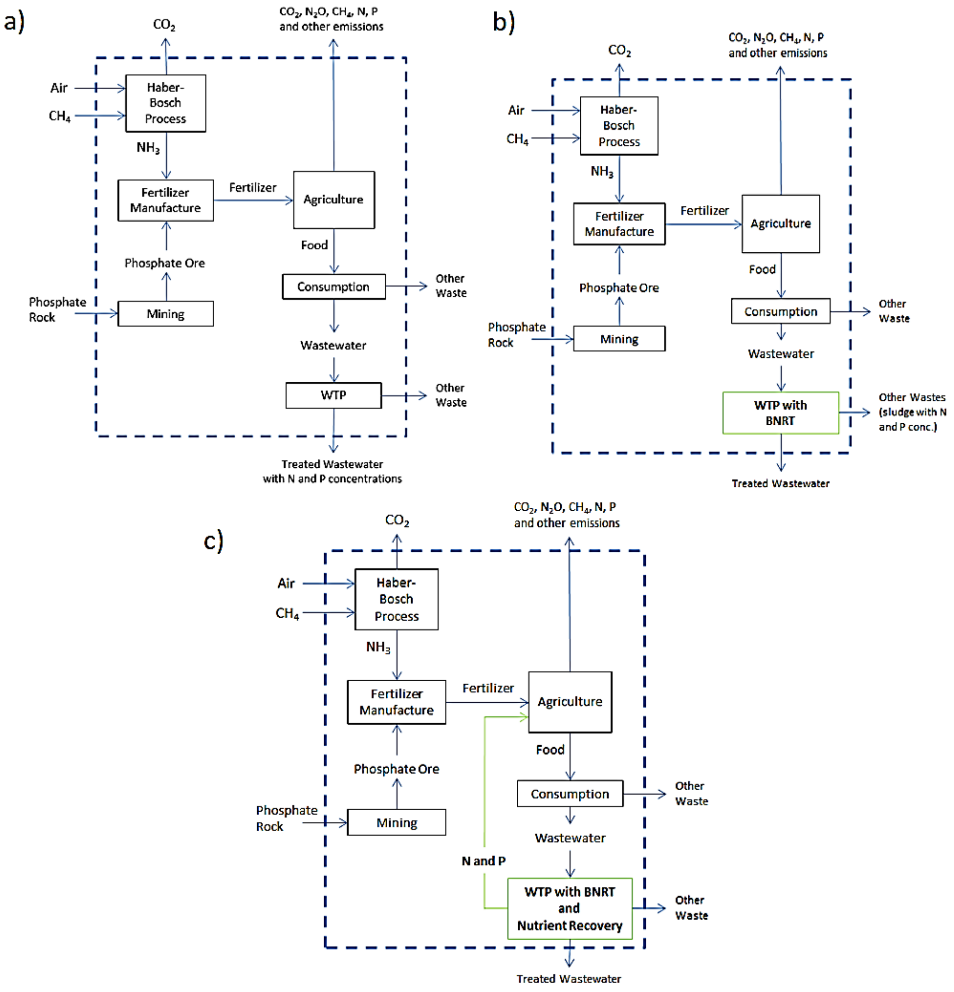

Figure 1: LCA Boundary system for a) first scenario (status quo), b) second scenario (with BNRT), and c) third scenario (with BNRT and nutrient recovery system)

The agricultural inputs to produce the food products in the food basket were then identified. The primary references for the inventory activities for fertilisers, agriculture and food processing are Ecoinvent (Wernet et al., 2016) and Agri-footprint (Durlinger et al., 2017). Scenarios 1 and 2 have the same inventory for fertiliser, agriculture, and consumption process blocks. Changes in commercial fertiliser demand due to the addition of struvite fertiliser in the agriculture block were adapted in Scenario 3. The energy, chemical., sludge waste data for all wastewater treatment scenarios were taken from Chai et al. (2015) and Linderholm et al. (2012).

Generally, food production activities use a large amount of electricity and thus contribute to adverse environmental impacts especially to global warming potential (De Marco et al., 2016). Since electricity is one of the main drivers of impact assessment results (Tatiana et al., 2016), appropriate local electricity mix must be used for the inventory to satisfy the geographical boundary. Hence, the Philippine electricity mix used is mainly composed of 37 % coal., 20 % natural gas, 14 % hydroelectric power, 14 % geothermal and 5 % oil (Durlinger et al., 2017).

The main process for wastewater scenario is the conventional activated sludge process wherein wastewater pollutants such as biological oxygen demand, chemical oxygen demand, total dissolved solids and heavy metals, among others are removed or minimized.

The second scenario, as shown in Figure 1b, is the integration of a BNRT into the WTP. The resulting wastewater effluent will have a discharge quality that is compliant with regulations at the minimum.

The third scenario as shown in Figure 1c covers the retrofit of Scenario 1 to a nutrient recovery system. The nutrient will be recovered from the wastewater through chemical precipitation that would result to struvite formation. Struvite ($NH_4MgPO_4{\cdot}6H_2O$) is formed during supersaturation when the equimolar ratio of magnesium, ammonium and orthophosphate ions in the wastewater streams is exceeded under controlled pH (Jaffer et al., 2002). In STPs, magnesium chloride hexahydrate is added to initiate struvite precipitation while sodium hydroxide to control the pH (Linderholm et al., 2012). Struvite is then be recovered from the nutrient recovery system and be utilized as an additional major input to agriculture aside from fertiliser creating a closed loop for the phosphorus life cycle in this context. Fertilisers from sewage sludge will have an estimated nitrogen-phosphorus content of 50/70 (N/P) available for plant uptake (Remy and Jekel, 2008). For consequential modelling, for every nitrogen and phosphorus equivalent produced in the form of struvite, the same amount of average nitrogen and phosphorus in inorganic fertilisers were considered as an avoided product. This means that the burdens brought about by the production of the avoided products will be subtracted from the impacts of producing struvite fertiliser (Weidema et al., 2018).

Space limitations do not allow presenting all of the input tables. To view the tables, copy and paste the following link https://drive.google.com/open?id=18AsSk7ie5ftWGDs4fDUVTvdbp4NhNi2v onto the address bar.

4. Life Cycle Impact Assessment Results

Table 1. Life cycle impact characterisation and normalization of selected environmental impacts. Highest impact is represented as 100 %.

Damage Category	Impact category	Unit	Scenario 1		Scenario 2		Scenario 3	
Ecosystem Quality	Aquatic ecotoxicity	kg TEG $_{water}$	$7.26x10^9$	99 %	$7.33x10^9$	100 %	$7.24x10^9$	99 %
	Terrestrial ecotoxicity	kg TEG $_{soil}$	$9.71x10^8$	100 %	$9.72x10^8$	100 %	$9.54x10^8$	98 %
	Terrestrial acidification/nutrification	kg $SO_{2\ eq}$	$5.91x10^6$	100 %	$5.93x10^6$	100 %	$5.90x10^6$	100 %
	Land occupation	m^2org.arable	$6.95x10^7$	100 %	$6.95x10^7$	100 %	$6.94x10^7$	100 %
	Aquatic acidification	kg $SO_{2\ eq}$	$1.65x10^6$	100 %	$1.60x10^6$	97 %	$1.59x10^6$	97 %
	Aquatic eutrophication	kg PO_4 P-lim	$3.63x10^4$	100 %	$3.19x10^4$	88 %	$3.13x10^4$	86 %
Global warming	Global warming	kg $CO_{2\ eq}$	$8.96x10^7$	94 %	$9.55x10^7$	100 %	$9.48x10^7$	99 %
Resources	Non-renewable energy	MJ primary	$1.15x10^9$	99 %	$1.16x10^9$	100%	$1.16x10^9$	99%
	Mineral extraction	MJ surplus	1.12x106	100 %	1.12x106	100 %	1.07x106	96 %

Table 1 shows the impact assessment midpoint category results of selected environmental impacts and the percent change with respect to highest impact characterisation magnitude which is also presented in Figure 2. Table 1 only contains selected categories. Others, like human health, were not included because of space limitations and they reflected only small changes. Since scenarios 2 and 3 follow the new wastewater effluent quality guidelines, a decrease in aquatic eutrophication is expected. Results show that Scenario 2 results in a significant decrease of about 12 %. This amounts to an annual reduction of 4,414 kg PO_4 P-lim from Scenario 1 for a relatively small treatment plant that serves only 80,000 people. If applied to a city of 12 million, the avoided pollution would be proportionately larger. Similarly, for Scenario 3, a substantial decrease of 14 % amounts to an annual reduction of 4,986 kg PO_4 P-lim. It must also be noted that Scenarios 2 and 3 comply with regulations, whereas Scenario 1 does not. For aquatic acidification, around 3.5 % decrease for both scenarios 2 and 3 is observed compared to the baseline scenario. Though this seems small, a 3.5 % decrease in aquatic acidification amounts to a decrease, in absolute terms, of 56,700 kg of SO_{2eq} in annual emissions for one STP. The amount of emission decrease is expected to be more substantial if we consider all of the STPs in Metro Manila. Thus, a seemingly small percentage decrease or increase in emissions should not be neglected. Furthermore, the 5 - 6 % increase in global warming potential for Scenarios 2 and 3 is expected due to the increase of energy and chemical consumption in both wastewater treatment scenarios. For the resources, a significant change on the mineral extraction for Scenario 3 is observed. Production of phosphorus-based fertilisers requires mining of phosphate rock. Since these inorganic fertilisers are avoided and replaced by struvite, the mineral extraction impact for Scenario 3 is lessened by 4 %. Generally, we see that while some environmental impacts are lessened, there is a trade-off in others.

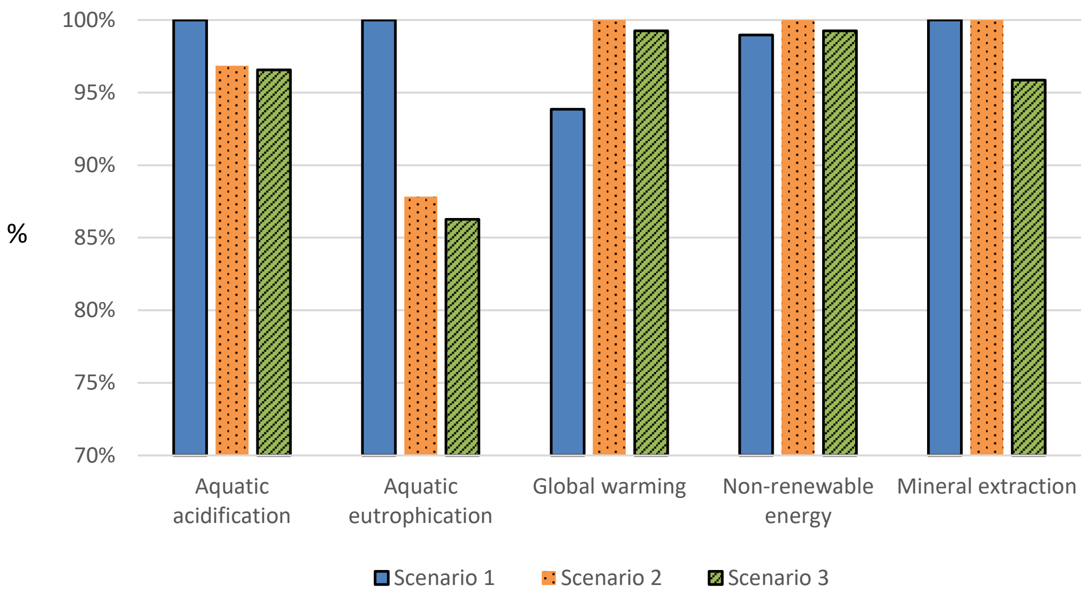

Figure 2: Comparison of notable changes in environmental impacts. Impacts are normalized such that the highest environmental impact is represented as 100 %

5. Conclusion

Considering the life cycle perspective, results generally show the potential to retrofit the current wastewater treatment scenario into nutrient recovery systems in terms of environmental performance in Metro Manila. Integrating nutrient recovery system to the current scenario could have a decrease of 14 % in aquatic eutrophication, around 4 % in aquatic acidification and 4 % in mineral extraction. However, there is an increase of 5 % in global warming potential. Since the increase in global warming potential is observed for both Scenarios 2 and 3, comparing both in terms of other impact categories show that indeed Scenario 3 is better in terms of life cycle environmental performance. The results could suggest to involved stakeholders and water companies that instead of resolving to BNRT, they could consider nutrient recovery systems. In the United Kingdom, the addition of commercially designed struvite recovery reactor to a wastewater treatment plant of about 250,000 person equivalent capacity could produce a revenue of £ 20,000 due to savings and struvite fertiliser sales (Kleemann et al., 2015). A similar trend may be observed in the Philippines that could justify the retrofitting of current wastewater plants with a nutrient recovery system. Hence, further studies will be done on the Life Cycle Sustainability Assessment of a wastewater nutrient recovery system that includes the life cycle cost. In order to objectively compare all scenarios considering different priorities, we could also integrate other decision-making tools, sensitivity analysis, and uncertainty analysis in the future works.

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