Integrated life cycle assessment-analytic hierarchy process (LCA-AHP) with sensitivity analysis of phosphorus recovery from wastewater in Metro Manila

Carla Mae J. Pausta, Luis F. Razon, Aileen H. Orbecido, Devendra P. Saroj, and Michael Angelo B. Promentilla

Chemical Engineering Department, Gokongwei College of Engineering, De La Salle University Manila, 2401 Taft Avenue, Manila, Philippines 1004
Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Surrey GU2 7XH, United Kingdom

Abstract. The adverse environmental impact caused by eutrophication has recently prompted the Philippine government to issue stringent regulatory standards for wastewater effluent quality. The involved stakeholders and industries are assessing the integration of biological nutrient removal (BNR) technologies in the current sewage treatment plant (STP) scenario. Moreover, efforts are being done to utilize wastewater as a resource such as recovery of nutrients as struvite fertilizer from the wastewater sludge. Since BNR and nutrient recovery systems are not yet integrated in STPs, the magnitude of the environmental impacts are yet to be evaluated in the Philippine setting. This study covers the holistic evaluation of the overall environmental performance scores of the following scenarios using a consequential Life Cycle Assessment (LCA) framework integrated with Analytic Hierarchy Process (AHP) in the context of Water-Energy-Food Nexus: 1) current STP scenario; 2) BNR technology; and 3) nutrient recovery system. The environmental impact assessment was done using IMPACT 2002+ methodology in terms of the following impact indicators: human health, ecosystem quality, climate change, resources, aquatic acidification, and aquatic eutrophication. Value judgments from relevant stakeholders were elicited to rank the relative importance of the impact indicators in the evaluation of the overall environmental performance score. The LCA-AHP results show that the integration of a nutrient recovery system is the most preferred scenario. Sensitivity analysis was also done to evaluate the effects of changes in diet and utilization of alternative energy.

1. Introduction

About 70% of the water pollution in Metro Manila can be attributed to the domestic sewage containing substantial nutrient concentration that contributes to eutrophication [1]. The Philippine government was then prompted to monitor the phosphorus and nitrogen loads in the effluent streams of all wastewater treatment plants by creating the new water quality guidelines and general effluent standards referred to as DAO 2016-08, that is a Department of Environment and Natural Resources Administrative Order. Due to the government intervention, industries, particularly the domestic sewage treatment plants (STP), are considering to integrate a biological nutrient removal technology (BNRT) into their current systems. The upgrade of BNRT usually employs the addition of several aerobic-anoxic-anaerobic process stages configurations to reduce nutrient content in the treated wastewater [2]. Consequently, several countries especially in Europe have also incorporated phosphorus and nitrogen recovery from sewage as a highly valuable product, such as struvite fertilizer, to promote resource recovery with financial savings [3]. Struvite fertilizer (MgNHPO₄·6H₂O) is a slow-release fertilizer that is formed through chemical precipitation of phosphate and ammonium using magnesium chloride [4]. Struvite recovery from wastewater has provided a sustainable approach to address global phosphorus deficiency and food security challenges due to population growth.

The BNRT and struvite recovery systems are yet to be integrated into the current STPs in Metro Manila. However, the integration and operation of these alternative scenarios would introduce additional...
use of energy, produce emissions, and generate waste, among others [5]. The trade-offs for the alternative scenarios have placed the stakeholders into a decision making dilemma as to which scenario could ultimately reduce the adverse environmental impacts considering that the decision will incur additional costs. It should be noted that different countries having different contexts such as in economic growth, adapt different nutrient removal and recovery systems [6]. Hence, there is a need to investigate the most appropriate scenario in terms of environmental impacts in a localized basis.

Life cycle assessment (LCA) is a quantitative approach to evaluate the environmental impacts of a certain product or system throughout its life cycle from raw material acquisition, production, utilization, end-of-life, waste treatment, recycling and disposal [7]. It is recommended to conduct LCA of wastewater treatment systems on a site-specific basis for improved assessment on impacts specifically on eutrophication and toxicity-related impact categories due to the spatial effects and characteristics of the emissions involved in wastewater treatment plants [8]. LCA has four stages: 1) the goal and scope definition; 2) the inventory analysis phase; 3) the impact assessment phase; and 4) the interpretation phase.

During the life cycle impact assessment (LCIA) phase, the damage impact categories are generally assigned with equal weights in order to generate a single environmental performance score. However, the burden of the decision-making lies into the involved stakeholders based on which environmental impact to be prioritized. A multi-criteria decision analysis (MCDA) tool could be utilized to objectively capture the stakeholders’ value judgement and to relatively identify the most important environmental impact to be considered for the evaluation of scenarios. Analytic Hierarchy Process (AHP) is an MCDA tool that utilizes pairwise comparisons of all criteria and alternatives to institute relationships within the hierarchical problem structure [9]. AHP method is simple and flexible as it has the capability to combine qualitative and quantitative criteria in the same problem structure [10]. Through AHP, an overall environmental performance score could be generated while relatively comparing the difference damage environmental impact category during the LCIA phase.

This study proposes an integrated life cycle assessment and analytic hierarchy process (LCA-AHP) to evaluate the environmental performance of integrating a BNRT and a struvite recovery facility into the conventional sewage treatment system in Metro Manila. The different nutrient life cycle scenarios in the context of agriculture, food consumption and wastewater that will be evaluated in this study are: 1) conventional STP scenario; 2) upgrade of STP with BNR systems; and 3) upgrade of STP with BNR and nutrient recovery system. The goal of the integrated LCA-AHP method is to evaluate the best STP life cycle scenario by generating an overall environmental performance score. Moreover, a sensitivity analysis is to be done in order to assess the effects of the changes in food consumption lifestyle and the utilization of alternative energy. The concept of the design of experiments (DoE) is utilized for the variation of the input parameters in the LCA-AHP framework [11].

2. Method

An integrated LCA-AHP was utilized in this study to come up with an overall environmental performance score. The life cycle impact assessment results were used for the quantitative pairwise comparison of the three scenarios with respect to the damage impact indicators. The LCA-AHP methodology generated the overall environmental performance scores of the three scenarios. After evaluating the values of responses for every run, a regression equation was generated following the DoE methodology. The effect of the input variations or factors on the rankings of the three scenarios was assessed.

2.1 Life Cycle Assessment

The system boundary and inventory analysis of the LCA model for this study were initially discussed in the early stages of the research, particularly on the evaluation of the midpoint environmental impact categories [12]. The scope covers raw material acquisition, production, utilization, end-of-life, waste treatment, recycling and disposal for the following major process blocks: fertilizers, agriculture and food processing, food consumption, sewage treatment, struvite production, and energy (See Figure 1 for the simplified system boundary). The geographical boundary includes the population served by an STP located in Metro Manila. The economic flows, environmental flows, and activities for each process were based mostly on the type of food commonly produced and consumed. Hence, the first approach for the inventory analysis was to establish a “food basket” that contains the information on the representative
food commodity [13]. Based on the food basket, the functional unit used was 13,744.64 tons of food consumed by the population served by the STP for one year [14]. The fixed functional unit dictates the required nutrient or fertilizer for agriculture cultivation needed for food production and consumption. This was the basis for the evaluation of the environmental performance of the proposed integration of a nutrient recovery system in an STP that will provide an alternative fertilizer. The references for the inventory activities for fertilizers, agriculture and food processing are Ecoinvent [15], Agri-footprint [16], Philippine Statistics Authority [14], and Food and Agriculture Organization of the United Nations [17]. Scenarios 1 and 2 have the same inventory for fertilizer, agriculture, and food consumption process blocks. Changes in commercial fertilizer demand due to the addition of struvite fertilizer in the agriculture block were adapted in Scenario 3. The fertilizer data for the first and second scenarios cover the commercial fertilizers applied for the agriculture process while for the third scenario, struvite fertilizer was used. It was assumed that all the required phosphorus for every plant agriculture product in the functional unit will be supplied by the struvite produced by the third scenario. In consequential modelling, for every nitrogen and phosphorus produced in the form of struvite, the same amount of nitrogen and phosphorus in commercial fertilizers are avoided on the third scenario. Among the commercial fertilizers, only the phosphorus-containing fertilizers are avoided since phosphorus is the limiting element for eutrophication. The burdens brought about by the production of the avoided products are subtracted from the impacts of producing struvite fertilizer [18]. The agriculture process block was divided into the following unit blocks: plants and crops cultivation; livestock; and fish aquaculture. Plants and crops cultivation have major inputs from fertilizers, pesticides, electricity and fuel for operations, and water, while the outputs were emissions to air, water and soil. Livestock include feeds (i.e. grass) from the plant cultivation process block, pesticides, electricity and fuel, and water as the inputs while the outputs include emissions to air (i.e. methane and N2O), wastewater and solid wastes. Fish aquaculture activities also involve feeds, fertilizers, water and energy. Furthermore, 30% of the agriculture produce input for food processing were allocated as waste, for all food types. The processed food will be transported for domestic consumption. The food is usually prepared through cooking, thus, the activity energy and water. Food consumption, referring to digestion and metabolism of food, provides the energy needed to sustain human activities but these result to formation of a by-product which are the human excreta and urine. These human wastes and excess water from food preparation are treated into the sewage treatment plant (STP).

In the STP, it was found that around 1.375 kg of carbon dioxide is emitted for every kilogram of biological oxygen demand removed [19] and a total of 0.246 kWh of electricity is utilized for every cubic meter of wastewater treated in the STP [20]. For the chemical data, approximately 7 kg of polymers are used per ton of dry sludge obtained [2]. The distance of chemical supplier to the sewage treatment plant was assumed to be approximately 60 km. The vehicle and fuel is assumed to follow EURO 3 standards since Philippines is still in transition to using EURO 4 standards. The data on the emission to water were taken from the local water utilities industry.

Scenario 1 covers the current scenario wherein commercial fertilizers are used for agriculture production and wastewater influent undergoes conventional treatment processes without any nutrient removal systems. Hence, the effluent is not compliant with DAO 2016-08 in terms of ammonia, nitrate and phosphate contents. This type of effluent quality is then being discharged into the water bodies. Scenario 2 will have the integration of a BNRT into scenario 1. The resulting wastewater effluent was assumed to have a discharge quality that is compliant to the DAO 2016-08, at the minimum. Thus, have a very minimal N and P concentrations. The assumption is that the sludge will be transported to the landfill areas as waste. There is additional electricity consumption due to the additional processes integrated. Since nitrogen removal involves denitrification, there is also around 0.01 kg of N2O emitted into the air for every kg of N denitrified [19]. Scenario 3 will have the integration of a nutrient recovery system with BNR technology into the STP. The nutrient will be recovered from the wastewater through chemical precipitation that would result to struvite formation. Struvite will then be recovered from the nutrient recovery system and be utilized as an additional major input to agriculture aside from fertilizer creating a closed loop for the phosphorus life cycle in this context. Some commercial fertilizers are avoided due to production of struvite. The STP is assumed to be producing an average of 0.02 kg of struvite per 1 m3 of wastewater treated [20].
2.2 Integrated AHP-LCA framework

The Analytical Hierarchy Process (AHP) framework was integrated with LCA in order to come up with an overall environmental performance score for each life cycle scenario. The first step is to translate the decision-making problem, into a hierarchical structure (See Figure 2).

In this study, the goal of the integrated AHP-LCA framework is to generate an environmental performance for each life cycle scenario while capturing the perspectives of stakeholders on the current priorities and state of the local wastewater quality and treatment systems. The goal is assessed by the following damage environmental categories from the life cycle impact assessment: Human Health (HH), Ecosystem quality (EQ), Climate Change (CC), Resources (RS), Aquatic Acidification (AA) and Aquatic Eutrophication (AE). This is represented by the downward arrow from the goal to the second level cluster. The life cycle scenarios on the third level cluster was evaluated quantitatively with respect to each impact category as represented by the downward arrow from the second cluster to the third cluster. The value judgements for the relative importance of each environmental impact category with respect to the goal were elicited from the academe, government and industry representatives through relative pairwise comparisons.

2.3 Sensitivity Analysis

The sensitivity analysis evaluated the effects of varying the input parameters in the life cycle inventory (LCI) analysis and the priority weights for the AHP method with respect to the overall environmental impact score. The livestock consumption of the population and the coal input in the Philippine electricity
mix were treated with a 50% variation in the inventory using the concept of the DoE for a total of 20 runs. The responses are the overall environmental performance scores of scenario 2 and scenario 3. The sampling method used was the Space Filling Latin Hypercube design in order to allow more sampling coverage with minimal runs. For this purpose, the JMP software was utilized in order to generate random runs and regression calculations.

The livestock consumption was chosen as one of the parameters to be varied in order to reflect the effect of changing the content of the functional unit. The functional unit contains the details on the food basket. The food basket contains different types of food products. Each type of food has different agriculture inputs. In general, the following food types require fertilizer inputs in their corresponding agriculture process blocks: Rice and Corn; Root Crops; Vegetables; Fruits; and Fish Aquaculture. The livestock products do not directly use commercial fertilizers in their process blocks. Thus, varying the livestock consumption could evaluate whether the change in human diet could lead to lesser or greater environmental impact. The inventory input for livestock consumption was varied from 1,177.32 tons to 3,531.96 tons per year. The total food consumed was held constant.

The coal input was chosen as the second factor because it could be avoided in the near future as the government and other agencies come up with various climate change mitigation projects that will promote the use of renewable energy sources. The inventory input for coal was varied from 0.183 MJ to 0.549 MJ. The total energy input for the production of electricity was held constant, that is 0.811 MJ based from the electricity mix in Table 4.3. The remaining energy input from other sources of energy depends on the difference between the total energy input and total coal input, having the same ratio.

After identifying the range of variation for every factor, 20 random runs were generated. Each run contains the input values of the two factors that were used for the life cycle inventory (LCI) and impact assessment (LCIA). The effect of the input variations or factors on the rankings of the three scenarios will then be assessed.

3. Results and Discussion

For the consumption of 13,744.64 tons of food, the life cycle impact assessment results for midpoint categories are summarized in Figure 3. The results are normalized with respect to the highest magnitude for every impact. Based on the figure, the results of the life cycle impact assessment for scenario 3 show that there is a relatively substantial decrease of carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organic, aquatic and terrestrial ecotoxicity, terrestrial acidification/nutritification, land occupation, aquatic acidification and eutrophication, and mineral extraction impacts released to the environment compared to scenario 1 and scenario 2. However, the impact assessment results of scenario 3 for global warming and non-renewable energy show that there is a significant increase in impacts compared to scenario 1 but of lesser magnitude as compared to scenario 2. Since the production of commercial phosphorus and nitrogen fertilizers are avoided in scenario 3 through the consequential LCA approach, the impact assessment will have lesser value compared to scenarios 1 and 2. However, the additional electricity for operations and processes for scenario 3 are evident in the increase of impacts in terms of global warming and non-renewable energy. Furthermore, despite the increase in climate change and non-renewable energy impacts, scenario 3 could be preferred over scenarios 1 and 2. In order to comply with the legal requirements, retrofitting to scenario 2 is required. Thus, the increase in climate change and other impacts are unavoidable. In terms of climate change and non-renewable energy impacts, scenarios 2 and 3 do not show any significant difference; however, for the rest of the results in LCIA, scenario 3 shows better environmental performance. Hence, retrofitting the STP with a nutrient recovery system is justifiable considering the life cycle system boundary.

The midpoint impact categories were converted into their respective damage category. The overall and combined results of the damage categories are summarized in Table 1. Results show that scenario 2 has higher impacts on Human Health, Ecosystem Quality, Climate Change, and Resources but has lesser impacts on Aquatic Acidification and Aquatic Eutrophication compared to scenario 1. Moreover, the results show that scenario 3 has lesser environmental impact on Human Health, Ecosystem Quality, Aquatic Acidification and Aquatic Eutrophication but has more impact on Climate Change and Resources with respect to scenario 1.
Figure 3. Normalized life cycle impact assessment results for midpoint categories

Table 1. Overall Damage Category Characterization

| Damage category         | Unit       | Scenario 1 | Scenario 2 | Scenario 3 |
|-------------------------|------------|------------|------------|------------|
| Human health            | DALY       | 100.92     | 101.08     | 100.25     |
| Ecosystem quality       | PDF/m2/yr  | 55.0 M     | 55.0 M     | 54.72 M    |
| Climate change          | kg CO₂ eq  | 86.16 M    | 86.46 M    | 86.43 M    |
| Resources               | MJ primary | 1.164 B    | 1.168 B    | 1.166 B    |
| Aquatic acidification   | kg SO₂ eq  | 1.432 M    | 1.414 M    | 1.414 M    |
| Aquatic eutrophication  | kg PO₄ P-lim | 51,619.43 | 46,143.85 | 44,889.47 |

The average environmental impact contribution breakdown of the different phases in the LCA system boundary for every damage impact category is presented in Figure 4. The LCA system boundary is divided into four major phases: agriculture-plants and aquaculture/fish; agriculture-livestock; food processing and consumption; and sewage treatment system. For human health, resources, climate change and aquatic acidification impact categories, food processing and consumption contributed the most followed by agriculture-livestock, agriculture-plants and aquaculture and sewage treatment. Food processing and consumption contributed the most due to the solid waste generated and electricity used for processing, preparation and consumption of around 13,700 tons of agriculture products (functional unit). For the ecosystem quality, the production of plants and fish agriculture products contributed the most impact followed by livestock production, food processing and consumption and sewage treatment. In terms of aquatic eutrophication, the production of plants and fish agriculture products contributed the most followed by sewage treatment, production of livestock agriculture products and, food processing and consumption. The high ecosystem quality and aquatic eutrophication adverse impact on the production of plants and fish is due to the agriculture water run-offs and leaching to terrestrial and waters caused by utilizing fertilizers. It must be noted that these agriculture water run-offs do not undergo any wastewater treatment.

Value judgments were elicited through pairwise comparisons to evaluate and rank the relative importance of the environmental impact indicators, for the overall environmental performance of the three scenarios. The resulting priority weights from the pairwise comparisons are shown in Table 2, where human health is the most important impact indicator for the evaluation of environmental performance of the systems according to the representatives. This is followed by the ecosystem quality, resources, climate change, aquatic eutrophication and aquatic acidification. Adverse impact on human health results to disability and impact on ecosystem quality involves death of species, thus, these two categories come out as the two most important factors to be considered.
Figure 4. Average environmental impact phase contribution for every damage category

Table 2. Priority weights of environmental impact indicator with respect to Goal

| Environmental Impact Indicator | Priority Weights |
|-------------------------------|------------------|
| Human Health (HH)             | 0.428449         |
| Ecosystem Quality (EQ)        | 0.269881         |
| Climate Change (CC)           | 0.061784         |
| Resources (RS)                | 0.132497         |
| Aquatic Acidification (AA)    | 0.051296         |
| Aquatic Eutrophication (AE)   | 0.056093         |

Table 3. Relative rank of scenarios with respect to the environmental impact indicator

| Scenario | Overall Performance Score |
|----------|---------------------------|
| Scenario 1 | 0.331355                 |
| Scenario 2 | 0.333193                 |
| Scenario 3 | 0.335452                 |

Considering the relative ranks of the environmental impact categories, the overall environmental performance scores were calculated. Results show that Scenario 3 is the most preferred scenario, closely followed by Scenario 2 and Scenario 1. Due to the high magnitude of the LCIA results, the relative difference for every scenario seems small. However, this small difference has a bigger effect or damage to the receiving endpoint. Since the AHP utilizes relative pairwise comparison, the small relative difference between each scenario compared to the total value of each scenario is too small. It is then
reflected in the very small differences in the overall environmental performance scores presented in Table 3.

The sensitivity analysis for the LCA-AHP of the three scenarios are done by varying two input factors in the life cycle inventory the concept of the DOE. Through variation of input factors and resulting responses, general regression equations were generated in order to predict the effect in the overall environmental performance scores of scenario 1 \( (y_1) \), scenario 2 \( (y_2) \) and scenario 3 \( (y_3) \), considering the variations. Using the general linear method following the normal distribution, the coefficients of the livestock consumption \( (x_1) \) and coal input \( (x_2) \) factors as well as the intercepts were generated as shown in Equation 1 for scenario 1, Equation 2 for scenario 2, and Equation 3 for scenario 3. The factors for scenarios 1 and 2 have positive coefficients. Thus, if the livestock consumption or the coal input increases, the overall performance scores of scenarios 1 and 2 increases and vice versa. Consequently, both of the factors for scenario 3 have negative coefficients. If the livestock consumption or the coal input increases, the overall environmental performance score of scenario 3 decreases. However, if the livestock consumption or the coal input decreases, the overall performance score increases.

\[
\begin{align*}
  y_1 &= 0.000113 x_1 + 0.000217 x_2 + 0.331325 \\
  y_2 &= 0.000102 x_1 + 0.000126 x_2 + 0.333171 \\
  y_3 &= -0.00022 x_1 - 0.00034 x_2 + 0.335503
\end{align*}
\]  

The sensitivity analysis for the livestock consumption is generally related to the food diet of the locals. If the people consumes lesser livestock agriculture products and consumes more plant agriculture and aquaculture food products, then scenario 3 is more favored in the life cycle context. Scenario 3 recovers phosphorus and nitrogen in the form of struvite fertilizers. This would relate to more avoided commercial fertilizers. Furthermore, if there is less er coal input in the electricity mix and more renewables, scenario 3 will produce more environmental benefits. Scenarios 2 and 3 have more electricity consumption compared to scenario 1. However, if coal input is lesser, then the life cycle impact on global warming potential will be lesser for both scenarios 2 and 3.

4. Conclusion

The integrated consequential life cycle assessment (LCA) and analytic hierarchy process (AHP) has provided the holistic evaluation of the environmental performances of the following three sewage treatment plant scenarios in Metro Manila: Scenario 1) current STP scenario; Scenario 2) biological nutrient removal (BNR) system; Scenario 3) nutrient recovery system. It is therefore concluded that the most preferred scenario in terms of life cycle environmental performance is the Scenario 3, that is the incorporation of a nutrient recovery system into the STP with BNR. This is followed by Scenario 2 with BNR system, which is the required scenario for industries in order to address the urgent matters regarding environmental legal compliance. Scenario 1, which is also considered as the baseline scenario, comes after scenario 2.

Based from the life cycle impact assessment (LCIA) results, the application of scenario 3 to the current scenario (scenario 1) produces environmental benefits in terms of the following midpoint impact indicators: carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic and terrestrial ecotoxicity, terrestrial acidification/nutrification, land occupation, aquatic acidification and eutrophication, and mineral extraction impacts. However, an increase of impacts in terms of global warming potential and non-renewable energy midpoint indicators are not avoided due to the increase of electricity usage for the nutrient recovery system operations. For the retrofitting of scenario 1 to scenario 2, there are environmental benefits in terms of aquatic acidification, aquatic eutrophication, carcinogens, land occupation and mineral extraction impact indicators. However, there are more adverse effects in terms of global warming, non-renewable energy, non-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aquatic and terrestrial ecotoxicity and terrestrial acidification/nutrification.

The normalization of the midpoint impact indicators into damage categories for the LCIA showed that scenario 3 produces lesser impacts on Human Health, Ecosystem Quality, Aquatic Acidification and Aquatic Eutrophication but has more impact on Climate Change and Resources compared to scenario 1. The results for scenario 2 compared to scenario 1 showed lesser environmental impacts on Aquatic Acidification and Aquatic Eutrophication but the increases of impacts on Human Health, Ecosystem Quality, Resources and Climate Change are observed.
Based from the value judgements of the relevant stakeholders, the most important environmental impact indicator that should be considered to evaluate the overall environmental performance scores is the Human Health, followed by Ecosystem Quality, Resources, Climate Change, Aquatic Eutrophication and Aquatic Acidification.

The sensitivity analysis shows that changes in the food diet and electricity mix could have effects on the overall environmental performance scores of the three scenarios. Thus, the results also presented a better understanding of the food-energy-water-nutrient nexus. Generally, if the livestock consumption is increased in the food diet, the overall performance scores of scenarios 1 and 2 increases while to that of scenario 3 decreases. If the electricity mix has more coal input, the overall performance scores of scenarios 1 and 2 increases while the score for scenario 3 decreases. Hence, the nutrient recovery system is more favorable when people consume less livestock food products and when there is lesser coal input in the electricity mix.

This study has presented the LCA-AHP of the different STP scenarios using food consumed by the population served by one STP as the functional unit. Since this study considers a very broad system boundary, the extent of the life cycle is more comprehensive. However, it requires intensive data gathering. Though current databases have more comprehensive inventory data for most processes and products, some localized products and processes may not be available. Thus, there may be inconsistencies in the extent of input and output data. Furthermore, future studies could involve the whole population of Metro Manila. This may or may not widen the change in impact values between the three scenarios. One of the improvements that could also be done in this study is to consider the midpoint impact indicators as sub-criteria to the damage impact indicators in the AHP problem structure. The results may show a wider range between the scenarios. Moreover, the results can also be compared to the default weighting and characterization factors of the chosen LCIA methodology such as IMPACT 2002+ and ReCiPe. A life cycle sustainability assessment (LCSA) of the scenarios could create a better understanding of the food-energy-water-nutrient nexus in cities considering the economic and social aspect. This may further help the stakeholders in their decision-making as to what scenario is the best to address sustainability.

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