THE BIOFACTORY: LIFE CYCLE SUSTAINABILITY ASSESSMENT FOR WASTEWATER BIOREFINERIES

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ABSTRACT (500 WORDS MAXIMUM)

The circular economy offers an opportunity for wastewater to be utilized as a valuable resource within the increasingly scarce global food-water-energy nexus. Many promising technologies for recovering resources, such as biogas, bio solids and nutrients, and improving effluent quality, from wastewater have been implemented across the world. Life Cycle Assessment (LCA) studies of these technologies demonstrate improved environmental impacts to promote their implementation, however, this tool is difficult for decision makers to interpret due to the diverse range of environmental impacts. LCA also fails to address sustainability trade-offs between additional economic and socio-cultural factors that influence decisions regarding the implementation of resource recovery in wastewater treatment plants (WWTPs). Life Cycle Sustainability Assessment (LCSA) is a tool that can compare alternative technologies across integrated aspects of sustainability, combining LCA, Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA). The knowledge surrounding the application of this model to WWTPs and circular economies is limited. This study implements the monetization of LCSA for two real wastewater resource recovery plants referred to as The Bio-factories 1 and 2. Considering a 44,500 kg BOD_5/day p.e. of wastewater treated functional unit, each Biofactory was assessed under four scenarios expanding system boundaries across 1. Water Recovery, 2. Biosolids Recovery, 3. Energy Recovery; and 4. Advanced Nitrogen removal, comparing the environmental and economic benefits of different technologies.

KEYWORDS

LCA, LCC, SLCA, Biorefinery, Wastewater, Circular Economy

PRESENTER PROFILE

Madeline is from Waihopai in Mirihiku, Southland, a graduate in civil and natural resources engineering from the University of Canterbury. Having studied Spanish from a young age, she pursued a career working in community engineering projects with Engineers Without Borders in Chile. Her experienced ranged across water scarcity and supply projects in the rural south, to infrastructure projects in the central regions. She also participated in research, development and training in the humanitarian engineering space with universities, businesses and communities. She is now undertaking her doctoral studies between Chile and Aotearoa, promoting the implementation of circular economies in wastewater treatment.

INTRODUCTION

The Biofactory is a wastewater biorefinery that implements a circular economy with technologies for advanced wastewater treatment and resource recovery (Nancharaiah et al., 2016). The role of the Biofactory in the food-water-energy nexus promises to decrease environmental impact (Neczaj and Grosser, 2018) of treatment processes while improving economic and social performance of a system overall (Opher et al., 2018). This can be achieved by implementing a wide range of treatment processes for the recovery of biomaterials and biogases while improving discharged effluent quality (Gherghel et al., 2019). Across the globe, Life Cycle Assessment (LCA) studies have been conducted on treatment schemes for recovering biosolids (Collivignarelli et al., 2019), biogas (Mills et al., 2014) and nutrients (Sena and Hicks, 2018) for investigating their respective environmental impacts or benefits. Complementary to this, Life Cycle Costing (LCC) studies have addresses economic impacts or benefits of some of these technologies (Hall et al., 2018). Social Life Cycle Assessment (SLCA) is the least developed methodology as this deal with qualitative information that is difficult to integrate with qualitative LCA and LCC assessments (Alejandrino et al., 2021). Life Cycle Sustainability Assessment (LSCA) combines LCA, LCC and SLCA for quantifying impacts across three sustainability pillars in a systematic way (Valdivia et al., 2021). The applications of these studies vary methodologically and geographically where a dearth of case studies exist for the global south, therefore is was recommended that LCSA methodologies be developed and implemented across different regions around the world to promote the implementation of circular economies through wastewater biorefineries (Furness et al., 2021).

The diversity of wastewater quality and respective populations served by a treatment plant implicates that no one process scheme exists to take advantage of the circularity of wastewater. Bottlenecks arise across technical, economic, and social paradigms such as unfamiliarity of new technologies, high cost of implementation and public rejection of resources recovered from a toxic raw material (Kehrein et al., 2020). Deciding between alternative treatment schemes for implementing a circular economy becomes a complex task where decision makers must deal with interpreting information of both quantitative and qualitative natures (Kalbar et al., 2012).The objective of this study was to develop and apply a LCSA based decision making tool for comparing and identifying the most sustainable treatment technologies to contribute to methodological advances and provide a case study from Latin America. Two real Biofactories were examined and compared to quantify benefits of implementing circular economies in this context and to compare the different treatment processes of each. This paper presents and discusses the LCA and LCC results and makes recommendations on the feasibility of a LCSA decision making model.

METHODOLOGY

LIFE CYCLE SUSTAINABILITY ASSESSMENT

GOAL AND SCOPE

The goal of this study was to identify and compare environmental and economic benefits of two real Biofactories operating in Santiago, Chile implementing different treatment configurations. These results are later integrated with the current SLCA study being undertaken with the LSC. The first objective quantified the benefits across four scenarios of increasing circularity for each Biofactory (8 total scenarios). The second objective compared the final circular system of each Biofactory to determine to most sustainable treatment configuration. Subsequently, further improvements of the treatment configurations and areas of further research are recommended. With collaboration from a Local Sanitation Company (LSC) in Santiago, Chile, this research is intended to serve not only these stakeholders, rather any sanitation industry seeking to implement circular economies and compare alternative technologies for advanced treatment or resource recovery. The functional unit describes the overall function of the system to be studied to provide a normalization factor for fair comparison between alternatives using LCSA. In this case, the function of a traditional wastewater treatment plant is to treat m^3 of wastewater, however in the context of a circular economy the function shifts from treatment to resource recovery. Resource recovery is not dependent primarily of m^3 of wastewater rather the organic loading of the served population. Therefore, the functional unit of this study was set to the treatment of a 1,000,000-population equivalent (p.e.) of wastewater using a reference flow of 44.5 mg/L of Biological Oxygen Demand (BOD_5), corresponding to 44,500 kg of BOD_5 treated during one day of operation. The system boundaries consider the influent of wastewater post preliminary filtration of large solids, sand and grit, including the impacts of all output flows to the environment. The life cycle of a wastewater treatment plant as a critical infrastructure was assumed as 20 years from construction to demolition. Considering a long-life cycle excludes the impacts of construction and demolition phases and focuses on operation. The scenarios considered are organized by resource recovery and advanced treatment function. These are described in Table 1.

Table 1: Biofactory scenarios considered in this study for investigating benefits of increased circularity and comparison of alternative resource recovery configurations.

Scenario	Biofactory 1	Biofactory 2
1 Baseline	Linear Wastewater Treatment Plant • Primary Sedimentation • Activated Sludge • Sludge Thickening • Anaerobic Digestion with Thermal Hydrolysis Pre-treatment • Digestate Thickening • Biosolids to Landfill • Biogas Flare	Water Recovery • Primary Sedimentation • Activated Sludge • Water Recovery for Irrigation • Sludge Thickening • Anaerobic Digestion • Digestate Thickening • Biosolids to Landfill Biogas Flare
2 Biosolids Recovery	Biosolids Management • Biosolids to Landfill replaced with 87:13 Agriculture: Landfill management due to improved biosolids quality through THP	Biosolids Management • Biosolids to Landfill replaced with 87:13 Agriculture: Landfill management due to improved biosolids quality
3 Energy Recovery	Biogas Upgrading Cogeneration Heat and Energy • Biogas flare replaced biochemical biogas upgrading system • Upgraded biogas used in cogeneration unit	Biogas Upgrading Biomethane Production • Biogas flare replaced with biochemical biogas upgrading system • Upgraded biogas further upgraded to biomethane for domestic consumption

4 Nutrient Management	Sequencing Batch Reactor Anammox • Sludge returns treated	Nitrification-Denitrification Anammox • Sludge returns treated

DATA INVENTORIES

Infrastructure and Capital Expenditure

Even though impacts of construction and demolition are not included in this study, the environmental impacts of the materials required for implementing different treatment technologies are to incorporate the environmental component of capital costs. These materials were simplified to concrete, reinforcing steel, wooden moldings, PVC plastics, FBR and land use. The quantity of materials was normalized to the functional unit considering a 20-year life cycle. This data was sourced from LWC and modeled with ECOINVENT DATABASE. The capital expenditure (CapEx) assumed for each Biofactory 1 and 2 was $8,000,000,000 and $6,000,000,000 CLP respectively. This was divided across land area occupation to demonstrate process contributions; this is a large assumption and does not reflect real investment costs of each process. This information was not available from the LWC.

Materials and Operational Expenditure

The data inventories for this study considered the inputs and outputs displaying figure X. The first step involved establishing a substance flow analysis of wastewater characteristics total solids (TS), volatile solids (VS), BOD_5, chemical oxygen demand (COD), total nitrogen (TN), total phosphorous (TS) normalized to the functional unit. Additionally, heavy metals arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), zinc (Zn), iron (Fe), calcium (Ca), magnesium (Mg) and manganese (Mn) were also considered in influent, effluent and Biosolids flows. The removal of VS across anaerobic digestion provides biogas productivity and biogas quality, provided by the LWC. This provided a basis for calculating normalized flows of input chemicals required for treatment across different technologies including O2 and Cl for water treatment, FeCl and Polymers for sludge treatment, NaOH, MgO, H2SO4 and FeCl for biogas upgrading. This data was provided by daily monitoring data from the two Biofactories from the LSC registered during 2019. Data regarding chemical additives production was selected from ecoinvent database system cut-off. Costs of materials include the cost of chemicals in Table 2.

Table 2: Costs of chemicals consumed in Biofactory 1 and 2 for different processes.

Process	Chemical	Biofactory 1 (M) $CLP / kg	Biofactory 2 (F) $CLP / kg
Water Treatment/Recovery	Cl	546	546
Sludge Treatment	FeCl	-	212
	Polymer	1700	1700
Energy Recovery	Nutrients	10,000	10,000
	NaOH	5000	5000

Nutrient Management	H2SO4	8,000	8,000
	MgO	7,000	-
	NaOH	5000	5000

Energy and Operational Expenditure

The energy balance was conducted by calculating the power demand of each of the technologies involved in the system and fitting this to the overall power consumption of each Biofactory, 0.28 and 0.25 kWh/m3 for Biofactory 1 and 2 respectively. The impact of the Chilean energy system is provided in the ecoinvent database. The cost of energy consumption was set at 189,000 CLP $/kWh across the entirety of both systems.

Transport and Operational Expenditure

Transport processes were quantified in terms of ton-kilometers (t-km) and calculated considering a round trip of different capacity trucks for delivering chemicals to the plant from different locations around Chile, as well as the delivery of biosolids to either landfill or agricultural land with different distances set for each plant. The cost of materials transport is included in the cost of material supply, whereas the cost of Biosolids transport to landfill and agricultural application are displayed in Table 3.

Table 3: Biosolids disposal costs for landfill and agricultural application.

Disposal Costs	Landfill ($ CLP/kg)	Agriculture ($CLP/kg)
Biofactory 1 (M)	29.56	22.85
Biofactory 2 (F)	29.56	14.12

Products and avoided products (Incomes and Operational Cost Savings)

The main source of income for the LWC is the community service charge, due to privatized water sector, therefore, $ CLP 5000 /m^3 of wastewater was set as the rate. The avoided products are identified as avoided water consumption for water used in irrigation based on volume, but this does not represent an income for the Biofactories. Avoided Diammonium Phosphate (DPD) application, a common fertilizer used in Chile, where biosolids are applied is based on equivalent mass of Phosphorus. These costs are excluded from the LCC. The farmers receiving the Biosolids are the stakeholders who benefit from costs savings of avoided fertilizer use, these are excluded from the study for the Biofactories income. However, in a circular economy the economic value for revalued goods must be compared to avoided products for analysis of economic competition. Avoided LPG consumption for biogas biomethane supply avoided energy consumption from cogeneration are based on equivalent energy capacities. The sale of biogas to the community is priced at 700 $ CLP/Nm^3. These costs are also excluded from the LCC. The local community receiving the biogas are the stakeholders who potentially benefit from costs savings of avoided LPG use; these are excluded from the study for the Biofactories income.

Emissions

The SFA provided a basis for which to estimate emissions using the emission factors displaying in Table X. calculated using stoichiometric reaction equations, either literature sources or the IPCC emissions factor database. The costs of emissions are not direct, but any incompliance with local emissions policies is included in the SLCA study. For detailed calculations of inventory data please contact the authors.

IMPACT CHARACTERIZATION AND UNCERTAINTY

Impact characterization required SimaPro, a leading LCA software in the market. The characterization method selected was the international ReCiPe 2016 Midpoint (H) V1.03, World (2010) H. The results were normalized to kg CO^2 equivalents (eq.) and result in nine overall impact categories of importance, presented in Table 4, that are weighted to a single score total cost to the environment using the conversion of the recipe midpoint environmental shadow prices method to $ CLP. This weighting methodology was compared with equal weighting of impact categories to demonstrate overall contribution too. The quantification of costs in Capital Expenses (CapEx), Opex and Income are characterized into the net present value (NPV) to quantify economic performance across scenarios of increasing circularity considering 5% discount rate and the 20 year life cycle. The uncertainty of environmental impacts was quantified using Monte Carlo assessment of operational data standard deviations assuming lognormal distributions.

Table 4: ReCiPe 2016 Midpoint (H) V1.03, World (2010) H impact categories considered in this study and corresponding environmental cost shadow prices, adapted (De Bruyn et al., 2018).

Impact Category	Abbreviation	Unit	Shadow Price ($ CLP /unit)
Climate Change	C.C	kg CO^2 eq.	131.02
Freshwater Eutrophication	F.Eut	kg P eq.	4367.43
Marine Eutrophication	M.Eut	kg N eq.	7148.80
Terrestrial Ecotoxicity	T.Eco	kg 1,4-DCB eq.	20434.99
Freshwater Ecotoxicity	F.Eco	kg 1,4-DCB eq.	84.82
Marine Ecotoxicity	M.Eco	kg 1,4-DCB eq.	17.38
Human Carcinogenic Toxicity	H.T.C	kg 1,4-DCB eq.	85.05
Human Non-carcinogenic Toxicity	H.N.T	kg 1,4-DCB eq.	85.05
Water Consumption	W.C	m^3	1105650*

***CALCULATED BASED OF PROJECTED GDP DECREASE DUE TO DROUGHT IN CHILE**

INTERPREATION AND DECISION MAKING

The results of the LCA, LCC and SLCA assessments provide performance scores input into a Multi-Objective Decision Making (MODM) model. LCA, LCC and SLCA provide multi-attribute decision-making matrices for Environmental, Economic and Social decision-making criteria respectively. This paper presents the results of LCA and LCC assessments that will serve as performance scores in future decision-making model simulation. The SLCA is in development for quantifying social benefits and criteria weighting of each sustainability pillar by conducting expert interviews and general surveys of the stakeholders of the LSC.

RESULTS AND DISCUSSION

INCREASING CIRCULARITY TO BUILD A BIOFACTORY

Figure X and Figure X display environmental impact results with uncertainty for Biofactory 1 and Biofactory 2 respectively. The increase between LW and LW+BR in C.C, F.Eut and M. Eut in Biofactory 1 is due to biosolid recovery, where a slight decrease in F.Eue between S2 and S3 is attributed to energy savings for biosolid production. C.C. appears less significant due to the comparison of the impact intensities with the disposal of effluent where direct disposal of effluent caused higher F.Eut and M.Eut. However, F.Eco, M.Eco, H.C.T and H.N.T decreases gradually as BR and ER are added to the system. The benefits of energy recovery are observed across the entire system as 95% of energy consumption is decreased in each process. The large uncertainties for F.Eco, M.Eco and H.C.T are due to high NaOH consumption during CHP and highly dose variability during operation. These results are less reliable but still lay within a range to provide environmental benefits, the NaOH production process from ecoinvent databases may not represent that of the actual chemical sourced. The variability of N, P and heavy metals loadings cause mild uncertainty for F.Eut, M.Eut and H.C.T. Figure X displays the change in costs over increasing circularity, only slight change in CapEx is observed where ER and SBR-Anammox are implemented, as Biosolids management infrastructure does not change when alternative uses are implemented. The advantage of ER is also observed for where significant OpEx

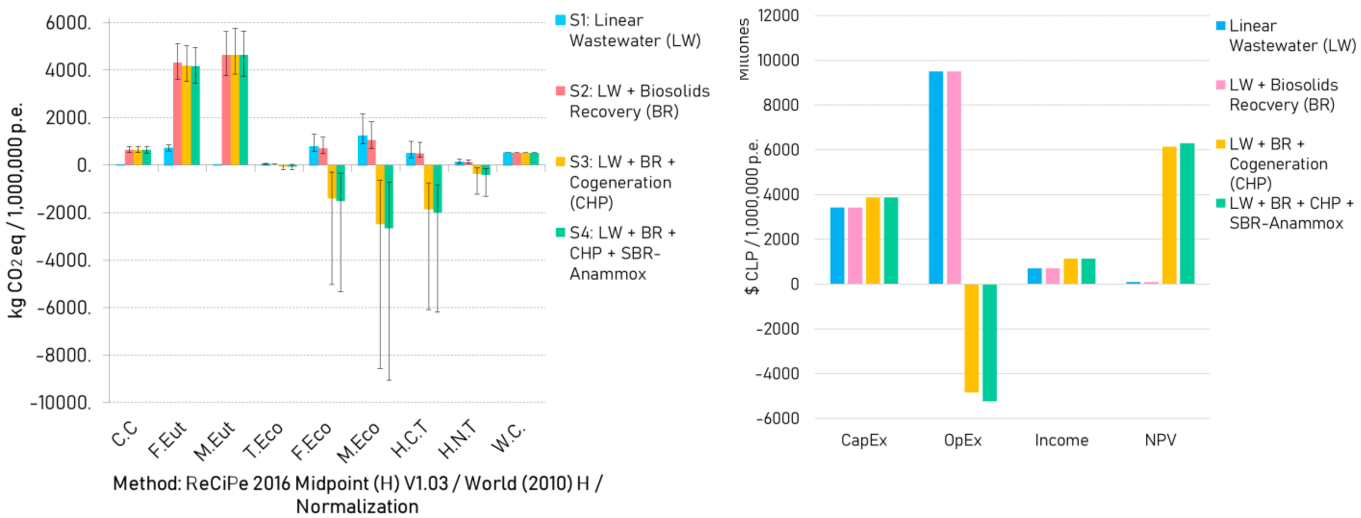

Figure 1: Environmental impact results across increasing scenarios of circularity for Biofactory 1.

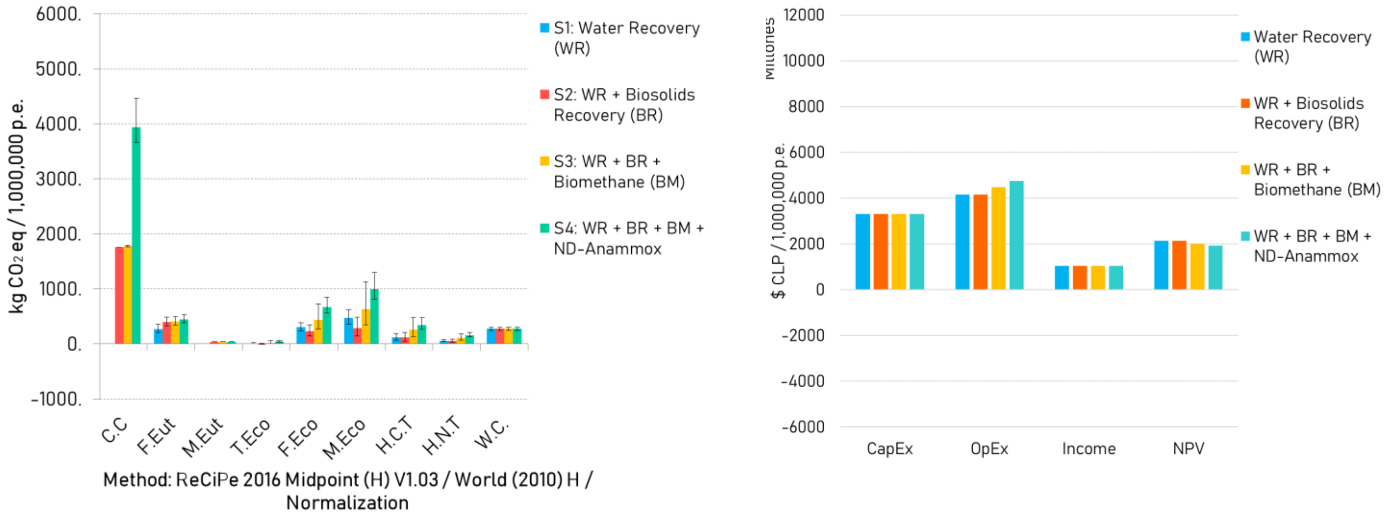

Figure 2: Environmental impact results across increasing scenarios of circularity for Biofactory 2.

savings occur, along with income. Overall, this increased the plant NPV across increasing circularity. The uncertainty analysis of costs is in development.

Biofactory 2 increased in C.C from S1 to S2, this due to the impacts of Biosolids transport and increased energy consumption, as more processes were included in the system, an additional 55% where aeration increased for nitrification-denitrification for nutrient management in S4. F.Eut increases due to increased agricultural Biosolids use. F.Eco and M.Eco decrease slightly from S1 to S2 due to the addition of biosolids management, followed by increases due to the addition of chemicals for BM and ND-Anammox. H.C.T also increases with increased chemical and energy consumption. The uncertainty is less overall for Biofactory 2, where NaOH also influences in C.C., F.Eco and M.Eco impacts. Figure X. displays the inventory costs and demonstrate the advantage in CapEx of the BM process where infrastructure requirements are low, however a disadvantage overall for Biofactory is seem where adding process increases OpEx across scenarios, Income does not increase due to low value of BM, corresponding to overall decrease in NPV. Uncertainty analysis of cost data is under development.

COMPARING BIOFACTORIES

Figure X shows S4 of both Biofactories for comparison of the implemented circular economies, displaying the process contributions. Biosolids management has the greatest overall contribution for both Biofactories when normalized. The benefits of energy recovery are again demonstrated where the processes all achieve environmental savings. Due to improved quality of biosolids in Biofactory 1, more emissions are apparent due to increased transport and impacts land application.

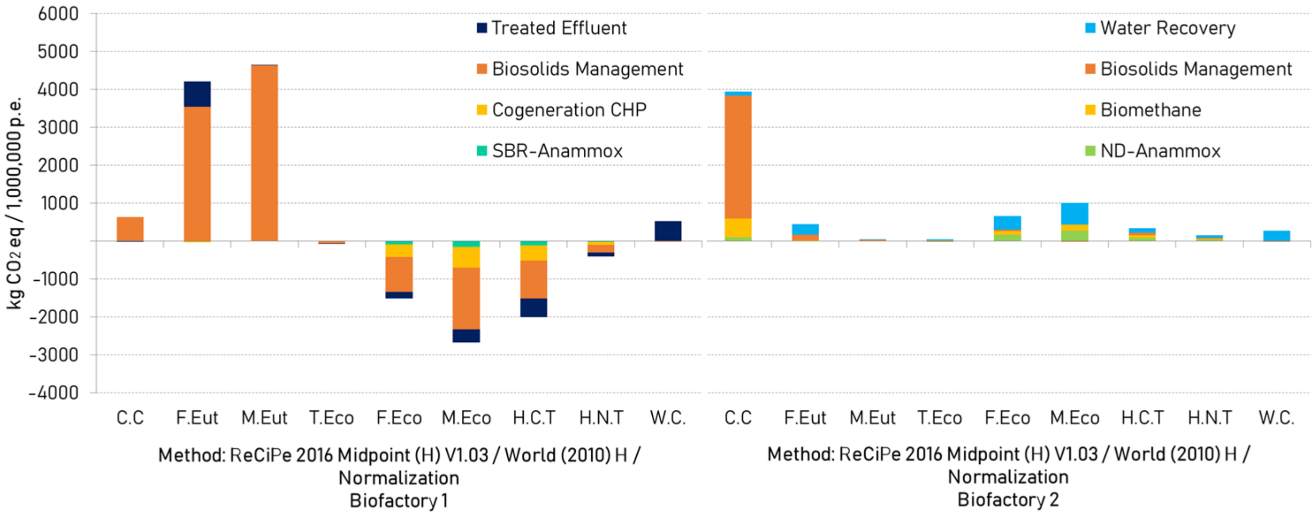

Figure 3: Comparison of process contributions to environmental impacts of Biofactory 1 and 2 in scenario 4.

Figure 3 displays a side-by-side comparison of the Biofactories S4 LCA and LCC results, where Biofactory 1 shows better environmental and economic performance overall. This demonstrates that a closer the loop in a circular economy, especially for energy recovery, will incur more benefits to the environment, especially in the context of the Chilean energy grid with only 30% renewable energy. Figure 4 shows the weighted characterization results considering a) equal weighting of all environmental impact categories and b) weighting using environmental impact shadow prices. These figures are key for demonstrating the challenge of interpretation stages of LCA. Biofactory 1 does have high impact across all categories, but in other categories savings are made. When applying the environmental prices adapted to Chile, due to high water stress in the region, the water recovery becomes most beneficial overall, reverting the results to show Biofactory 2 as the better overall system. How can one impact be compared to another? These two graphs effectively demonstrate the environmental trade-off between different environmental impacts. This brings to

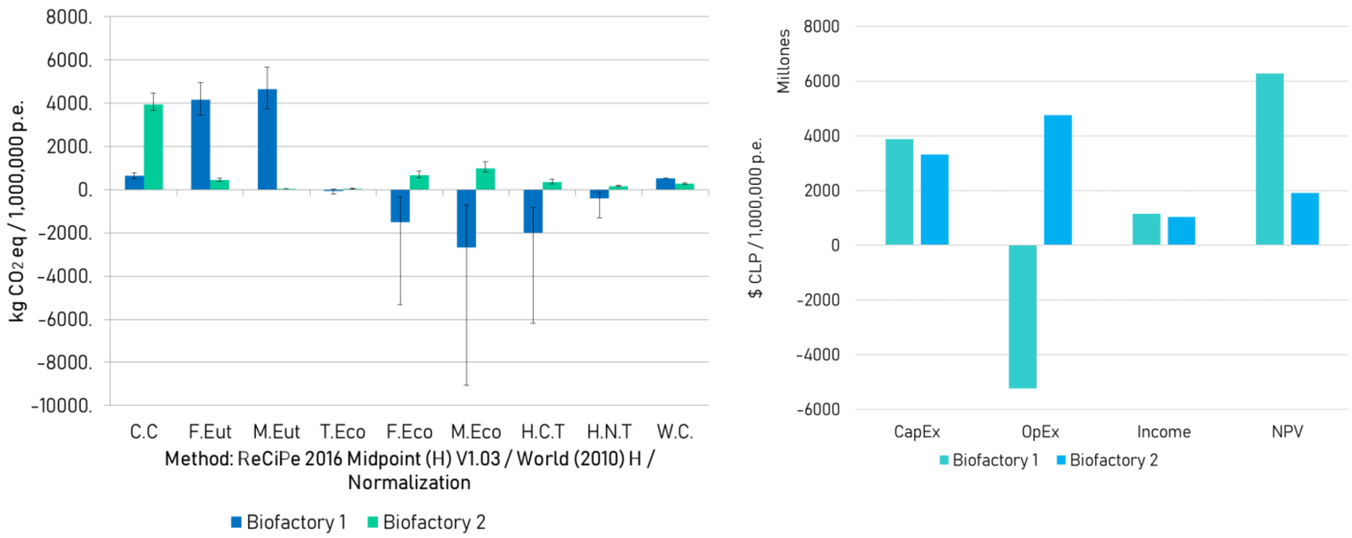

Figure 3: Comparison of process contributions to environmental impacts and costs of Biofactory 1 and 2 in scenario 4.

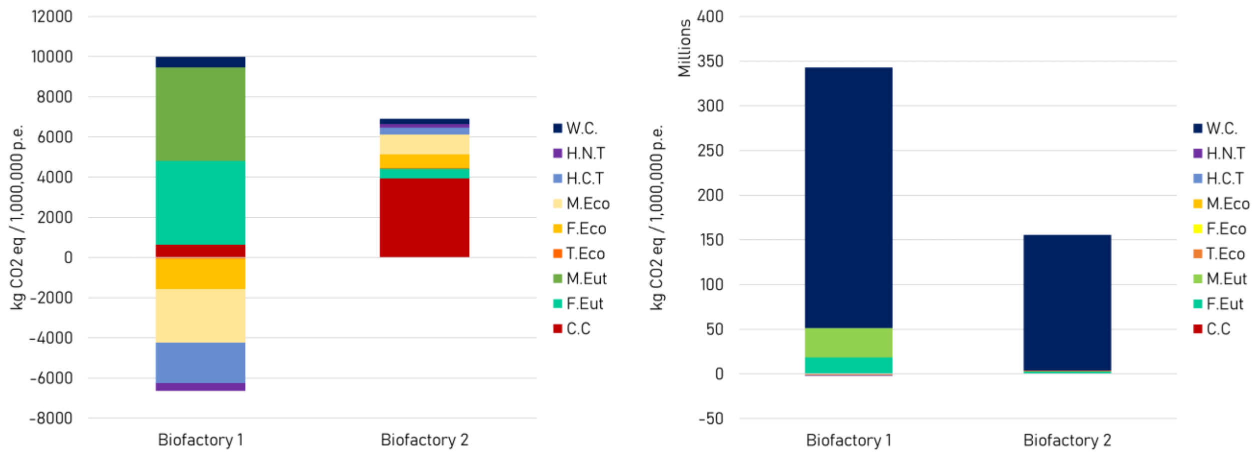

Figure 4: Comparison of environmental impact contributions for Biofactory 1 and 2 in scenario 4.

light the discussion of how these different impacts are valued, economically, or socially. The environmental pricing method is interesting for providing a single score, however, some environmental impacts of the 18 Recipe are not quantified such as the case for W.C. For example, water consumption is a factor that affects GPD in zones of water scarcity and could increase overtime, such is the case for Chile. Should other environmental prices also be adjusted to the level of local contamination, as Dutch scenarios will be different conditions geographically and industrially. Valuing based on economic commodity does not perhaps guarantee better decision making, but perhaps this can be explored with decision makers. Therefore, the SLCA will use a survey to capture stakeholder level of relative importance using AHP (Opher, 2019). These weighting methods will be discussed in future research. From a technological perspective, thermal hydrolysis is a beneficial technology for improving biosolids and biogas production quality, however, must be accompanied by cogeneration to offset increased energy demand. Even where higher energy consumption occurs, the impact in C.C. is not as high as other impact categories for Biofactory 1. A recommendation would be to explore cogeneration together with biomethane production as a technology for Biofactory 2 as 40 % of the biogas produced is still sent to flare, that could be achieved using the data from Biofactory 1. Biofactory 1 could explore water recovery options also.

In terms of costs, in a privatized water sector it is difficult to achieve appropriate cost analysis where transparency of data is lacking. During SLCA, expert interviews will be focused on discussing financial benefits of the circular economy and verifying whether these results align with LWC business strategies. The uncertainty analysis needs to explore more, as reliability of data and results obtained through LCA and LCC should be considered in the decision-making model. The LCA data inventory is extensive and complete where detailed consideration was made for different processes in material flow analysis, energy consumptions, transport processes and emissions. It must be highlighted that data requirements for LCA in general are extensive, even more so for LCSA. A sensitivity model of the LCA variables and parameters will determine where data quality can be improved, or assumptions further explored. This will also be implemented for LCC where cost assumptions will require analysis. The lay out of the scenarios for analysis are complex, perhaps an assessment of the performance of individual technologies would be beneficial for comparing more treatment scenarios, i.e., adding cogeneration to Biofactory 2 or water recovery to Biofactory

1, or swapping between nutrient recovery systems. However, the scenarios reflect the real-life treatment schemes of the two Biofactories and reflect the complexity of wastewater treatment in general. This assessment model will be useful for assessing a further alternative resource recovery or advanced treatment scenarios. Once the SLCA is complete, with flows across workers, value chain actors, local community and clients translating to impacts across working conditions, environmental responsibility, socio-cultural responsibility and governance, the multi-criteria decision-making matrices will be determined. The weighting factors for environmental, economic, and social criteria will allow for overall performance of the different scenarios to be assessed. These three matrices will provide the basis of the multi-objective decision involving environmental, economic, and social pillars.

CONCLUSIONS

Life Cycle Sustainability Assessment is a tool that quantifies sustainability impact indicators in a systemized way through creating data inventories for both LCA and LCC assessments. This study applied LCA and LCC to compare wastewater resource recovery scenarios across of increasing circularity and advanced nutrient management. Data requirements were extensive but addressed effectively with robust inventories being constructed, including infrastructure, materials, energy, transport, emissions, and products. These inputs and outputs were accounted for economically with CapEx, OpEx, Income and a calculation of NPV. Biofactory 1, showed better environmental performance due to the benefits of replacing energy consumption with cogeneration across all processes involved in the system. This also corresponded to cost savings that improved NPV even when CapEx increased due to increased infrastructure. Uncertainty analysis showed higher variability in data for Biofactory 2, however, within the range to still provide benefit to the environment. Uncertainty of costs must be explored. Upon interpretation of results, the weighting of environmental impact categories is of important consideration, where shadow prices should be explored more through SLCA methodologies to determine how decision makers values different aspects of environmental conversation. The closer the loop of resource recovery the lesser the impact as observed through the overarching contribution from biosolids management to impacts and the benefits sought through energy recovery. A sensitivity analysis will help establish where model assumptions influence final impacts, however, this model is detailed and robust. The final impacts serve as performance scores for a decision-making matrix where SLCA will provide weighting from human perception of sustainability criteria.

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