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LIFE-CYCLE ASSESSMENT OF FULL-SCALE MEMBRANE BIOREACTOR AND TERTIARY TREATMENT TECHNOLOGIES IN FRUIT PROCESSING INDUSTRY

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Abstract: Life-cycle assessment was conducted to quantitatively assess the total environmental benefits and impacts of typical wastewater treatment technologies in fruit processing sector, comparing the impacts of different treatment options, including impacts without on-site treatment. Results were carried out under the guideline of ISO 14040 and assessed using SimaPro software. Results showed that MBR combined with RO and UV caused the least damage to ecosystem, while dramatic eutrophication risk was brought by sewage released without treatment. Treating wastewater in municipal wastewater treatment plants (WWTP) could mitigate eutrophication effects, but would bring more damage to other impact categories such as climate change and human health compared with implementing on-site treatment systems.

1 INTRODUCTION

Fruit processing sector is one of the major water-consuming industries. Large amounts of wastewater are discharged by fruit processors containing high biological oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN) and total phosphorus (TP). If not properly treated, the receiving waters will be contaminated with the risk of eutrophication. Membrane bioreactor (MBR) is a feasible technology for treating fruit processing wastewater, and when combined with tertiary treatment technology such as reverse osmosis (RO), water reuse is possible. Effluent parameters are typically used as indicators to estimate the performance of treatment systems. To entirely identify the total environmental benefits and impacts of a treatment technology, cradle-to-grave life-cycle assessment (LCA) is usually conducted.

LCA is a methodology that quantitively assesses the environmental impacts of a product or system throughout its life-cycle (ISO 2006). It has been used as an environmental management tool in assessing wastewater treatment technologies. Many studies have been conducted on analyzing the environmental footprints of MBR systems (Tangsubkul et al. 2005, Ortiz et al. 2007, Hospido et al. 2012, Ioannou-Ttofa et al. 2016, Cashman et al. 2018). Most of these have focused on membrane systems in municipal WWTP and none has been conducted in fruit processing wastewater, where BOD level can be as ten times higher than municipal sewage. In addition, the objectives of previous studies were mainly to compare among different technology alternatives and not considering a no-treatment scenario.

The objective of this study is to use LCA as a tool to quantitatively analyze the total environmental impacts of wastewater treatment technologies in fruit processing sector, including impacts without on-site treatment. The quantitative metrics will show other users the benefits of being environmentally proactive, and provide scientific evidence for all stakeholders in the fruit processing sector on how to optimize their treatment options and make informed policy decisions.

2 METHODOLOGY

The LCA study was carried out under the guideline of ISO 14040, the international standard for life-cycle assessment. The software SimaPro 8.0.4.26 was applied as assessment tool and two methods were chosen for quantifying the life-cycle impact results, namely ReCiPe v1.11 and TRACI v2.1 (PRé 2018). Four scenarios were defined for the assessment: (1) discharge without treatment; (2) treatment in local WWTP; (3) MBR; (4) MBR + RO + UV. Life-cycle inventory of the membrane and UV systems was collected from the full-scale sewage treatment facility of an apple and juice producer located in the rural area of Durham Region, Ontario. A sensitivity analysis was performed by giving a ±20% disturbance to each phase, to determine the influence of data uncertainty on the results.

2.1 Goal and Scope

As previously mentioned, the aim of this LCA study is to quantitatively assess the environmental impacts of MBR and tertiary treatment technologies in fruit processing sector from raw material acquisition through production, construction, transportation, operation and sludge disposal, comparing with the impacts of direct discharge as well as treatment in local WWTP. The functional unit of this study was set as “1 m^3 of wastewater treated/discharged”. The system boundaries comprise raw material extraction and processing, transportation, construction, operation and maintenance. The end-of-life phase of membrane systems was excluded since it has been found to be negligible compared to other phases (Emmerson et al. 1995).

2.2 Life-cycle Inventory (LCI)

Data required in this study was collected and estimated based on the full-scale treatment facility, professional databases and previous literatures. Sewage in direct discharge scenario was assumed to be discharged into the nearest lake of the industry by underground pipeline. Prior to discharge, a steel water tank was used in the facility for temporal storage. For performing an impact assessment in SimaPro, the amounts of product output, material input and emissions generated from unit processes have to be incorporated in the software. No-treatment scenario entailed wastewater discharge into the nearby lake, so that pipeline material and soil excavation for subsurface pipeline were accounted in the inventory calculation. For the scenario of treating sewage in local WWTP, it was assumed to be treated by primary screening and stored on-site, then transported to the nearest WWTP by truck for further treatment. Here, the centralized WWTP infrastructure was excluded in the system boundary, however, energy cost for treatment was considered. In the membrane and tertiary treatment systems, wastewater goes through primary screening, anaerobic/anoxic chamber, two ultra-filtration (UF) membrane tanks, reverse osmosis (RO) and UV disinfection. The electricity mix of Ontario was collected from the annual energy output report of 2018 supplied by the Independent Electricity System Operator (IESO). Sludge generated from membrane systems was hauled weekly to the water pollution control plant serving the target area, where sludge is 100% incinerated.

2.3 Life-cycle Impact Assessment (LCIA)

ReCiPe Midpoint (H) V1.11 / World Recipe H and TRACI 2.1 V1.02 / Canada 2005 were selected as LCIA methods that further quantify the LCI results into different impact categories (PRé 2018). The site-specific models were chosen as project was developed in Canada. Both methods provide quantified metrics at midpoint level with relatively higher accuracies for a timeframe of 100 years. LCI results in ReCiPe were classified into 18 impact categories, while it resulted in 10 categories using TRACI (PRé 2018).

3 RESULTS AND DISCUSSION

For all scenarios, complete life-cycle inventories were developed, with two methods applied for impact assessment and result comparison. Among all impact categories available in the two methods, eutrophication, global warming, ozone depletion, ecotoxicity, human health and photochemical oxidant formation were emphasized as environmental hot spots as common practice.

3.1 LCIA and Sensitivity Analysis

Impacts caused by the four scenarios were specified using the two methods. Figure 1 demonstrates the comparison of quantified impacts by showing the ratio of each scenario to the one with greatest damage, with negative values representing net profits to the corresponding category.

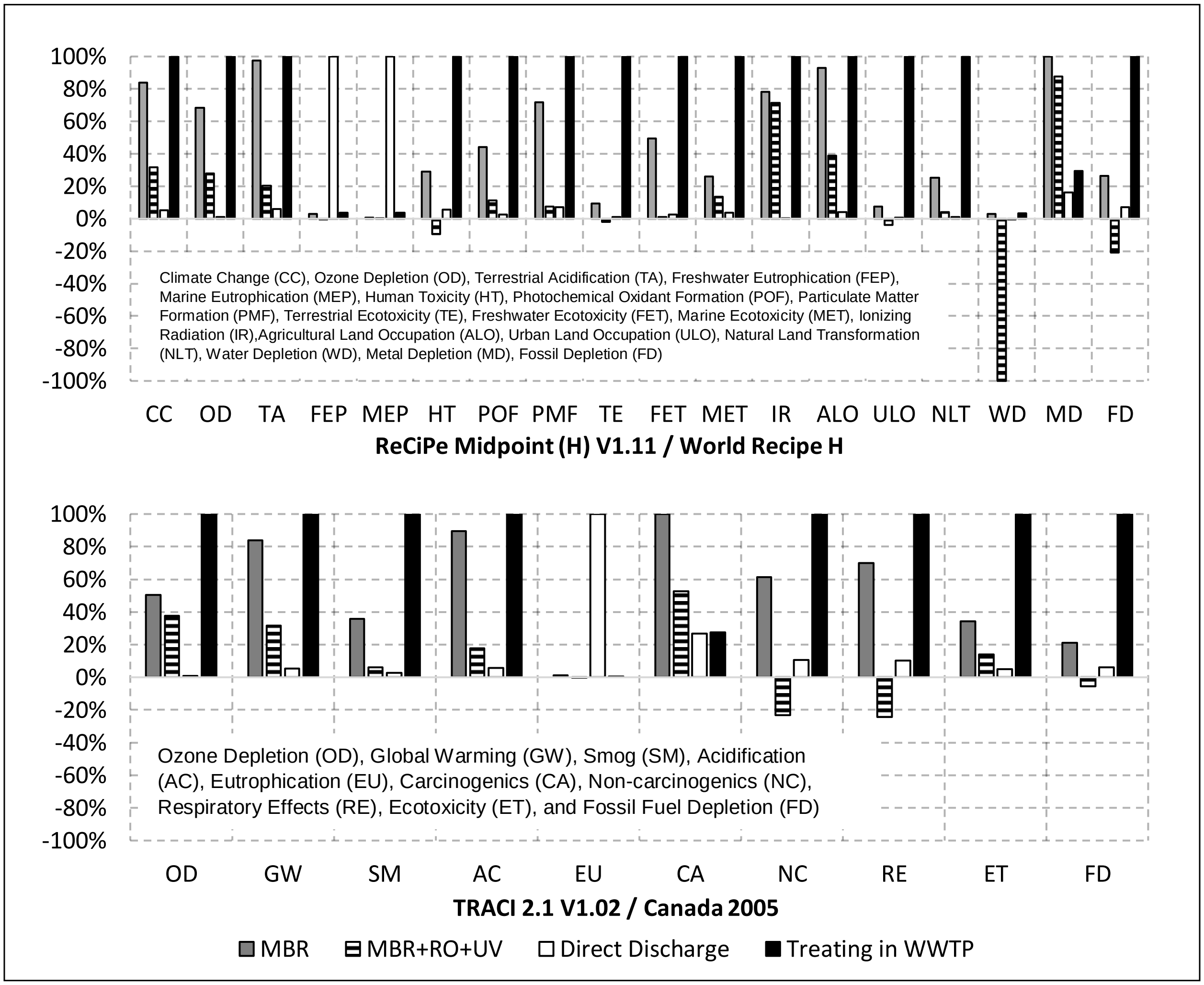

Figure 1: Comparison Results of Characterized Impacts (ReCiPe and TRACI)

In general, MBR combined with tertiary treatment processes was identified as the best scenario according to the results of both TRACI and ReCiPe since it had the lowest impacts in most categories. Some net environmental offsets were also revealed due to the equal amount of water saved from water reuse. Compared with direct discharge into water body, wastewater treatment using the combination of MBR+RO+UV could avoid 0.7 kg CO_2 equivalent per one m^3 wastewater, with over 65% mitigation than no-treatment scenario. Meanwhile, eutrophication risk was reduced to a negligible level because of the high treatment efficiency of RO. Slight benefits were found to the category of ecotoxicity. Extraction and processing of raw materials in the system turned out to be the most important process contributing around 50% to climate change, 60% to ozone depletion, and more than 90% to other categories. Although electricity consumption brought negative effects, impacts of operation phase generally showed net benefits due to the water saved by recycling. Discharge into lake without treatment had enormous eutrophication impact compared to other scenarios, with 0.12 kg N equivalent and 0.01 kg P equivalent predicted in ReCiPe and 0.58 kg N equivalent in TRACI. Nevertheless, minor impacts were noticed on other categories such as global warming and ecotoxicity, which is justifiable, as few materials and energy are required during direct discharge process. Materials for pipeline construction were identified as major contributor to most impact categories except eutrophication. Construction activities including excavation and material transportation were not significant. Eutrophication could be effectively mitigated by treating wastewater using MBR or sending wastewater to WWTP instead of direct discharge. However, treating wastewater in municipal WWTP had most significant impacts in all other categories. Sewage transportation and sewage plant operation was the main influence factors, as transportation contributed more than 90% to ecotoxicity, human toxicity and smog, while more than half of the damage to ozone depletion and eutrophication was caused by operation. Compared with sending to municipal WWTP, MBR was proved to be a most environmental friendly approach with 15, 50, 60, and 65% impact reduction in climate change, ozone depletion, photochemical oxidant formation and ecotoxicity, respectively. Significant discrepancy between results obtained from TRACI and ReCiPe was found in human toxicity impact. In ReCiPe, human toxicity impact of MBR was only 30% of that treating in municipal WWTP, whereas in TRACI, it was 3 times over the latter scenario calculated as carcinogenics impact. This was mainly due to the distinctions of two methods in classification considering human health (PRé 2018, Bare 2012). Sensitivity analysis results showed that, with a disturbance of ±20%, changes greater than 40% were only found in the impacts of fossil fuel depletion within maintenance and material acquisition phases in membrane systems. In all other categorise, the changes of results were less than 20%, which means influence of data uncertainties were acceptable, especially for the most important categories assessed.

3.2 Discussion and Limitations

LCA was innovatively implemented to quantify the environmental impacts of typical wastewater treatment technologies in fruit processing industry. The study is also unique as it compares impacts of treatment systems with no-treatment scenario. This approach was proved to be feasible, and could be a scientific evidence for all stakeholders in the fruit processing sector on how to optimize their treatment options and make informed policy decisions. The limitations of this study were mainly caused by deficiency of data sources, especially for the scenarios of direct discharge and treating sewage in municipal WWTP, which were built on the basis of assumptions and average secondary data. Environmental footprints of different sludge treatment options should be considered to eliminate the uncertainties with respect to such cases.

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