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INTEGRATED LCA-LCC ANALYSIS FOR METAL REMOVAL FROM WASTEWATERS USING MICROORGANISMS

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Abstract

The persistance of heavy metals in wastewaters and the environment has determined the scientific community to find innovative and sustainable methods and materials for their removal. In this pursuit, microorganisms have gained increasing popularity due to their diversity, resilience to extreme environmental conditions, complex structure and chemical mechanisms. Most of all, the excellent performance of microbial biomass in the uptake of metal ions is of high interest for the development of more sustainable remediation alternatives to conventional treatment methods. The most applied methodology for sustainability analysis is the Life cycle assessment (LCA) for the environmental component and Life cycle costing (LCC) for the economic one. Applied together these two frameworks can offer a cost-effective and environmentally-friendly way to use microorganisms for wastewater remediation. Thus, this paper aims to look into the LCA and LCC methodologies and the way these can be used in an integrated way to evaluate the metal removal process facilitated by microorganisms.

***Key words**: heavy metals, integrated LCA-LCC, microorganisms, sustainability, wastewater treatment.*

INTRODUCTION

The use of living or dead biomass for the uptake of heavy metals contributes to the development of the bioeconomy and circular economy and the replacement of the synthetic conventional materials used in industry, including wastewater treatment area (Hlihor et al., 2021). Although the performance of microorganisms in the removal of heavy metals from wastewaters has been successfully and extensively demonstrated, the sustainability of the microbial remediation processes has received far less attention from the scientific community in both batch and column studies (Filote et al., 2021). The common standardized methodology established for the analysis of the sustainability of processes and products is the Life Cycle Analysis. The framework attributed to the environmental component is the Life Cycle Assessment (LCA or E-LCA). There is also one assigned to the evaluation of the economic impact, named Life cycle costing (LCC) and one for the analysis of the social dimension of the sustainability concept, social life cycle assessment (S-LCA) (Furness et al., 2021). All these three methodologies have been rarely applied together in scientific studies so far. The integrated approach applying LCA together with LCC is more common though in research. The integrated approach of the LCA and LCC methodologies has already been applied in several areas such as the compressed air energy storage system of a photovoltaic power plant (Petrillo et al., 2016), vineyard production (Falcone et al., 2015), construction industry (Alshamrani, 2021) and also wastewater treatment (Harris et al., 2021). To our knowledge, the LCA-LCC integrated approach has not been applied yet though in case of heavy metals removal from wastewaters using microorganisms. Therefore, the current study aims to provide an overview of the LCA-LCC integrated approach and how it can be applied in the sustainability evaluation of wastewater remediation processes carried out using microbial biomass.

LIFE CYCLE ASSESSMENT (LCA)

The Life Cycle Assessment (LCA) methodology is based on the conversion of emissions and consumed materials into environmental impact values and includes several established steps (Figure 1): the goal and scope definition, inventory analysis, impact assessment and interpretation (Kamble et al., 2019). In terms of damage pathways, the LCA methodology can be applied on several levels: the midpoint level which focuses on a medium time-frame, endpoint which considers the longest time frame and individualist using the shortest time frame (Hoogmartens et al., 2014). Before the life cycle analysis is carried out it is important that the system boundaries of the microbial-based remediation of wastewaters are defined. This includes setting the necessary sequential processes and identifying the optimum parameters for each step.

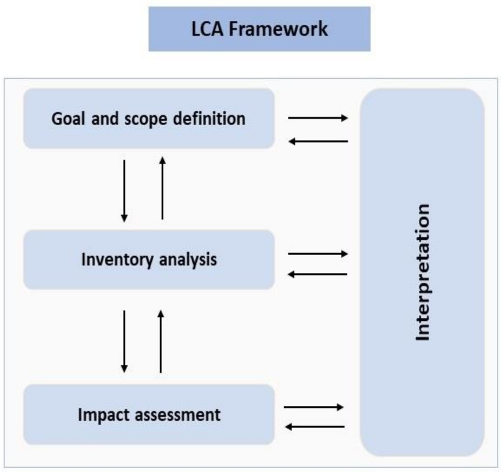

Figure 1. Life cycle assessment (LCA) framework.

The optimization of the microbial bioremediation processes is key for obtaining maximum performances with minimum consumed resources, including financial ones. The number of LCA studies carried out for the environmental impact analysis is scarce in case of both heavy metals removal from wastewaters using microorganisms as adsorbents as well as in case of the application of conventional adsorbents (Filote et al., 2021). Since its increase in popularity and application in the 1990s, LCA methodology has been applied through various methods (Corominas et al., 2013). Nowadays, the most common ones are CML2016 and ReCiPe2016.

LIFE CYCLE COSTING (LCC)

Similar to LCA methodology, LCC can be applied for the analysis of the complete life cycle of the metal removal through bioremediation process, including stages starting with the preparation of the biosorbent or biofilm containing microorganisms down to the disposal of the residual microbial biomass (Simion et al., 2021). The LCC methodology includes several sub-methodologies: societal LCC (sLCC), financial LCC (fLCC), environmental LCC (eLCC), and full environmental LCC (fLCC) (Hoogmartens et al., 2014). In case of metal uptake from wastewaters by microorganisms, similar with LCA, the scientific literature presents few research endeavours. A few studies have been carried out to analyse the environmental and economic impact of using microorganisms in wastewater treatment, for the removal of other pollutants than heavy metals. Furthermore, a strong attention was given to the cultivation of microorganisms for the generation of biofuels and other value-added compounds (Parsons et al., 2018; Resurreccion et al., 2012).

APPLICATION OF INTEGRATED LCA-LCC IN WASTEWATER TREATMENT USING MICROORGANISMS

Due to the fact that they cannot be fully removed in the primary and secondary wastewater treatment phases, metals are necessary to be removed in a tertiary treatment step (Rosca et al., 2021). This is however a challenge for most developing countries, since wastewater treatment facilities are based only on primary and secondary treatment (Parra-Saldivar et al., 2020). To ensure sustainability on both the environmental and the economic dimensions, the integration of LCA and LCC results is required. Most of the research conducted so far has applied the two types of evaluation separately. In order to upscale the metal removal process using microorganisms, an integrated approach is advisable. The integrated approach is thus very important for developing countries where environmental savings must be ensured with minimum resources.

In case of wastewater treatment, associated costs usually include equipment investments, consumables, chemicals, maintenance costs, data source costs and salaries (Rosca et al., 2021). A summary of the environmental impacts and the costs based on each phase of the microbial-based bioremediation processses is included in Table 1.

Table 1. The environmental impact and the costs associated with each stage of the bioremediation processes of metal loaded wastewaters using microorganisms.

Microbial-based remediation processes (Life cycle phase)	**Environmental impact**	**Economic impact**
Active biomass preparation	Transport Energy Heating	Transport costs Energy costs Heating costs Nutrients cost
Biomass inactivation	Energy	Energy cost
Biosorption	Energy Wastewater loaded with residual metal ions	Energy cost Equipment investment and maintenance costs Environmental impact cost
Biosorbent disposal	Transport Energy Heating	Transport costs Energy costs Heating costs Environmental impact cost

In order to obtain a thorough perspective on the life cycle impact, be it environmental or economic, it is important to apply the integrated LCA and LCC in all main scale-up stages: lab-scale, pilot plant and industrial scale.

Furthermore, to obtain a comprehensive and realistic perspective through the application of integrated LCA-LCC, the mandatory LCI (Life cycle inventory) step for the quantification of inputs and outputs should be carefully carried out before the data analysis (Innocenzi et al., 2021). The integrated application of LCA and LCC methodologies for the evaluation of metal removal from wastewaters using microorganisms has numerous benefits: a larger perspective on the impact of the remediation processes, environmental savings, reduction of energy and materials consumption, financial savings. Environmental savings are doubled by economic efficiency. Thus, a more sustainable process, be it biosorption or bioaccumulation, is obtained.

All of these advantages are even more important at pilot and industrial scale where due to the large quantities of treated wastewater, the environmental impact and the associated costs increase significantly. It is very important to reach a higher number of studies with integrated LCA-LCC results for heavy metals removal using microorganisms at large scale since additional parameters are involved in pilot and industrial treatment facilities in comparison to the ones at lab-scale and values for the common ones can still differ to some extent.

CONCLUSIONS

Microorganisms are complex living systems with insufficiently explored potential in metal removal from wastewaters at industrial scale. The advantages of their use have been highlighted though in various studies through lab-scale research. There are thus many studies available in the scientific literature in this sense. The sustainability of the bioremediation processes using microorganisms has been very briefly considered so far. The current paper therefore reviewed the life cycle analysis methodology applied for the context of metal removal from wastewaters using microorganisms, with a focus on the integrated LCA-LCC approach.

This unexplored area of research is very important for the development of a more sustainable alternative to the conventional treatment methods, from an environmental as well as economic point of view.

To fulfill this, we have discussed also about the three stages of scale-up and how the life cycle analysis fits into the development process. Sustainability analysis of metal removal from wastewaters using microorganisms contributes to the development of the bioeconomy. Extensive research is necessary to fill the gap.

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