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SUSTAINABILITY ASSESSMENT OF PHYTOREMEDIATION-DERIVED BIOMASS VALORIZATION INTO BIOENERGY

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ABSTRACT: This study presents the results of a comparative environmental and economic Life Cycle Assessment (LCA) of biomass-to-bioenergy valorization scenarios integrated into the phytoremediation of dredged sediment using perennial reed *Arundo Donax*. A mathematical baseline was developed based on empirical data as a prerequisite for parametric life cycle inventory models for both economic and environmental assessments. The baseline enabled the estimation of bioenergy yields in various forms: solid, liquid, gas, and the eventual generation of green electricity that could potentially be obtained from biomass valorization per m³ of sediment during phytoremediation. The models were applied to assess the environmental and economic impacts of phytoremediation integrated into biomass valorization alongside conducting sensitivity and uncertainty analysis. Inferred from the comparative LCAs, it was concluded that the valorization of biomass, derived from phytoremediation, into bioenergy could partially or totally compensate for the environmental and economic impacts of phytoremediation. The model developed in this study is a general model applicable to different types of plants and phytoremediation scenarios along with biomass to bioenergy valorization schemes.

Keywords: biomass, bioenergy, life cycle assessment (LCA), sustainability

1 INTRODUCTION

Biomass, the only renewable resource of carbon, could be converted into solid, liquid, and gaseous fuels through thermochemical and biochemical pathways (Saikia et al., 2015) as a substitute for fossil fuels-based energy sources. Phytoremediation has been identified as a cost-effective, eco-friendly, solar-driven and in-situ technology for bio-remediation of contaminated sediment (Zaghloul, 2020). Integrating biomass valorization into the phytoremediation of chloride-rich sediment, as a common pollutant in all marine dredged sediments, could synergize biomass production and carbon sequestration with phytoremediation. This integration could offer social, economic, and environmental benefits during the whole period of the remediation process (Nascimento et al., 2021). The objective of this study was to evaluate the environmental sustainability and economic viability of sediment phytoremediation by *A. donax* combined with biomass valorization. Life cycle assessment (LCA) is the most popular analytical framework for comprehensively assessing the environmental impacts and identifying the hotspots associated with the entire life cycle of a product or process (Soleimani et al., 2023). To perform a comparative life cycle assessment, a mathematical model was developed to estimate the yield of biomass to bioenergy valorization chain including the estimation of biomass yield, bioenergy yield from valorization schemes and green electricity yield per m³ of sediment. The mathematical model was applied to develop life cycle inventories (LCIs) for further economic and environmental life cycle assessments.

2 MATERIAL AND METHOD

2.1 Biomass valorization to bioenergy

As a prerequisite for developing life cycle inventories for harmonized economic and environmental life cycle assessments, a mathematical model was developed to

estimate biomass yield, bioenergy yield, and green electricity generation (Soleimani et al., 2023).

2.1.1 Biomass yield

The quantity of dry biomass per one cubic meter of sediment (kg/m³) per harvest was calculated from equation 1.

$$dm = ((PD * (SR/100) * FB * (1 - MP/100)) / H) \quad (1)$$

In which dm is the average yield (kg/m³) of dry mass expecting from each m³ of sediment per harvest, PD is the density of plant cultivation per m², SR is the survival rate (%) of the plants, FB is the average quantity (kg) of fresh biomass per plant per harvest, MP is the percentage of the moisture content (%) in fresh biomass, H is the depth (m) of sediment (soil).

2.1.2 Biomass valorization to bioenergy

The potential energy theoretically obtained from the biomass harvested from phytoremediation of 1m³ of sediment was calculated from equation 2.

$$BE = dm * HCV * f \quad (2)$$

In which BE is the average of potential bioenergy from phytoremediation of one m³ of sediment per year, dm is the average yield (kg/m³) of dry mass expecting from each m³ of sediment per harvest, HCV is the heat calorific mean value (kJ/kg dry biomass), and f is the frequency of harvest per year.

2.1.3 Bioenergy yield estimation

The bioenergy yield in the forms of gas, liquid, and solid biofuels from the biomass of *A. donax*, were obtained from equations 3, 4, 5 and 6.

$$\text{Solid combustible yield (kg)} = DM \quad (3)$$

$$\text{Bioethanol yield (liter)} = DM * BETY \quad (4)$$

$$\text{Biomethane yield (Nm}^3\text{)} = VS * BMY \quad (5)$$

$$\text{Biogas yield (Nm}^3\text{)} = \text{VS} * \text{BGY} \quad (6)$$

In which DM is dry biomass (kg) of *A. donax*, BETY is bioethanol yield (litre) per kg dry biomass, VS is volatile solid (kg) of biomass, BMY is biomethane yield (Nm³) per kg volatile solid of *A. donax*, and BGY is biogas yield (Nm³) per kg volatile solid of *A. donax*.

2.1.4 Electricity yield estimation

The quantity of renewable electricity from valorization bioenergy schemes, based on kilowatt hour (kWh), was obtained from equation 7:

$$\text{Electricity (kWh)} = \text{HCV} * \text{BEY} * \text{PPE} / 100 * 1 / 3600 \quad (7)$$

In which HCV is heat calorific mean value on kJ/kg for combustible solid, kJ/l for bioethanol, kJ/Nm³ for biomethane and biogas, BEY is bioenergy yield in forms of solid (kg), liquid (l) or gas (Nm³), PPE is efficiency of bioenergy power plant in percentage (%). Since every hour is 3600 seconds, the quantity is divided into 3600 to convert kJ to kWh.

2.2 Phytoremediation-derived biomass from *A. donax*

A laboratory-based experiment was integrated into economic and environmental life cycle assessment to offer a holistic approach to assess the feasibility and sustainability of biomass valorization combined with phytoremediation. The feasibility of phytoremediation of contaminated chloride-rich sediment by *A. donax* and its bioaccumulation performance was assessed through cultivation, growing and treatment trials. The mean deposition rate of chloride in aerial parts of *A. donax* cultivated in nontreated sediment, 9940 mg/kg dry biomass, was retained as the chloride bioaccumulation performance of *A. donax*.

2.3 Environmental assessment

The life cycle inventories (LCIs) of the biomass valorization scenarios were developed in openLCA based on the inventories from the database ecoinvent v.3.5 for further LCA and sensitivity and uncertainty analysis. All the processes in the biomass valorization scenarios and phytoremediation were considered in the cradle-to-gate system boundary. The ReCiPe midpoint (H), was applied to assess environmental impacts comprises 18 categories at the midpoint level. One cubic meter (1m³) of sediment was adopted as the functional unit in this study. In order to keep comparability of results, consistency was sustained in all parameters and inventories.

2.4 Cost and revenue evaluation

Since economic evaluation is an essential part of sustainability assessment, a complementary Life Cycle Cost Analysis was required to be performed for biomass valorization chain combined with the phytoremediation. Accordingly, a Cost Revenue Analysis was conducted in Excel based on the equations of 1 to 7, the literature background and the market prices of raw materials, energy, transportation, labor, equipment, and maintenance in France to provide insight into the viability of scenarios.

3 RESULTS AND DISCUSSION

3.1 Comparative economic and environmental impacts assessment

The environmental and economic impacts of the scenarios, normalized to the corresponding of phytoremediation are integrated into a single score and are superimposed in a graph illustrated in Fig.1.

The visual comparison of economic and environmental impacts, illustrated that biomass valorization could result in negative overall environmental impacts and partially compensate the costs of phytoremediation, offering a more sustainable remediation scenario. The decrease in the environmental impacts of phytoremediation due to integration into biomass-to-bioenergy valorization can be attributed to bioenergy production from biomass as a substitute for fossil fuels. Since the environmental and economic profits of the solid digestate from the anaerobic digestion, which is nutrient-rich to be a substitute for chemical fertilizers, are not considered in this study, additional environmental and economic benefits would be expected from biomass valorization.

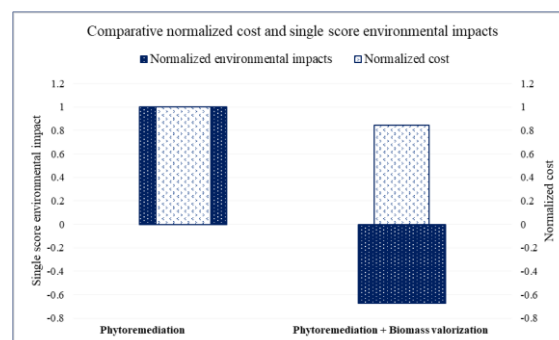


Fig. 1. Singles score environmental impacts and cost of scenarios, normalized to corresponding of phytoremediation.

4 CONCLUSIONS

Inferred from the comparative economic and environmental assessments, integrating biomass-to-bioenergy valorization chain into sediment phytoremediation would offer superior sustainability in terms of economy and environment. Integrating biomass valorization into phytoremediation may offer a carbon negative scenario thanks to carbon sequestration and avoiding fossil fuels, partially compensate cost of phytoremediation as well. Due to importance of the depth of plant rooting system in the efficiency of phytoremediation, a volume-based functional unit is more applicable than an area-based functional unit in LCAs of soil phytoremediation.

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