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Environmental and economic performance of chemical and biological processes for treating petroleum hydrocarbon-contaminated soil: An experimental study

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ABSTRACT

Over the past ten years, researchers have applied various approaches to treat petroleum hydrocarbon-contaminated soil and assess its performance based on removal efficiencies and not on its environmental and economic impacts. In this study, the environmental and economic performances of the operational stages of electro-Fenton and bio-slurry technologies are investigated and compared using a life cycle assessment to assess the environmental and economic performances in treating petroleum hydrocarbon-polluted soil. The data used in this study were collected from primary and secondary sources, and the potential 18 environmental impacts were calculated using the ReCiPe 2016 characterization approach in SimaPro 9.5 software. The electro-Fenton process is the most environmentally friendly method, identifying chemicals and energy as major contributors to the environmental impact. Energy is the main hotspot, accounting for 90 % of the total environmental impact. Energy and biosurfactants are the main environmental hotspots in bioslurry processes, accounting for 60 % of the total. The bioslurry process has the highest environmental impact owing to the use of biosurfactants and electricity consumption. The bioslurry process is the most cost-effective, with a life-cycle cost of 7.13$/kg, while the electro-Fenton technique is the most expensive (661.25$/kg) owing to the use of BDD as the electrode, costing 323$/kg.

1. Introduction

The rapid growth of municipal, agricultural and industrial activities coupled with the global population growth rate, has led to a high demand for petroleum production, with the global demand expected to reach 100.90 million barrels per day [1]. Petroleum industrial activities, such as transportation, drilling, storage, exploration, refining and processing, are major sources of petroleum hydrocarbon spillage and terrestrial oil pollution. An estimated 0.6 Mt of crude oil leaks into the environment annually, leading to soil pollution, nitrogen deficits, and the depletion of oxygen reserves [2]. Petroleum hydrocarbons (PHC) in soil can enter the food chain and seriously threaten the health of animals and humans [3]. Therefore, a cost-effective, eco-friendly soil remediation approach is required. Bioremediation technology, such as bioslurry, is a traditional approach that is effective and environmentally friendly and has been proven to remove many pollutants, especially petroleum compounds [4]. However, the bioavailability of PHC to microbes remains challenging. Hence, adding a stimulant, such as a biosurfactant, or integrating it with another technology, such as an advanced oxidation process, can enhance the bioavailability of a pollutant, thereby increasing its degradation [5].

Electro-Fenton processes have emerged as the most appealing advanced oxidation processes because of their fast reaction times, high efficiencies, and wide range of targeted pollutant degradation [6]. The electro-Fenton technique has become increasingly popular for the remediation of organic contaminants [7]. However, despite its higher

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removal efficiency, the Fenton process uses H_2O_2 and Fe^{2+} as catalysts, making it expensive in large-scale applications. Furthermore, Fe^{2+} consumption results in secondary contamination and needs further treatment [8]. Boron-doped diamond (BDD) electrodes can overcome these limitations by regenerating ferrous ions and producing hydrogen peroxide, thereby preventing secondary pollution [9,10]. BDD electrodes exhibit low background currents, long-term responses, chemical stability, and high corrosion resistance, making them suitable for electro-Fenton processes [11]. Furthermore, including biosurfactant-assisted biological processes and a BDD anode in the electro-Fenton process would make the enhanced process an effective and eco-friendly alternative [11]. However, there is a lack of knowledge about the economic and environmental impacts of operating parameters, including chemical addition, material and energy consumption, gaseous emissions, material, and solid waste production, and the remaining transformation products [12]. A life-cycle approach should be considered to incorporate all the impacts related to the production of biosurfactants and energy consumption, as well as the chemicals utilized in the treatment, in addition to the efficiency of the processes themselves, to obtain a valid impact assessment of the treatment process [13].

Life cycle assessment (LCA) is a widely used tool for environmental assessment, focusing on technical feasibility and environmental sustainability. It has been proven effective in various applications such as waste treatment options [14]. LCA has evolved over the past three decades, becoming more systematic and robust for identifying and quantifying the potential environmental impacts associated with a product's life cycle [15]. LCA is of paramount importance in the domains of product and process design, optimization, and selection [16]. Organizations can effectively ascertain the environmental implications of their operational decisions by integrating LCA with simulation methodologies and design tools [17]. LCA is widely recognized as a highly effective instrument for conducting environmental assessments; enhancing the quality of materials, fuels, and energy sources; optimizing production technologies; evaluating waste treatment scenarios; and formulating plans to promote responsible and sustainable practices in the production, consumption, and management of materials, by-products, and waste [18,19]. Additionally, LCA attempts to identify potential areas for improvement to minimize environmental impact.

LCA has been employed to examine the potential consequences of soil remediation treatments on soils contaminated with diverse organic contaminants, such as petroleum hydrocarbons [11]. These studies provide evidence that LCA is a viable tool for management purposes to evaluate the environmental impacts of different techniques on soil remediation for various contaminants [20,21]. However, comprehensive environmental and economic studies that directly assess the impact of electro-Fenton and bioslurry treatment methods on petroleum hydrocarbon pollution are still lacking. To the best of our knowledge, this is the first comparative environmental and economic LCA study of bioslurry and electro Fenton for the remediation of soil polluted with petroleum hydrocarbons using experimental data as in put in LCA.

Hence, the main objective of this study was to apply LCA to identify environmental hotspots and compare the environmental impacts of electro-Fenton and bioslurry remediation processes using experimental data as input in the LCA. A comprehensive economic analysis was conducted to assess the cost of the technology. The results are expected to help develop an eco-friendly technique for remediating soil polluted with petroleum hydrocarbons, meeting international law limits in future engineering applications.

2. Materials and methods

The methodology employed in this study for conducting a Life Cycle Assessment (LCA) was derived from the ISO 14040 and ISO 14044 standards, as outlined by Spreafico et al. [22]. This research encompasses four fundamental stages: goal and scope definition, determination of inventory for each process, assessment of impacts, and interpretation of the resulting impacts. This section provides a description of the initial two stages and the methodologies employed, while the outcomes section presents and discusses impact assessment and interpretation. The LCA model and impact analysis were constructed using the SimaPro 9.5. Furthermore, the ReCiPe 2016 v1.1 midpoint methodology, namely the Hierarchist variant, was chosen as the preferred option [11].

2.1. Goal and scope

The objective of this study is to conduct a comparative analysis of the two different approaches employed for petroleum hydrocarbon pollution. These methods consider bioslurry and electro-Fenton processes. These approaches were selected based on their efficacy in remediating soil contaminated with petroleum hydrocarbons on a laboratory scale. However, additional investigations, such as environmental and economic evaluations, are necessary for pilot-scale applications [11].

The environmental impacts were assessed and compared using a laboratory-scale approach, focusing on the functional unit (FU) for three different soil treatment methods: bioslurry (100 g, 24.5 kWh) and electro-Fenton (100 g, 12 kWh). These remediation methods were evaluated for their effectiveness in treating soil contaminated with an initial total petroleum hydrocarbon concentration of 4500 mg/kg. Standardization of functional units (FUs) for soil remediation is currently lacking, but they are commonly employed for comparison and evaluation. Correlation factors for energy capacity (in kWh) and weight (in kg) were provided to calculate the impacts [11]. Table 1 lists the chemical quantities, energy inputs, and operational conditions used in our previous experiments.

Table 1
Experimental conditions used for Electro Fenton and bioslurry treatment options.

Reference	Types of reaction	Working conditions
[5]	Biotreatment	275 mL of distilled water and 100 g of soil (soil-to-water ratio of 1:5) should be mixed and aerated at 10 mL/minute while stirring at 200 revolutions per minute. Based on PHCs loading as a C measure (Smith et al. 2015), nutrients 1.5 g KNO3 and 0.1 g (NH4)2HPO4 were added at the outset of biotreatment to achieve C: N:P molar ratio−100:10:1; additionally, biosurfactant was added to 275 mL to boost the bioavailability of PHCs (Chebbi et al., 2021). The mesocosm experiment demonstrated a significant decrease of 72.8 % in total petroleum hydrocarbons (TPHs) over a period of 20 days following the introduction of biosurfactant, nutrients, and activated sludge.
[11]	Electro-Fenton (EF)	1-litre capacity glass cylinder with a removable, adjustable lid. A direct current of 2 V is run between a graphite felt cathode (width = 5 cm, length = 6 cm) and a BDD plate anode (length = 6 cm, width = 4 cm). These electrodes have a 2-cm separation (Xu et al. (2015) To Avoid high salinity, 100 mg /L of Na_2SO_4 as a supporting electrolyte was added, mixed with 100 g of PHCs -PHCs-contaminated soil (dry weight) in 500 mL distilled water. Sulfuric acid was added to lower the slurry pH and was adjusted to pH 3. Reactors were continuously stirred at 300 revolutions per minute to prevent concentration gradients—ferric sulfate 0.1 mM was used as a catalyst (Feng et al., 2014). Aeration of the solution was initiated 5 min before electrolysis, and 1 L/minute compressed air was bubbled by a solution to saturate it in O_2 while stirring reaction media. The research findings indicate that a significant reduction of 70.6 % in TPHs was successfully accomplished within 12 h.

Fig. 1A and B illustrate the system boundary of the present analysis, encompassing the bioslurry, and electro-Fenton processes. The figure also includes pertinent input data, such as power usage, as well as output data, such as sludge waste. According to Yao et al., the operating stage of soil recovery and treatment possibilities is not influenced by the end-of-life stage, and therefore, it is not considered in the analysis. The inclusion of biosurfactants in both treatments is justified by their significant influence on the breakdown of petroleum hydrocarbons and the environmental efficacy of the treatment methods.

2.2. Life cycle inventory

The environmental impact of electro-Fenton and bioslurry remediation processes were assessed using the primary data obtained from laboratory studies [1]. This encompasses experimental procedures aimed at biosurfactant production [13] The inventory was linked to the Ecoinvent v3.6 database (allocation, cut-off by classification), which provides comprehensive background information on materials and energy sources. A full summary of the inputs and outputs utilized in this study is described in supplementary file S1, S2 and S3.

2.3. Life cycle impact assessment

The environmental implications of the two technologies were calculated using SimaPro 9.5, the LCIA model, and Hierarchist version of ReCiPe 2016 v1.1 midpoint. SimaPro 9.5 assesses the environmental impacts of soil and soil bio(re)mediation across a range of 18 categories. These categories include terrestrial ecotoxicity, water consumption, human non-carcinogenic toxicity, carcinogenic toxicity to humans, scarcity of fossil and mineral resources, marine eutrophication, global warming potential, formation of fine particulate matter, land use, marine eutrophication, stratospheric ozone depletion, non-carcinogenic toxicity to humans, ionizing radiation, marine ecotoxicity, human health, freshwater ecotoxicity, formation of fine particulate matter, ozone formation, terrestrial ecotoxicity, and their impacts on terrestrial ecosystems. The assessment included various processes and materials, and the impacts were standardized to represent their relative magnitudes and relevance. Normalization factors were selected based on the environmental consequences of Ecoinvent.

2.4. Cost estimation

The overall costs associated with each technique were determined by considering the same functional unit, which was defined as 1 kg of treated soil. These costs encompassed all components included in the life cycle assessment (LCA) inventory. The overall cost includes amortization charges (ACs) and operating costs (OCs). The components of ACs encompass the expenses associated with graphite felt, biosurfactant, and

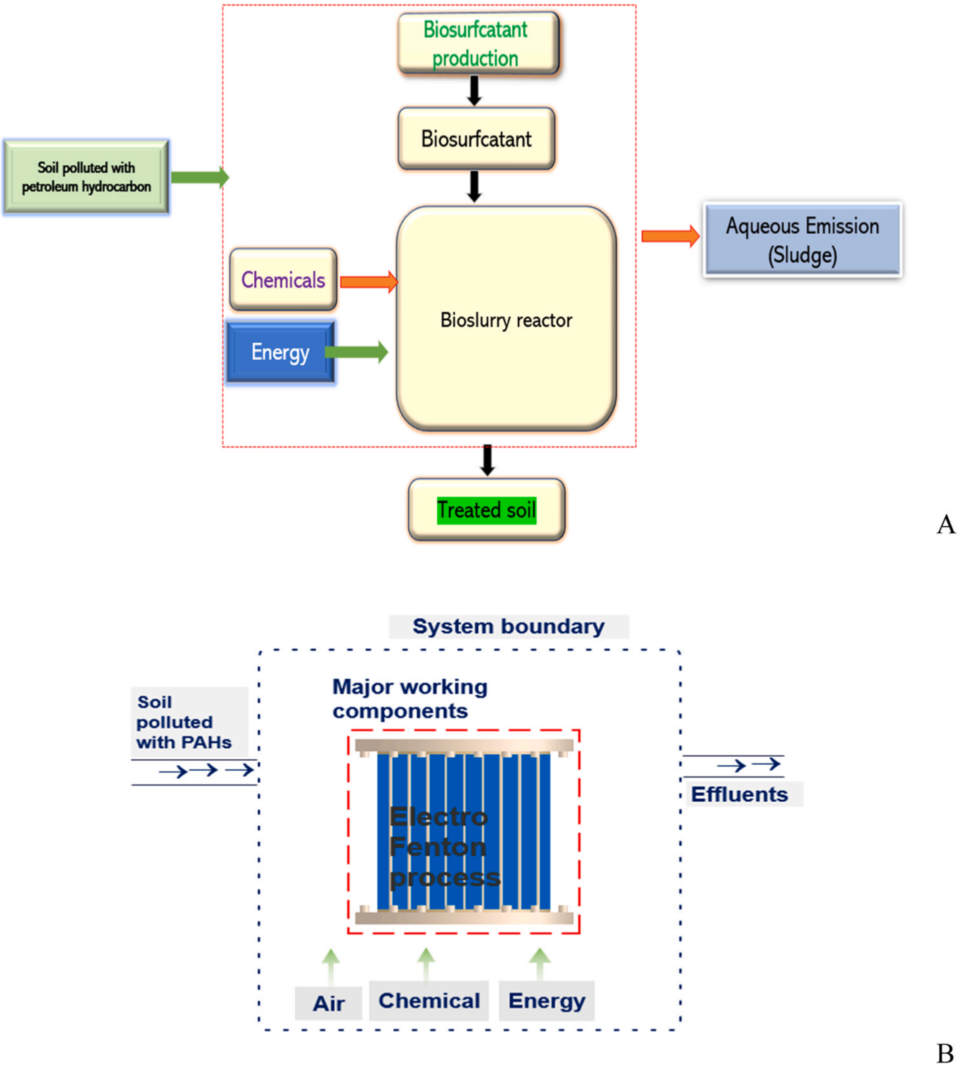

Fig. 1. represents the system boundaries for three distinct processes: Bioslurry system (A), and electro-Fenton process (B).

boron-doped diamond. Operating costs (OCs) encompass the expenses associated with material and energy use. The average values for the cost of all materials were obtained from the website www.sigmaaldrich.com. Table 4 presents a comprehensive depiction of the costs and calculations. The annual amortization schedules were adjusted using a consistent interest rate of 6 %, as outlined in Equation (1) [14]

$$ACs = iACs\left(\frac{(1+i)^{L}i}{(1+i)^{L}-1}\right)$$

In this context, "iACs" refers to the present value of an item, where "i" represents the continuous interest rate. The exclusion of labor expenditures throughout the operation of the reactors in this analysis is attributed to the significant disparity in salaries across different countries.

3. Results and discussion

3.1. Interpretation of impacts of environmental hotspots by technology

3.1.1. Electro-fenton

The principal contributor to all environmental effect categories can be determined from the data shown in Fig. 2, revealing that energy consumption in the electro-Fenton process is the leading factor. It is vital to recognize that the power referenced in the inventory is categorized as a low-voltage electrical blend procured from the grid. This suggests that the primary sources of power generation are predominantly fossil fuels, such as coal, oil, and natural gas – depending on the energy mix of the country at hand. The extraction-to-delivery process of harnessing energy from fossil fuels leads to the release of substantial amounts of greenhouse gases, notably carbon dioxide, along with non-methane volatile organic compounds, such as sulfur dioxide [11,14]. Renewable power generation approaches like solar panels are recommended for electro-Fenton processes to reduce environmental impact and enhance sustainability compared to alternative soil remediation technologies. Using sodium sulfate as an electrolyte yields significant outcomes, ranging from 1 % to 100 %, with a particular emphasis on its impact on human toxicity, terrestrial ecotoxicity, and marine eutrophication. The presence of extra inputs and outputs did not have discernible impacts.

3.1.2. Bioslurry process

The primary factors contributing to the environmental implications of the bioslurry process are the production of biosurfactants and electricity consumption, as depicted in Fig. 3. Energy consumption has a relatively high impact on certain midpoint impact categories, including ionizing radiation, ozone layer depletion, land use, and marine and freshwater ecotoxicity.

A distinct examination of the many processes involved was conducted to gain insight into the comprehensive implications of biosurfactant production, as depicted in Fig. 4. Fermentation contributes to an increase in the possible scarcity of fossil and mineral resources and the occurrence of global warming, terrestrial ecotoxicity, and abiotic resource depletion. Ethyl acetate has significantly contributed to various categories of effects, including ionizing radiation, ozone layer depletion, terrestrial ecotoxicity, global warming, and abiotic resource depletion. It is important to acknowledge that the inclusion of recycled ethyl acetate alters the environmental effects [11]. Furthermore, it is imperative that future studies prioritize the investigation of ultrafiltration-based purification technologies to mitigate environmental consequences associated with biosurfactant production.

3.2. Comparison of electro-Fenton and bioslurry treatment methods

Table 2 and Fig. 6 provide a detailed analysis of the environmental impacts of the electro-Fenton and bioslurry processes, enabling a comparative comparison of their respective technologies.

The bioslurry process showed greater potential across all the evaluated environmental impact parameters. The primary factors contributing to these elevated potentials can be ascribed to the increased energy consumption associated with the agitation of the reactor and the production of biosurfactants. The electro-Fenton process demonstrates the lowest potential in terms of several environmental impact criteria. This can be attributed to the lower energy consumption and utilization of boron-doped diamond (BDD) electrodes as an anodic material in the Fenton process, which effectively mitigates the risk of secondary

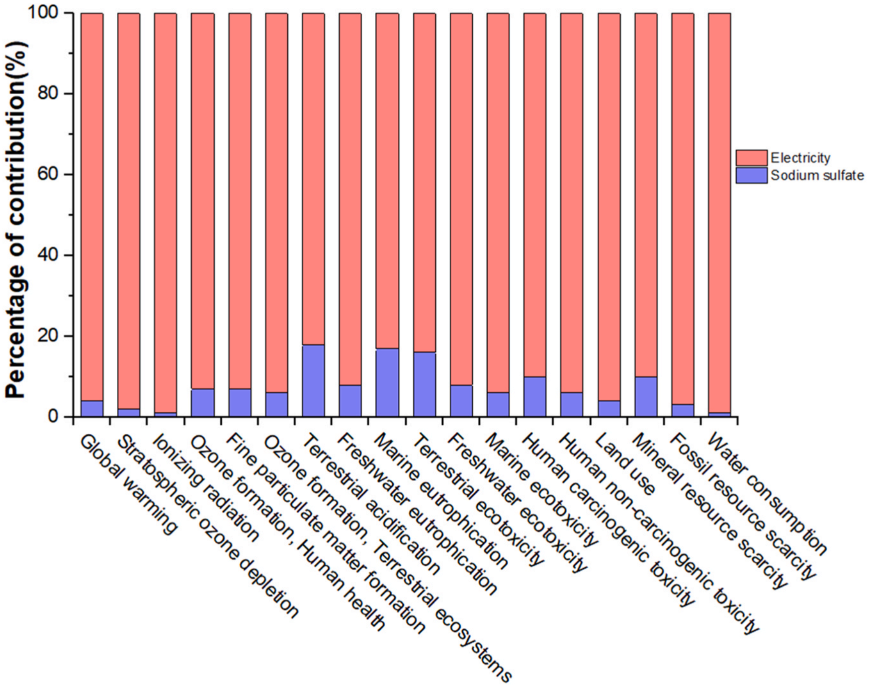

Fig. 2. illustrates the outcomes of the electro-Fenton in terms of environmental impact across all midpoint impact categories. These effects were quantified and measured using a functional unit of 100 g of treated soil. Positive numbers indicate adverse environmental impacts.

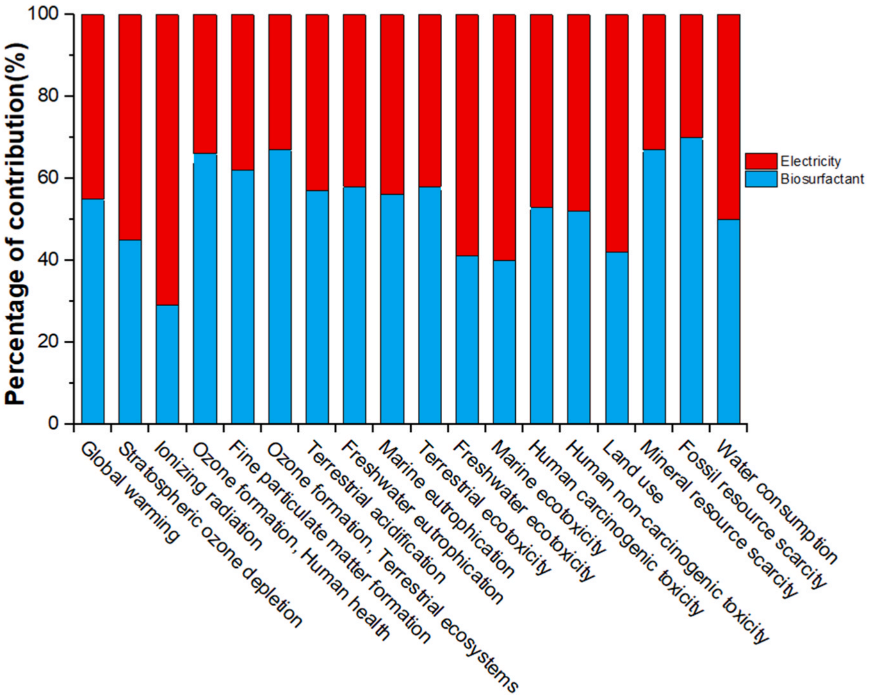

Fig. 3. illustrates the outcomes of the bioslurry in terms of environmental impact across all midpoint impact categories. These effects were quantified and measured using a functional unit of 100 g of treated soil. Positive numbers indicate adverse environmental impacts.

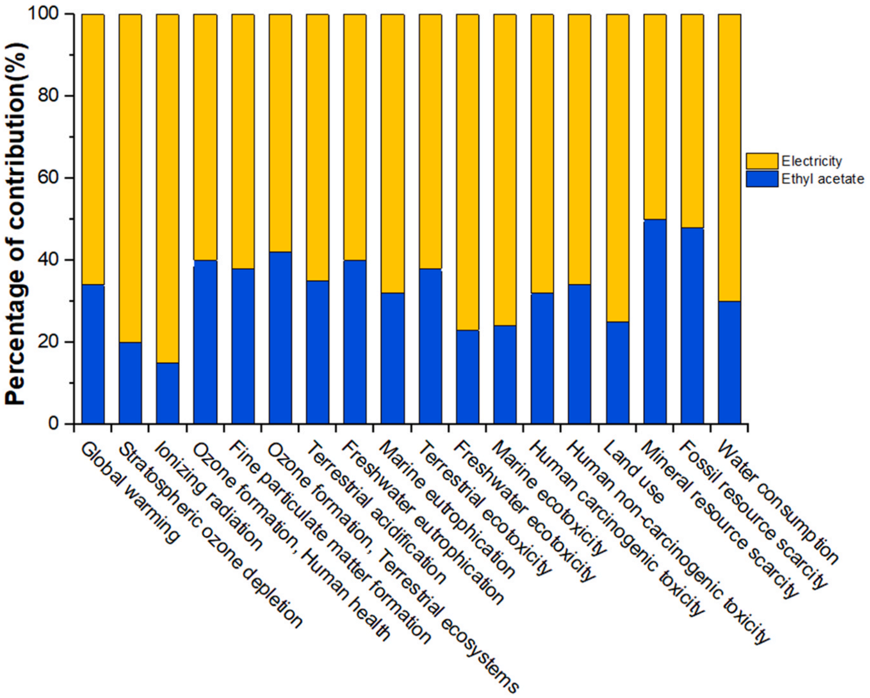

Fig. 4. demonstrates results of the contribution analysis for the fermentation and purification processes for biosurfcatant production (10 mg.).

pollution.

The primary driver of global warming is the generation of energy through the combustion of fossil fuels. Hence, the primary contributor to the significant global warming potential associated with the bioslurry process can be attributed to the substantial electricity consumption from the grid during both the mixing stage and the production of biosurfactants during the fermentation process. According to Magdy et al. [14], it has been observed that the global warming potential associated with the remediation of soil contaminated with petroleum hydrocarbons is notably larger compared to other types of organic pollutants. As an illustration, the electro-Fenton process exhibits a global warming potential of 26.778 kg CO2 Eq, while the biological process demonstrates a potential of 700 kg CO2 Eq. In contrast, the electro-Fenton process yields a modest global warming potential of 8.73 kg CO2 Eq owing to its reduced energy consumption. A similar pattern can also be observed in terrestrial ecotoxicity, human toxicity, and ozone layer depletion. In

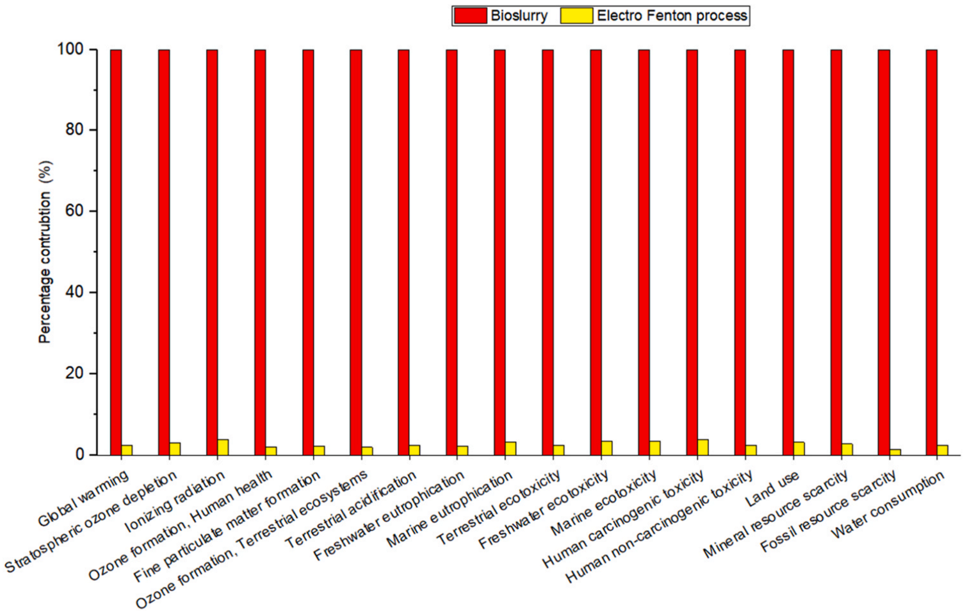

Fig. 5. Comparative analysis of the environmental impact data associated with the bioslurry, and electro-Fenton treatment. These effects were quantified and measured using a functional unit of 100 g of treated soil. Positive indicators indicate adverse environmental consequences.

Table 2
Environmental impacts of the two processes performed in laboratory scale experiments. The functional unit is 100 g of treated soil.

Impact category	Unit	Electro-Fenton	Bioslurry
Global warming	kg CO2 eq	8.730000	359.000000
Stratospheric ozone depletion	kg CFC11 eq	7.070000	0.000225
Ionizing radiation	kBq Co–60 eq	0.959928	24.100000
Ozone formation, Human health	kg NOx eq	0.015726	0.783000
Fine particulate matter formation	kg PM2.5 eq	0.011130	0.497010
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.016029	0.824956
Terrestrial acidification	kg SO2 eq	0.032641	1.350000
Freshwater eutrophication	kg P eq	0.002571	0.111086
Marine eutrophication	kg N eq	0.000205	0.007006
Terrestrial ecotoxicity	kg 1,4-DCB	25.700000	1.060000
Freshwater ecotoxicity	kg 1,4-DCB	0.879556	25.600000
Marine ecotoxicity	kg 1,4-DCB	1.090000	32.300000
Human carcinogenic toxicity	kg 1,4-DCB	0.434362	11.100000
Human non-carcinogenic toxicity	kg 1,4-DCB	7.780000	319.000000
Land use	m2a crop eq	0.302025	9.520000
Mineral resource scarcity	kg Cu eq	0.028003	0.999902
Fossil resource scarcity	kg oil eq	2.590000	175.000000
Water consumption	m3	0.132893	5.340000

CFC-11: Trichlorofluoromethane.
1,4-DB: 1,4 dichlorobenzene.

general, among all the environmental mid-impact categories considered, the bioslurry process emerged as the primary contributor to environmental problems, followed by electro-Fenton processes. The primary factors responsible for these effects are the use of energy attributed to electricity and the production of biosurfactants. In freshwater and marine aquatic ecotoxicity, both bioslurry and land farming have been found to exhibit significant potential, albeit to a lesser degree. This can also be attributed to the substantial energy consumption associated with the electrochemical reactions and the production of biosurfactants.

Following a comprehensive analysis of various technologies, their potential was standardized using globally recognized reference inventories. The results are shown in Fig. 6. Normalization is a crucial process that aims to establish a standardized scale for assessing relative environmental impacts across different categories. The primary objective is to enable a fair and equitable comparison by accounting for proportional differences. Marine water, aquatic freshwater, and ecotoxicity have the most notable impacts. The primary factor contributing to this discovery is the analysis of energy usage, which was extensively examined in the interpretation section. In the context of land use and marine eutrophication, the electro-Fenton process can cause significant harm, primarily owing to sodium sulfate.

3.3. Uncertainty analysis

LCA results are used to inform decision-making, so it is crucial to quantify their uncertainty. Hence the environmental impact of bioslurry and electro-Fenton remediation techniques on soil contaminated with petroleum hydrocarbons, considering the associated uncertainties. Monte Carlo analyses involved 1000 simulations for each process, resulting from various life cycle inventory (LCI) parameter values. Uncertainty was assessed by comparing values' spread to their average. The comparative effects of the two entities were assessed using Monte Carlo simulations. According to the Monte Carlo simulation results, using 100 % bioslurry has a greater impact on the environment, with statistically significant differences across all categories of environmental impact. The topics of interest included water consumption, terrestrial ecotoxicity, terrestrial acidification, stratospheric ozone depletion, ozone formation, terrestrial ecosystems, ozone formation, human health, mineral resource scarcity, marine eutrophication, marine ecotoxicity, and land use. Ionizing radiation possesses the ability to loosen electrons that are tightly bound to atoms. The impact categories examined in this study included human non-carcinogenic toxicity, human carcinogenic toxicity, global warming, freshwater eutrophication, freshwater ecotoxicity, fossil resource scarcity, and creation of fine particulate matter (Fig. 7 and Table 3). In addition to this, Fig. 7 shows a Monte Carlo comparison between bioslurry (A) and electro-Fenton (B) processes. Bioslurry has a higher environmental impact than electro-Fenton, making it less desirable. On the other hand, electro-Fenton results in a lower environmental impact than bioslurry, making it more desirable. Table 3 also presents a probabilistic comparison of 1000 simulations using a Monte Carlo analysis with a confidence level of 0.95. The correlation between the positive probabilistic means and 100 % probabilistic percentages indicates a greater impact of bioslurry on all environmental impact categories, whereas the electro-Fenton process

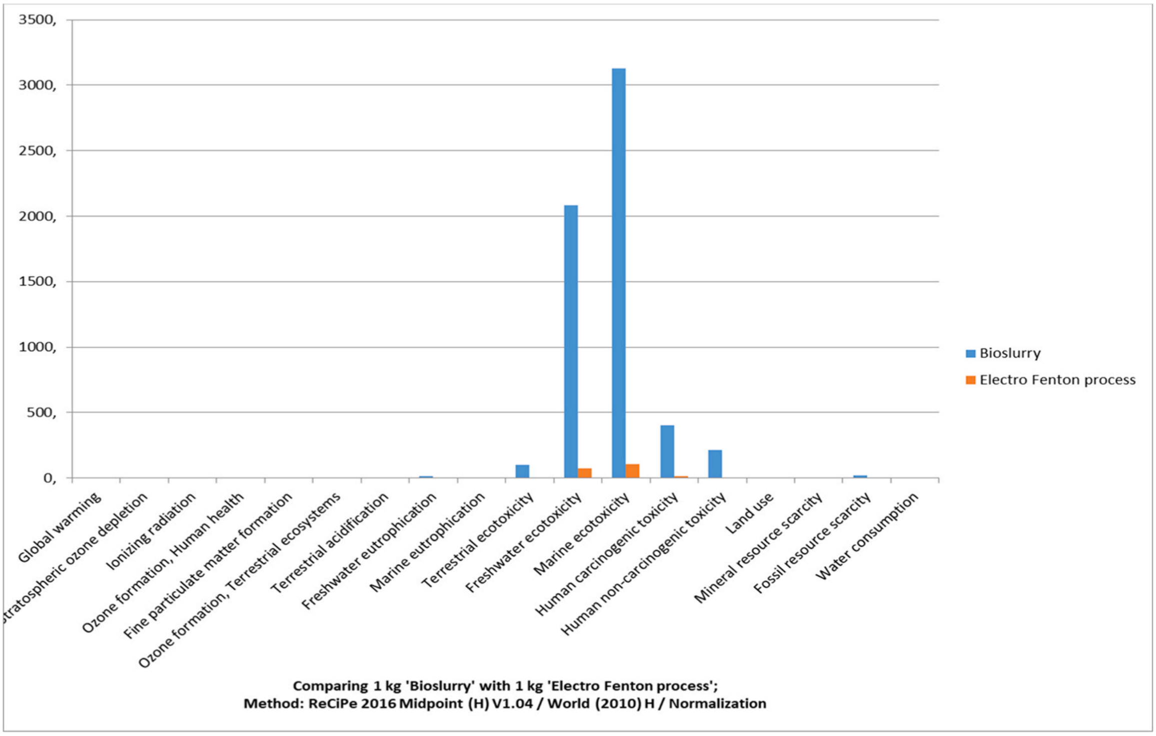

Fig. 6. Comparison of normalized environmental impacts of all environmental impact categories for bioslurry and electro-Fenton remediation processes. These effects were quantified and measured using a functional unit of 1 kg of the treated soil.

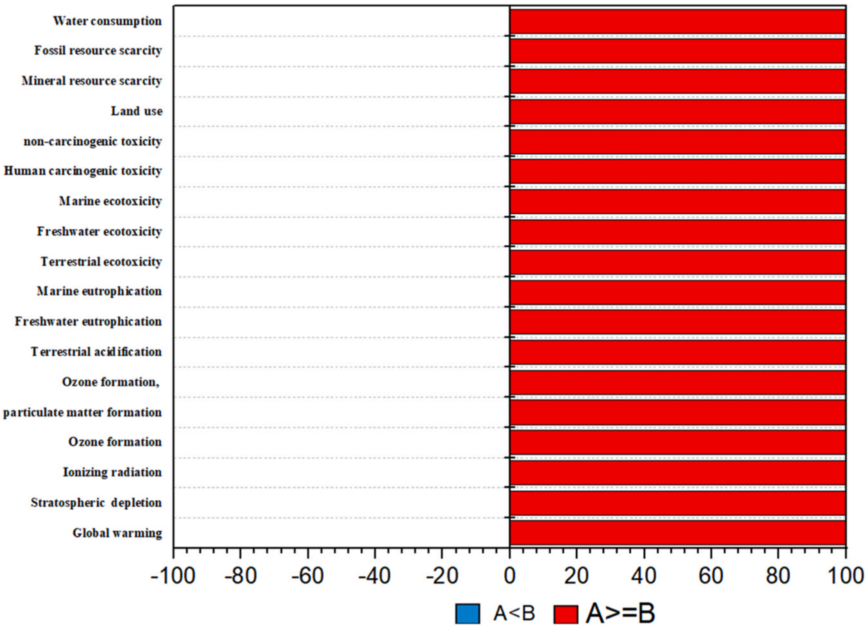

Fig. 7. The graph presents a Monte Carlo comparison between bioslurry (A) and electro-Fenton (B) processes. A positive value (red bar on the right) indicates the percentage among all analyzed environmental impact categories that bioslurry has a higher impact on the environment than electro-Fenton (i.e., bioslurry is a less desirable process). A negative value (open bar on the left) indicates the percentage of the analyzed environmental impact categories, where electro-Fenton results in a lower impact on the environment than bioslurry (i.e., electro-Fenton is a more desirable process). The left and right percentages have been added at 100 %.

has a lower environmental impact.

In Table 3, the uncertainty analysis shows that the human noncarcinogenic toxicity impact category had the most uncertainty. The GW impact of bioslurry and electro-Fenton ranged from 3.59 to 3.64 CO2e per kg, with a confidence interval of 2.5–97.5 %. This low uncertainty confirms the dataset's reliability and shows that variations in data selection and inherent variability did not have a significant influence on the examined impact categories.

Therefore, the utilization of a bioslurry at 100 % results in a greater environmental burden than that of the electro-Fenton system, with a substantial disparity between the two approaches. This proposition suggests a correlation between the increase in power consumption from the national grid and a heightened negative impact on the environment. Furthermore, the use of electricity in the manufacturing process has a

Table 3
presents a probabilistic comparison between the bioslurry (A) and electro-Fenton (B) processes using a Monte Carlo analysis of 1000 simulations with a confidence level of 0.95. The positive probabilistic means were correlated with 100 % probabilistic percentages. This means that the bioslurry process has a greater effect on all categories of environmental impact, whereas the electro-Fenton process has a lower impact on the environment.

Impact category	A >= B	Mean	Median	SD	CV	2.50 %	97.50 %	Std. errs. of mean
Water consumption	100 %	5.2	5.21	0.109	2.1	5.02	5.43	0.0218
Terrestrial ecotoxicity	100 %	1.03000	1.04000	19.3	1.87	1×10^3	1.08×10^3	3.86
Terrestrial acidification	100 %	1.32	1.32	0.0259	1.96	1.28	1.37	0.00517
Stratospheric ozone depletion	100 %	0.000218	0.000219	5.75×10^{-6}	2.64	0.000208	0.00023	1.15×10^6
Ozone formation, Terrestrial ecosystems	100 %	0.808	0.81	0.0126	1.56	0.788	0.835	0.00252
Ozone formation, Human health	100 %	0.767	0.768	0.0124	1.62	0.747	0.793	0.00248
Mineral resource scarcity	100 %	0.971	0.973	0.0133	1.37	0.95	1	0.00266
Marine eutrophication	100 %	0.0068	0.00681	0.000138	2.03	0.00657	0.00708	2.76×10^5
Marine ecotoxicity	100 %	31.2	31.3	0.843	2.7	29.8	32.9	0.169
Land use	100 %	9.21	9.24	0.243	2.64	8.8	9.72	0.0487
Ionizing radiation	100 %	23.2	23.3	0.782	3.38	21.8	24.8	0.156
Human non-carcinogenic toxicity	100 %	311	311	5.83	1.88	301	323	1.17
Human carcinogenic toxicity	100 %	10.6	10.7	0.214	2.01	10.3	11.1	0.0428
Global warming	100 %	350	351	6.99	2	3.58	3.64	0.014
Freshwater eutrophication	100 %	0.108	0.109	0.00198	1.83	0.105	0.113	0.0000396
Freshwater ecotoxicity	100 %	24.7	24.8	0.679	2.75	23.5	26.1	0.136
Fossil resource scarcity	100 %	172	172	2.06	1.2	169	177	0.413
Fine particulate matter formation	100 %	0.486	0.487	0.00858	1.77	0.472	0.504	0.00172

Note: SD: Standard Deviation, CV: Coefficient of Variation, CV unit is in %. SEM: Standard Error of the Mean (SEM) (standard deviation of the sample distribution of the mean).

greater negative impact on the ozone layer, climate change, radiation, and acidification than the use of hydropower or solar energy as alternative energy sources.

3.4. Economic analysis

The cumulative expenses for all the technologies are shown in Fig. 8 and Table 4. One of the most expensive technologies in terms of cost is the electro-Fenton process, with an approximate price of $661.25 per kilogram. The primary factor responsible for the incurred expenses is the utilization of boron-doped diamond (BDD). The bioslurry treatment technology, which costs 7.13$/kg, exhibits a significant disparity in terms of cost when compared to the electro-Fenton method. The primary factor influencing this expense is the utilization of biosurfactants. The investigation of costs indicated that the utilization of renewable energy, implementation of boron-doped diamond at a reduced expense, or use of Magnéli Ti_4O_7 electrodes can substantially reduce the costs associated with the treatment process.

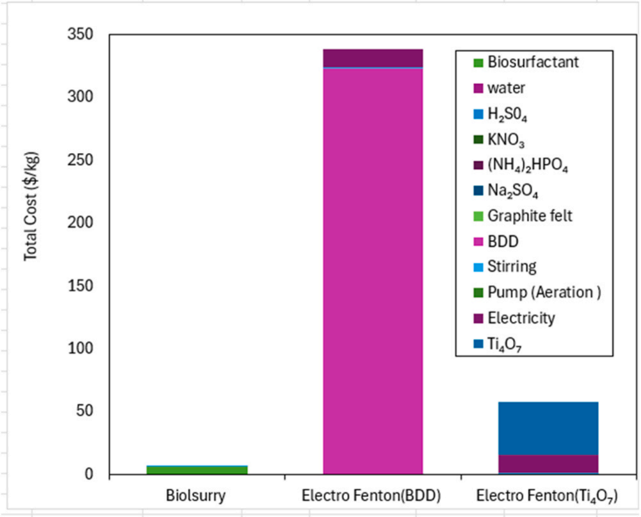

Fig. 8. The comprehensive expenses associated with the remediation of 1 kg of soil contaminated with petroleum hydrocarbons, utilizing bioslurry and electro-Fenton techniques.

4. Practical applications and future research

Based on the LCA results, the Fenton process was deemed environmentally friendly. The use of boron-doped diamond (BDD) as an electrode can minimize the amount of H_2O_2 and Fe^{2+} used as catalysts, which can result in secondary contamination. BDD electrodes enhance soil biodegradation in anodic oxidation processes; however, their widespread use remains uncertain. Further research is needed to reduce costs, scale-up fabrication while maintaining stability, and address issues such as separating BDD film from substrate surfaces and cracking. Large-scale applications may be challenging because of the unique properties of soils polluted with PHCs, such as low organic contaminants and other radical scavengers [11].

This study has some limitations, including the need for more accurate engineering data, better simulations of sludge with special properties, and potential environmental burden transfer from sludge to waste liquid with increased iron content. Future studies should expand the system boundaries to cover subsequent soil treatment processes and compare LCA with other advanced oxidation processes for horizontal and vertical comparisons. In addition to the Fenton process, environmental hotspots are largely due to variations in the operating conditions. The main drawbacks are treatment time and acidic pH, which affect the energy consumption and infrastructure. To mitigate these issues, research should focus on the design of experiments and optimization of the interaction effects of critical factors such as parameter increasing reaction rate and extending the efficient pH range using response surface methodology (RSM), full factorial design (FFD), and artificial neural networks (ANN) [23–25].

The LCA results indicate that the bioslurry treatment process is environmentally unfriendly owing to its high electricity consumption for the production of biosurfactants, which enhances the biodegradation of PHC in oil-polluted soils, and that the use of electricity in electro-Fenton and bioslurry experiments significantly increases the global environmental impact. The main conclusions derived from this study are applicable exclusively to Europe and other regions, where electricity is predominantly generated from non-renewable energy sources. In Europe, the primary sources of electricity, ranked in descending order, are nuclear, hydro, oil, natural gas, lignite, and coal. The increased use of renewable energy sources during electricity generation can significantly reduce environmental impacts and lead to a more sustainable national policy, thereby reducing the potential for permanent environmental degradation [26-28].

Table 4

Cost distribution and economic indicators with the remediation of 1 kg of soil contaminated with petroleum hydrocarbons, utilizing bioslurry and electro-Fenton techniques.

Item	Unit	Bioslurry	Electro-Fenton (BDD)	Electro-Fenton (Ti_4O_7)	Price per kg	Total Price Bioslurry	Total price Electro Fenton (BDD)	Total price Electro Fenton (Ti_4O_7)
Materials:								
Biosurfactant	kg	0.275	0.00	0.00	22.5	6.19	0.00	0.00
water	kg	0.275	0.5	0.50	0.00137	0.00	0.00	0.00
H_2S0_4	kg	0.00	0.044	0.044	0.148	0.00	0.01	0.01
KNO3	kg	0.0015	0.00	0.00	174	0.26	-	0.00
$(NH_4)_2HPO_4$	kg	1.0×10^{-4}	0.00	0.00	112.8	0.01	-	0.00
Na_2SO_4	kg	0.00	1.0×10^{-4}	1.0×10^{-4}	85.9	-	0.01	0.00
Graphite felt	kg	0.00	0.0086	0.0086	45	-	0.39	0.00
Boron doped diamond	kg	0.00	1.00	0.00	323	-	343.00	0.00
Ti4O7	Kg	0.00	0.00	1.00	42.58	0	0	42.58
Process:								
Stirring	KWH	0.3749	0.3749	0.3749	1.8	0.67	0.67	0.67
Pump (Aeration)	KWH	1.2×10^{-7}	1.2×10^{-7}	1.2×10^{-7}	1.8	0.00	0.00	0.00
Electricity	KWH	39.375	7.875	7.875	1.8	0.00	14.18	14.8
Sum $/Kg						7.13	338.25	57.83

The global biosurfactant market is experiencing a surge in demand owing to its versatility and eco-friendliness, replacing chemical alternatives. Technological advances have made the production and processing of biosurfactants easier and more economical. However, their low production is due to high costs, low yield, and time, making them more expensive than chemical alternatives. This highlights the challenges in the commercialization of biosurfactants. To overcome these challenges, a more economically favorable and eco-friendly process should be developed for biosurfactant production from carbohydrate wastes such as agro-waste and industrial wastes. This would facilitate large-scale fermentation of carbohydrate substrates, leading to commercial success. Proper medium optimization through statistical methods and downstream processing is also necessary to reduce production costs and improve the biosurfactant yield [29].

Establishing universally recognized standard methodologies for Life Cycle Costing (LCC) is essential for conducting accurate life cycle sustainability assessments for soil remediation [30,31]. Future research should prioritize the development of streamlined, accurate, and user-friendly LCC approaches to enhance their practicality and reliability. Although there is a significant amount of research on LCC, the majority of the literature is theoretical and lacks empirical evidence about its practical implementation, cost model, and specific cost data. Researchers are becoming more interested in quantifying the monetary worth of environmental and social aspects to incorporate them into LCC studies. Society of Environmental Toxicology and Chemistry has issued rules; however, additional endeavors should be undertaken to establish a comprehensive integrated framework for analyzing LCA and LCC. The integration of modern cost estimation methodologies and process costing methods with LCC theory allows for the full cost of activities, precise allocation of resources, and overhead costs. One can delve into the theories of time-driven activity-based costing and life-cycle costing. There is a requirement for a standardized system for LCA of soil treatment and standardization of the data used as input. End-of-life costing, which is frequently omitted from LCC analysis, can be enhanced and simplified for calculation purposes. The objective of this study was to offer decision support by identifying crucial factors that affect the life cycle impacts of soil treatment and provide accurate estimations of their environmental impact [32,33].

5. Conclusions

This study investigated the environmental impacts of bioslurry, and electro-Fenton processes for treating soil polluted with petroleum hydrocarbons. An economic analysis of these processes was conducted. The results show that electro-Fenton is the most environmentally friendly method, causing lower impacts for all ReCiPe 2016 characterization approach categories. Nevertheless, it can be argued that bioslurry exerted the most significant influence across several categories. The two most prominent inventory elements across all techniques are energy usage and biosurfactant utilization. Further research should investigate the environmental consequences associated with these operational phases. The results of the Monte Carlo simulation confirmed that the utilization of 100 % bioslurry yielded a greater impact across all environmental impact categories. In addition to this the uncertainty analysis shows that the human noncarcinogenic toxicity impact category had the most uncertainty. The GW impact of bioslurry and electro-Fenton ranged from 3.59 to 3.64 CO2e per kg, with a confidence interval of 2.5–97.5 %. This low uncertainty confirms the dataset's reliability and shows that variations in data selection and inherent variability did not have a significant influence on the examined impact categories.

The economic analysis indicates that the most expensive items in the inventory are energy usage and boron-doped diamond electrodes. In conclusion, the electro-Fenton process is eco-friendly and bioslurry is the most economical method.

This study suggests using renewable energy sources and developing low-cost materials for treating soil polluted with petroleum hydrocarbons. This emphasizes the economic and environmental sustainability of the electro-Fenton process for PHC remediation using reusable catalysts and materials. Magnéli Ti_4O_7 electrodes can reduce economic impact, demonstrating the potential of this method for advancing sustainable soil remediation methods.

CRediT authorship contribution statement

Andrea Franzetti: Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition. **Mentore Vaccari:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition. **Ana Lima:** Visualization, Writing – review & editing. **Teklit Gebregiorgis Ambaye:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesca Formicola:** Writing – review & editing, Visualization. **Silvia Sbaffoni:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jece.2024.113672.

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