SUSTAINABLE ELECTROREMEDIATION: AN INNOVATIVE TECHNIQUE FOR THE REMEDIATION OF CONTAMINATED SOILS †

[ELECTRORREMEDIACIÓN SOSTENIBLE: UNA TÉCNICA INNOVADORA PARA LA REMEDIACIÓN DE SUELOS CONTAMINADOS]

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SUMMARY

Background: Electroremediation is an *in-situ* technology for the remediation of low-permeability soils contaminated with heavy metals or polar organic compounds. Regarding its application, only its biotechnological processes are considered. However, it is important to consider sustainable aspects within the technologies in order to influence socio-environmental and socio-economic issues of the affected areas. In addition, a histogram must be applied to visualize some pattern of soil behavior. **Objective:** To determine sustainable electroremediation as a viable tool for the recovery of contaminated soils, in addition to applying multi-criteria decision-making for an evaluation of the sustainability of contaminated areas using sustainable electroremediation, through diagnostic criteria, and sustainability indicators; whose qualitative or quantitative value allows comparing results oriented at the same time on policies, strategies, actions and decision-making in the area. **Methodology:** A bibliographic review (1960-2023) was carried out with a focus on remediation and electroremediation of contaminated environments with a sustainability perspective. Using the PRISMA method, the information was systematized, and, with it, a scientific analysis and critique of the information was developed to make an innovative contribution to the use of sustainable electroremediation through tools and indicators of sustainability of contaminated soils. **Results:** A first approach is shown to the compilation of the concept and scope of sustainable electroremediation to remediate and recover areas affected by contamination, seeking social, governmental and business participation for better decision-making in the sanitation of the socio-ecosystem. In addition, a multi-criteria decision analysis is provided to develop sustainable electroremediation projects that consider the social-anthropological, ecological-biological and economic-administrative aspects for a better remediation process of contaminated soils. **Implications:** The determination of soil indicators is described as a decision-making tool for the evaluation of the sustainability of contaminated areas using the electroremediation technique, but it is expected that the projects achieve a legitimate interest in the environment and its recovery. **Conclusions:** through criteria in decision-making and sustainability indicators, they provide an opportunity to apply sustainable electroremediation as an innovative technique, whose qualitative or quantitative value allows comparing the results and, at the same time, guiding policies, strategies and actions in decision-making in the contaminated area.
Key words: multicriteria decisions; contaminants; remediation; soils; sustainability.

RESUMEN

Antecedentes: la electrorremediación es una tecnología *in situ* para la remediación de suelos, de baja permeabilidad, contaminados con metales pesados o compuestos orgánicos polares. En cuanto a su aplicación solo se consideran sus procesos biotecnológicos. Sin embargo, es importante considerar dentro de las tecnologías los aspectos sostenibles para incidir en temas socioambientales y socioeconómicos de las áreas afectadas, además, se debe aplicar un histograma para visualizar algún patrón de comportamiento del suelo. **Objetivo:** determinar la electrorremediación

† *Submitted March 28, 2024 – Accepted September 10, 2024.* http://doi.org/10.56369/tsaes.5540

ISSN: 1870-0462.
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sostenible como herramienta viable para la recuperación de suelos contaminados, además, de aplicar la toma de decisión multicriterio para una evaluación de la sostenibilidad de las zonas contaminadas utilizando la electrorremediación sostenible, mediante criterios de diagnóstico, e indicadores de sostenibilidad; cuyo valor cualitativo o cuantitativo permite comparar resultados orientado a la vez sobre las políticas, estrategias, acciones y en la toma de decisiones en el área. **Metodología:** se realizó una revisión bibliográfica (1960-2023) con un enfoque de remediación y electrorremediación de ambientes contaminados con una perspectiva de sostenibilidad, con el método PRISMA se sistematizó la información y, con ello, se desarrolló un análisis y crítica científica de la información para realizar una aportación innovadora en el uso de la electrorremediación sostenible mediante herramientas e indicadores de sostenibilidad de los suelos contaminados. **Resultados:** se muestra un primer acercamiento a la recopilación del concepto y alcance de la electrorremediación sostenible para remediar y recuperar zonas afectadas por la contaminación, buscando la participación social, gubernamental y empresarial para una mejor toma decisiones en el saneamiento del socioecosistema. Además, se aporta el análisis decisión de multicriterio para desarrollar proyectos de electrorremediación sostenible que tome en cuenta lo social-antropológico, ecológico-biológico y económico-administrativo para un mejor proceso de remediación de los suelos contaminados. **Implicaciones:** se describe la determinación de indicadores de suelo como una herramienta para la toma de decisiones para la evaluación de la sostenibilidad de zonas contaminadas utilizando la técnica de electrorremediación, pero se espera que los proyectos logren un interés legítimo por el medio ambiente y su recuperación. **Conclusiones:** mediante criterios en la toma de decisiones e indicadores de sostenibilidad dan una oportunidad de aplicar una electrorremediación sostenible como una técnica innovadora, cuyo valor cualitativo o cuantitativo, permita comparar los resultados y orientado, a la vez, las políticas, estrategias y acciones en la toma de decisiones del área contaminado.

Palabras clave: decisiones multicriterio, contaminantes, remediación, suelos, sostenibilidad.

INTRODUCTION

Soils are part of ecosystems and agroecosystems that provide important environmental functions and services that maintain and support the social and economic activities of humanity (Burbano-Orjuela, 2016). However, when soils are contaminated with organic, inorganic and emerging components, physical, chemical and biological parameters are damaged, affecting living beings and the environmental health of the socio-ecosystem (FAO and UNEP, 2021). In this sense, to provide a solution to these contaminated areas, there are technologies and biotechnologies for the remediation and recovery of soils.

One of these technologies to remove contaminants from affected soil is electroremediation. Electroremediation involves the use of electrodes that pass direct current through the soil to remove contaminants. This technique can be performed *in-situ* and *ad hoc* and is effective for fine-grained soils with low hydraulic permeability, which are difficult to treat by other methods. In addition, research is still needed to understand and comprehend the phenomenon of transport of contaminants and, in turn, to recover a percentage of the soil's fertility and environmental health, as well as the relationship with the affected society (Page and Page, 2002; de la Rosa-Pérez *et al.*, 2007).

The advantages of electroremediation include close control over the direction of movement of water and dissolved contaminants, even though heterogeneous soils, retention of contaminants within a confined area, and low energy consumption. The mechanisms by which water and solutes are transported through soils under the application of electric fields involve several processes that contribute to the relative importance of the system, and this can vary from one socioecosystem to another (Page and Page, 2002; Méndez *et al.*, 2012). For this reason, electroremediation is an effective support, which is used in contaminated soils, since it helps to understand the complexity of the matrix of the contaminated site, in addition, it generates knowledge about the fate of contaminants in the soil and toxicology (Rodríguez-Eugenio *et al.*, 2018).

As a technique for the remediation of contaminated soils it is fascinating, however, the involvement of sustainability must be considered. In this sense, its evaluation is using methods and techniques to determine environmental, social, economic and governance indicators; this allows observing trends in the development of the affected socio-ecosystems. Likewise, the usefulness and use of this methodological procedure is based on the detection of critical points of sustainability, to establish their causes and propose medium-term solutions in contaminated soils using the sustainable electroremediation technique to ensure that the technique balances the objectives of sustainability and its three dimensions to generate environmental goods and services essential for survival and social well-being (SEMARNAT, 2012; Chan-Quijano *et al.*, 2023a).

In addition, with the use of sustainable electroremediation, legitimate interest in environmental matters can be promoted since, by recovering contaminated soils, restoration strategies can be planned with plant species and with social participation to generate the necessary conditions for the development of environmental goods and services in the medium and long term and, thereby, achieve a reduction in pollution. For example, within the environmental justice of contaminated areas (cumulative burden), the aim is to develop, with the help of municipal and state officials, a variety of scientific tools, from maps and models to air, water and soil pollution sensors to identify those who are most threatened by the levels of contamination, in addition to the different social, geographic and historical inequalities (Castro-Salazar and Camacho-García, 2021; Tollefson, 2022).

These points are not considered in electroremediation as a biological technology, but is this possible? For this reason, the determination of sustainable electroremediation as a viable tool for the recovery of contaminated soils is described, in addition to applying multicriteria decision-making for an evaluation of the sustainability of contaminated areas through diagnostic criteria and sustainability indicators; whose qualitative or quantitative value allows for comparing results oriented, at the same time, to public policies based on evidence, strategies, actions and decision-making on management planning, remediation, restoration and recovery of the contaminated area.

METHODOLOGY

Bibliographic search and analysis

A bibliographic review was carried out on the approach to the remediation and electroremediation technique of contaminated environments with a sustainable perspective (Tripathi et al., 2015; Chang et al., 2017; Chan-Quijano et al., 2020; Vocciante et al., 2021) with which a scientific analysis and critique of the information was developed (Castillo-González and Dorta-Contreras, 2017) to contribute to the application of sustainable electroremediation. In addition, the bibliographic review process started with a search for data in digital repositories such as the Web of Science and Scopus, finding 17,481 documents, which were systematized with the PRISMA method (Preferred Reporting Items for Systematic reviews and Meta-Analyses) according to Page *et al.* (2020) (Table 1).

Keywords were used, in Spanish and English, such as remediation ("remediación"), sustainability ("sostenibilidad"), contamination ("contaminación"), contaminated soils ("suelos contaminados") and electroremediation ("electrorremediación"). Search operators "AND", "OR" and "NOT" were used; the latter to exclude certain words that are not of interest to the topic. This review considered the years 1960 to 2023 to answer how is sustainable electroremediation applied and what is it in contaminated soils?, based on the fact that there is little information on the subject that theoretically explains what it means to apply sustainability in the remediation and electroremediation processes of contaminated soils and that considers the axes, not only the environmental one, but also considers society and the economy. In addition, the information analyzed describes what sustainable electroremediation is and its scope, the indicators and methodological bases, as well as the contribution of the multicriteria decision.

Table 1. Flow of the systematic review of information.

Characteristics of information systematization	*Documents (scientific articles, books, book chapters, thesis)
Total documents found	17,481
Excluded	6,456
Excluded under full Reading	36
Review	10,989
Duplicates	3,231
Analyze in depth	7,758
Excluded due to in-depth analysis	3,567
Excluded due to specialized topic	2,314
Included	1,877

* Systematization of the information found with the PRISMA method.

Description of indicators and methodological bases

A description of the indicators and methodological bases was made as part of the strategic planning in sustainable electroremediation, and a multicriteria decision was applied to provide a solid basis for decision-making and, thereby, promote sustainability efforts in the electroremediation technique with the support of governmental and non-governmental organizations and society. Finally, the determination of indicators for contaminated soil is described so that it can be used as a decision-making tool to achieve the evaluation of the sustainability of contaminated areas through diagnostic criteria with qualitative or quantitative values (García *et al.*, 2012; Pinedo *et al.*, 2014; Isaac-Godínez *et al.*, 2017; Linkov *et al.*, 2020; Chan-Quijano *et al.*, 2021; Grifoni *et al.*, 2022). The methodology and this work seek to promote innovation in the remediation processes of contaminated soils and, at the same time, apply a socio-environmental impact on the recovery of contaminated areas by applying sustainable electroremediation.

RESULTS AND DISCUSSION

Sustainable electroremediation

Within electrokinetic remediation, it is important to consider the site and its entire environment; it is not enough to consider the environmental aspect. The social aspect must be considered, because there are empirical and social-anthropological studies on the impacts that contamination has on human health that are not considered as part of the human risk index (Khanna, 2017; Pinedo *et al.,* 2014; Chan-Quijano *et al.,* 2021). Contaminants, depending on their composition, can be toxic to highly toxic for beneficial soil organisms and humans. Toxicity is derived from the number of contaminants found in the soil. For this reason, the concentration is estimated based on chemical fractions and a variety of bioassays that include plants, invertebrates and microorganisms considering weathering, climatic conditions and different soil groups (Chang, 2017; Khan *et al.,* 2018).

In this sense, the ecology of degradation, bioaccumulation and recovery of contaminants should be reviewed, emphasizing the physical, chemical, biological and climatic factors that contribute to the composition, state and concentration of contaminants in the soil. In addition, dispersion and emulsification within electroremediation improve recovery rates in terrestrial and aquatic systems (Tripathi *et al.,* 2015). Thus, the absorption of contaminants at the electrodes and by soil particles is the key characteristic, together with temperature and oxygen and nutrient concentrations (Hou *et al.,* 2018). Considering that salinity, humidity, pH and pressure can affect biodegradation rates in some soils.

On the other hand, taking into account all the above, it is necessary to prioritize the sustainability aspects for a more environmentally friendly electroremediation, that is, the type of contaminant, soil biology, biodiversity and biochemistry, the socioeconomic components of the system to be electroremediated and the social issue of the affected area, in case there are surrounding communities, must be considered; using the human risk index. In addition, for contaminated soil recovery projects it is necessary to implement the ecological-biological, social-anthropological and economic-administrative aspects to have more complete solutions (Figure 1) (Pinedo *et al.,* 2014; Tripathi *et al.,* 2015; Luo *et al.,* 2017).

However, strategies must be sought to create a national or global plan for the recovery of contaminated soils and, with this, classify a complex task with social participation to achieve territorial governance that recognizes the tools to formulate environmental public policies for the remediation and recovery of the socio-ecosystem affected by contamination (Rodríguez-Jiménez, 2008; Chan-Quijano *et al.,* 2024) and, for this, new knowledge and methodological structures are needed to promote integrated knowledge in different disciplines and multi and interdisciplinary co-productions for problem solving and with social and economic impact (Tripathi *et al.,* 2016; Irwin *et al.,* 2018).

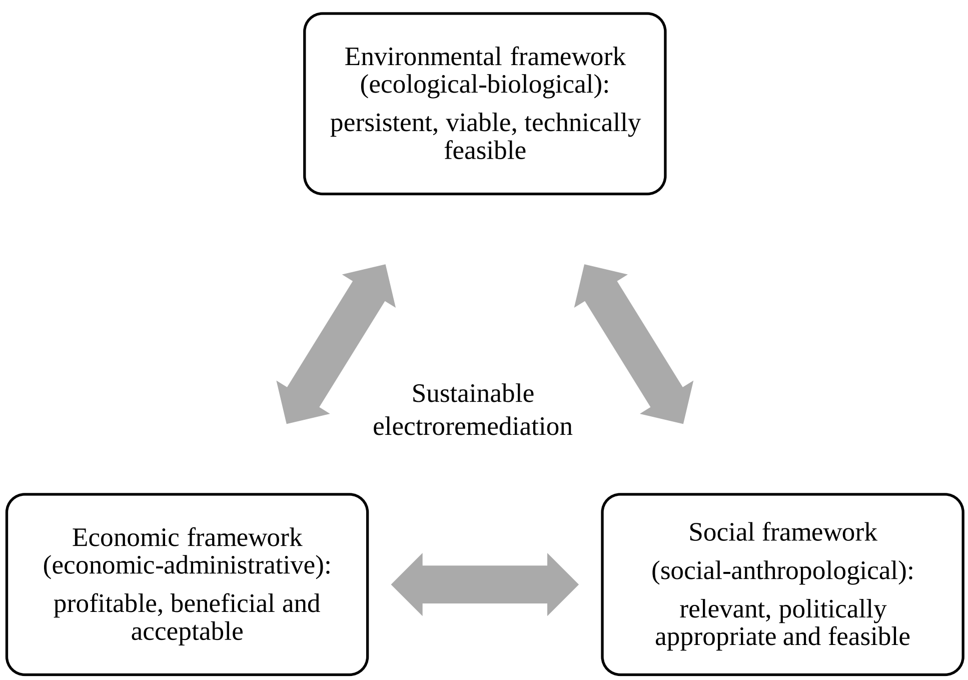

Figure 1. Sustainability values framework for sustainable electroremediation. Source: own elaboration based on Chan-Quijano *et al.* (2020).

In this sense, a methodological and reference framework is necessary to establish specific goals and objectives in the electroremediation, remediation and restoration projects of the contaminated ecosystem for self-regulation for a systematic analysis of legal instruments to exercise the laws, rules and regulations for a recovery of the affected area, this, with the help of the governmental, business and social will. In addition, a process of responsibility, incentives and regulation will be achieved for the rehabilitation of the soil affected by the contaminants and, with this, gradually reduce the inherited contamination. Adding an ecological value as well as a social-cultural-economic value and social participation in socio-environmental problems (Reyes-Ruiz, 2006; Ceccon *et al.*, 2015; Wagner *et al.*, 2015).

Chan-Quijano *et al.* (2015), López-Jiménez and Chan-Quijano (2016) and Grifoni *et al.* (2022) highlight that, to achieve the above, it is necessary to insert sustainability in contaminated areas, but first, it is necessary to leave the desire for denominating discourse and begin to set strategies and goals to achieve success stories where the three axes of sustainability interact by applying inclusive management and ontological relationships for an environmental democracy with a character of environmental responsibility (Figure 2). Likewise, by applying more robust public policies, it will be possible to recognize the best strategies for environmental, social and economic impact to improve electroremediation techniques. Also, it must be recognized that not all contaminated areas are the same, a central issue to generate multi and interdisciplinary groups by region to provide specific solutions with the help of the axes and objectives of sustainable development for sustainable electroremediation.

Now, to strategically plan a sustainable electroremediation, a multicriteria decision analysis must be carried out; a method to support decision-making, by exploring the balance between the pros and cons of different alternatives to achieve a specific objective in the project (Geneletti and Ferretti, 2015; Esmail and Geneletti, 2018). Likewise, the performance alternatives and guidelines for sustainable electroremediation must be framed, as well as a political-institutional sustainability for the search for solutions considering society (Figure 3), but we must be careful with iatrogenesis, that is, that, by trying to remediate and recover the contaminated area, we affect more (Domecq-Gómez *et al.*, 2020).

Environmental sustainability	• Risk assessment of the contaminated site. • Electroremediation and environmental health. • Planning for remediation and restoration. • Inclusive management and its productivity. • Immediate and short-term response actions. • Preserving and enhancing diversity. • Complexity of ecosystems. • Natural cycles and biodiversity.
Social sustainability	• Regulatory processes in accordance with the norms and laws in the various forms of political, regional and local power. • Human health, human risk index and socially accepted electroremediation technique. • Resolution of socio-environmental conflicts and social participation. • Preservation of cultural diversity (knowledge and perceptions). • Equity in the goods of nature, between genders and cultures, education, producers and their family group.
Economic sustainability	• Most profitable electroremediation projects. • Economic benefits of contaminant recovery. • Functional economic value between company, government and society. • Phases of economic latency due to contamination. • Human activities related to production, distribution and consumption of goods and services. • Efficiency of land, labor and capital resources. • Activities related to production, costs, income and benefits.

Figure 2. Processes and strategies to be used in sustainable electroremediation projects and ontological relationships. Photographs: José G. Chan Quijano.

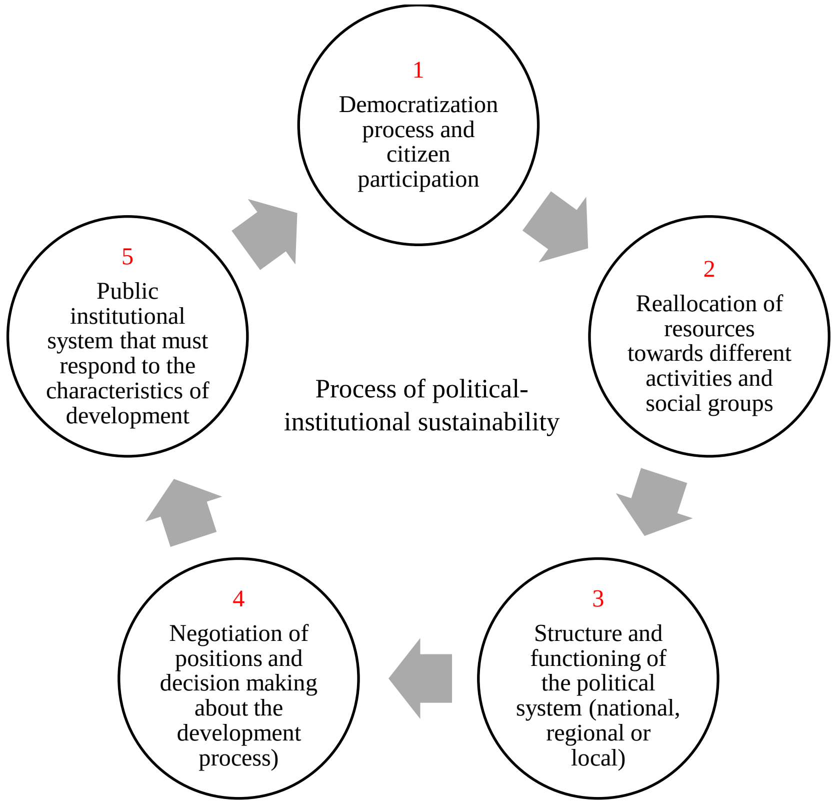

Figure 3. Sustainable political-institutional responsibility in sustainable electroremediation.

Sustainable electroremediation, indicators and methodological bases

The construction of an evaluation model is based on integrating the three stages into the strategic planning process: formulation, implementation and evaluation. Each stage interacts with the other two in a dynamic way and a sustainability matrix is generated by areas or evaluation dimensions with diagnostic criteria and the design of a broad set of sustainability indicators (Isaac-Godínez *et al.*, 2017). For strategic planning, the theoretical methodological design is essential to evaluate the level of sustainable development of contaminated areas considering the electroremediation technique.

These types of assessments require a lot of primary information on various aspects such as carbon footprint, type of pollutants and amount of concentration, diversity management, policy compliance, social participation, funding and institutional support, to name a few, which is obtained mainly from environmental, governmental, social and business monitoring networks, and which are translated in a simple and synthetic way under socio-environmental indicators (Galán *et al.*, 2013) and the knowledge generated must be communicated to the general population and to politicians for better decision-making. On the other hand, the large amount of data from the environmental, social and economic fields, which are used in environmental impact assessments, allow a particular phenomenon or process to be interpreted in a simpler and more systemic way in the management needs of each socio-ecosystem, a fundamental part that must be considered in sustainable electroremediation.

Likewise, sustainable electroremediation should seek to reduce risks and uncertainty, increase socio-ecological and socio-economic services, rehabilitate areas of soil degradation, clean up aquatic systems and conserve the biodiversity of the place, without diminishing the economic viability of the system, thus achieving the generation of indicators and methodological bases that support the remediation of the affected system. Esteves *et al.* (2012) mention that indicators and methodological tools are recognized as a fundamental need for sustainable development and are considered as variables that can be measured in a system over time. Generating information on the trends of the affected system and, in turn, that need to be analyzed to identify those forces that contribute to the improvement or degradation of economic, social and environmental conditions, allowing to establish precise goals for future actions, so that governments and civil society can evaluate progress in their actions.

Furthermore, the indicators are grouped by thematic area in relation to the environment affected by the potential impacts, such as water (consumption and contamination), atmosphere (contamination), waste (production and disposal), soil (use and contamination) and vegetation (biomass, diversity and deterioration), as well as complementary indicators of a socioeconomic nature, but in this case, focused on soils contaminated with the various bioelectroremediation techniques considering the type or group of contaminants (Perevochtchikova, 2013; Perevochtchikova and Rojo-Negrete, 2013; Gomes *et al.* 2015).

In this sense, when dealing with sustainable development with an integrated approach, a conceptual framework of indicators is used that considers the basic dimensions of sustainability: sociocultural, economic, environmental, political-institutional. However, it should be noted that the interactions between components of different dimensions can, at a given time and circumstance, be as important as the main components of a given dimension. Assessments in these dimensions are carried out through criteria and diagnoses that allow the construction of indicators of the affected system (Astier *et al.*, 2012). In this sense, by applying the above with the processes, techniques, methods and guidelines in the electroremediation of contaminated soils, sustainability would be achieved and applied in the remediation of environments affected by pollutants (Vocciante *et al.*, 2021).

Multicriteria decisions for sustainable electroremediation

Multicriteria decision analysis emphasizes how traditional practices of impact assessment of contaminated areas can be improved and, thus, apply sustainable electroremediation, including cost-benefit and toxicological risk assessment on human and environmental health of complex socio-ecosystems, thus seeking that the contribution of the economy to human well-being is valued fairly under environmental justice and within the ecological risk index for the recovery of the affected natural system (Linkov *et al.*, 2006; Esmail and Geneletti, 2018; Linkov *et al.*, 2020). In addition, this analysis provides a comparison of alternatives for electroremediation projects based on decision matrices and optimal for adaptive management with the axes and objectives of sustainable development (Linkov and Moberg, 2012; Hou *et al.*, 2018).

Linkov *et al.* (2020) highlights that multi-criteria decision analysis allows for comparing alternatives against a set of explicitly defined criteria that consider the most relevant aspects in each decision-making process such as sustainable electroremediation, as well as its guidelines, versatility and flexibility. This allows combining different disciplines, techniques and tools to reach a solution with viable, safe criteria and with hierarchical levels for an analytical process within electroremediation. In addition, the social acceptability of the technique must achieve a status quo within the natural and human, socio-political, community and socio-economic environment (Balland-Bolou-Bi *et al.*, 2023). In this same sense, multi-criteria decision-making will succeed in focusing on sustainable electroremediation as part of the responsibility that actors have and the political and environmental justice challenges to achieve the recovery of the contaminated socio-ecosystem at a local or regional scale.

Therefore, multi-criteria decision analysis allows integrating methodologies for and from theoretical-evaluative and applied complexity to create recovery alternatives, but considering social-anthropological, ecological-biological and economic-administrative indicators and tools for sustainable management of the territory (Figure 4), which allow making informed decisions towards sustainable remediation. From this perspective, simultaneous socio-environmental processes and complex interactions between the natural, cultural, economic and human environment can be achieved to intervene in the environmental crisis to prevent more serious damage to the soils (Trejo-Barrientos, 2019; Tsakalerou *et al.*, 2022; Chan-Quijano *et al.*, 2024).

Therefore, to apply the multi-criteria decision, the problem and its socio-environmental context must first be known, that is, the contaminated site, the affected areas and the types of contaminants must be recognized to plan the electroremediation and remediation strategy. Likewise, when applying the technique, it is necessary to consider what benefits, processes, viability and profitability will be obtained and applied for socioeconomic benefits, after the recovery of the contaminated system and, finally, to apply the strategies for restoring the socioecosystem to achieve conservation and preservation of the area (Figure 4). Considering and considering the participation of the actors (society, business, civil associations, government orders and academia) for better decision making.

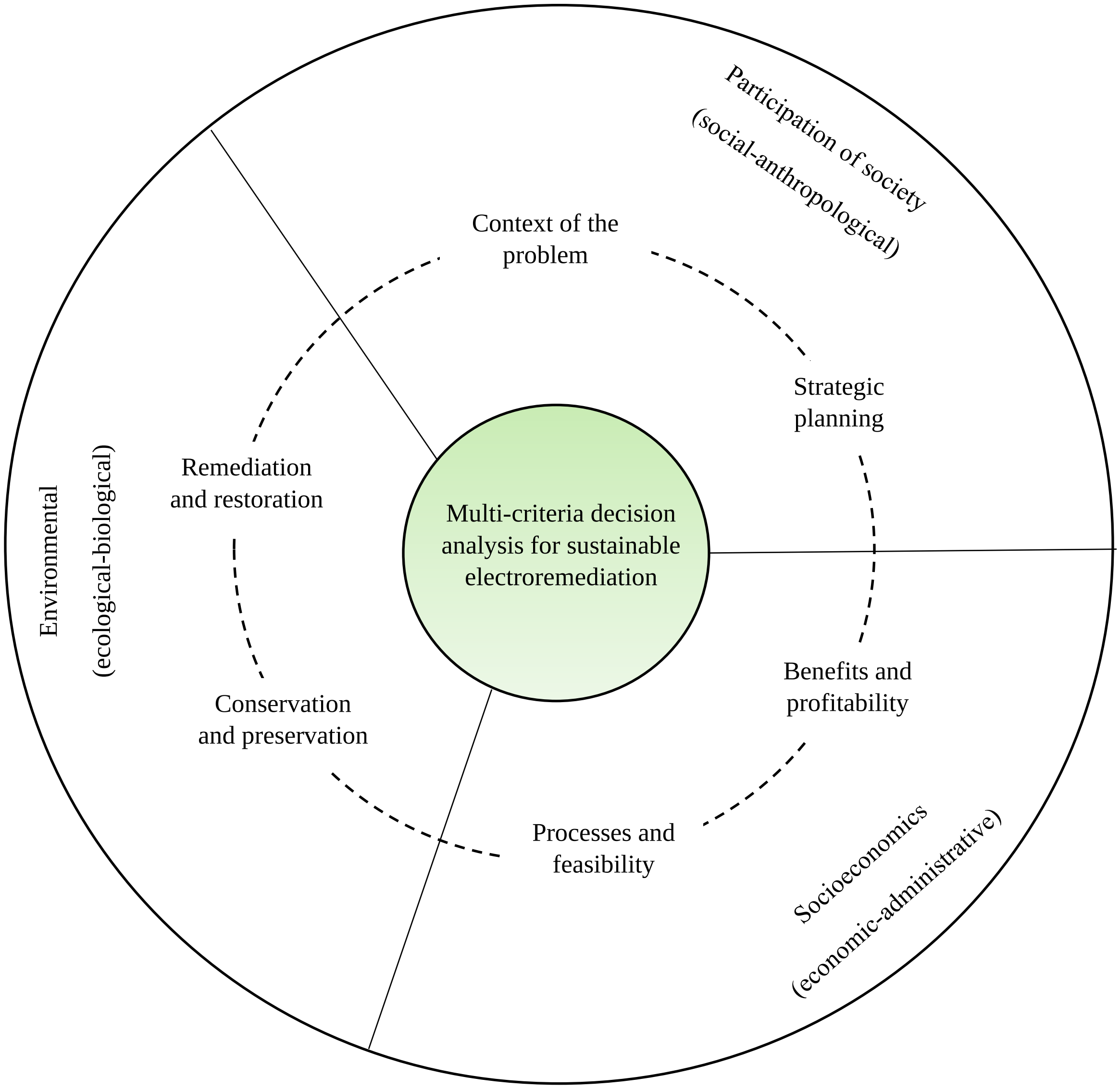

Figure 4. Framework for evaluating the efficiency and effectiveness of sustainable electroremediation from the multicriteria decision under the axes of sustainability. The circle is divided into three axes of sustainability. In each section there are dotted lines, which mean that these are some of the issues to be considered in each axis and, this, in turn, will help to reach the central point of the multi-criteria decision to apply sustainable electroremediation.

The interest in applying and taking seriously the sustainable electroremediation is that it can be interacted from a quantitative and qualitative approach (mixed model), where the interest in the degradation of environmental pollutants and their recovery brings an environmental, social and economic benefit. Without forgetting that each pollutant compound, social and economic behavior will differ by area (Sikkema *et al.*, 1992, 1995; Lemmer *et al.*, 2015). These multi and interdisciplinary projects will bring broader results of ecological-biological, social-anthropological and economic-administrative behavior to understand the system as a whole and achieve effective and affective conservation (Oyama and Castillo, 2006; Giraldo and Toro, 2020; Nature, 2022; Valdez-Hernández *et al.*, 2022).

It should be noted that when applying a multi-criteria decision analysis in conjunction with guidelines for the remediation of contaminated soils, recommendations must be updated as scientific information on risk factors and applicable technology and the theoretical matrices of electroremediation improve. On the other hand, when directing projects where environmental, social and economic rationality is applied, responsibilities should not be transferred to second or third parties or public or private entities as a way of evading or alleviating tension (Seefoó-Luján, 2005; Chan-Quijano *et al.*, 2015; Grifoni *et al.*, 2022).

It is precisely at this point that innovation must be made in science and technology for greater security and generation of knowledge for an application of sustainable electroremediation with positive results (Oyama and Castillo, 2006; Cereijido, 2009). In addition, de la Rosa-Pérez *et al.* (2007) highlights that the fundamentals of electrokinetics-hydrodynamics, the integration of the electrokinetic process with the treatment of wastewater generation and contaminated soils, the implementation of the renewable and sustainable electroremediation process, the electro-cultivation of different species are an important part of the experimental studies with biological technologies that generate knowledge to intensify processes and techno-economy.

Determination of indicators for contaminated soils: a tool for decision-making

For the evaluation of the sustainability of areas contaminated with organic and inorganic compounds, the remediation or electroremediation technique must be used. In addition, the importance of the attributes that control the main restrictions of the soil or are influenced by any of the soil functions being evaluated must be considered, that is, if any biotechnological alternative or natural attenuation is part of the guidelines for the recovery of the affected area (IMP, 2010; Navarrete-Segueda *et al.*, 2011). Likewise, there are different instruments where the different guidelines and indicators can be selected for the evaluation of contaminated soils according to the remediation and restoration objective (Mendoza-López *et al.,* 2013; Ruvalcaba-Sil, 2013). In this sense, the physical, chemical, biological and qualitative indicators of contaminated soil must be considered (Table 1; Etchevers-Barra *et al.,* 2009; García, 2012).

Table 1. Indicators for the evaluation of contaminated soils.

Physical indicators	Characteristics	Reference
Texture (% sand, clay, silt) Soil depth (cm) Infiltration (cm min^{-1}) and bulk density (g cm^{-3}) Infiltration rate Available water capacity Porosity and compaction Moisture retention (%) Penetration resistance (Mpa) Root system (cm) Aggregate stability (% 1-2 mm diameter)	The physical characteristics of soil cannot be easily improved, and the measurement of attributes is influenced by the use and management practices that are associated with the efficient use of water and nutrients and lead to an increase in agricultural production.	Dexter (2004)
Chemical indicators		
Organic matter (C and N) pH Electrical conductivity (dS m^{-1}) Extractable N, P and K Cation exchange capacity (meq 100 g^{-1}) Available heavy metals	They affect the soil-plant relationship, such as: water quality, soil buffering capacity and the availability of nutrients for plants.	Etchevers-Barra *et al.* (2009)
Biological indicators		
Microbial biomass (C and N) Mineralizable N (kg N ha^{-1}) Edaphic respiration, water content, soil temperature (kg CO_2-C ha^{-1} day^{-1}) Earthworms m^{-2} Crop yield	Microbial biomass is more sensitive to change than total C and directly affects the processes of incorporation and redistribution of various materials, in the formation of microbial communities, functions such as respiration rate, decomposition rates of plant residues, and N and C of microbial biomass are included.	Navarrete-Segueda *et al.* (2011)
Relief indicators		
Slope Land orientation Altitude Geomorphological unit (position in the relief)	It is based on visual attributes that show changes in the soil, reflecting decreases in the quality of soil processes such as: erosion by runoff, both diffuse and concentrated, the loss of surface horizons, as well as poor development of vegetation and derived from nutritional deficiencies.	Etchevers-Barra *et al.* (2009).

Source: modified and adapted from García (2012).

Environmental or sustainability indicators allow for the evaluation of the progress of environmental public policy and the effectiveness of implemented programs. They offer a practical tool that visualizes the follow-up through monitoring and evaluation of changes, their management and communication (García *et al.,* 2012), which depends primarily on the quality and quantity of the data and is reflected in terms of sufficiency, efficiency and representativeness of the information on contaminated soils.

Although there is no formalized procedure for the creation of environmental indicators, each country has followed different guidelines coupled with the characteristics of the place (Astier-Calderón *et al.,* 2002). In addition, various diagnostic methods have been proposed that are used in several Latin American countries, one of the most successful being the framework method for the evaluation of natural resource management systems through sustainability indicators (Masera *et al.,* 2000). Sustainability indicators must be developed considering the specific problems of each community or territory, in this case contaminated areas, and if a quantifiable indicator cannot be found, a qualitative assessment can be used (García *et al.,* 2012). Therefore, a compilation of information can be carried out and adapted in cases of contaminated soils to consider social, environmental and political-institutional factors (Table 2).

Table 2. Sustainability indicators adapted for contaminated areas and use of electroremediation.

General characteristics to consider in indicators for contaminated areas	
Environmental sustainability indicators	Vegetation cover
	Number of surviving plant species with the ability to tolerate the contaminant
	Agrobiodiversity index
	Physical-chemical parameters of the soil
	Microbial biomass of the soil
	Soil quality and fertility
	Diversity of productive activities in the affected area
	Animal well-being and health
	Rate of reforestation or ecological restoration
	Water quality
Social sustainability indicators	Quality and availability of water sources
	Type of land tenure (contaminated soil)
	Extension of farms affected by contamination
	State of affected livestock infrastructure
	Access routes to the contaminated area
	Availability of public services
	Educational level
	Perception of families regarding the problem of contamination
	Recovery technologies applied in affected areas
	Innovation and capacity for innovation and biotechnological commercialization for remediation
	Generational change
	Production costs
	Decision making
	Distribution of income among productive activities
	Food sovereignty index in case the affected area is a crop area
	Concessions
	Use of local seeds of species with remedial capacity
	Degree of integration in strategic planning and direction for decision making
	Participation and organization in the community
	Participation in training activities for remediation of affected areas
Indicators of economic sustainability	Agricultural and livestock yield
	Soil productivity
	Number of affected crops per farm
	Livestock profit, benefit/cost ratio
	Financial capacity of the project to recover the affected area
	Net income of the production unit
	Net present value
	Generation of added value

Source: IMP (2010); Chan-Quijano *et al.* (2015); Arnés (2018); Chan-Quijano *et al.* (2023a).

When working with contaminated soils, the general sustainability attributes of stability, reliability and resilience of the socio-ecosystem must be considered, with their respective diagnostic and characterization criteria, as well as the diversity of natural resources affected in the area or that are in the remediation process. Likewise, to apply the guidelines for sustainable remediation, the types of management such as extractionist, protectionist, traditional, productive, collaborative, technical-biological, sociocultural, adaptive, holistic, integral, tetrapartite and self-management must be considered to generate the diagnostic criteria and, with it, know what biotechnology to apply to the contaminated area, since each area is different. On the other hand, the sustainability indicators and attributes must consider the control/distribution of resources, self-sufficiency, organization and participation of the affected communities (López-Jiménez and Chan-Quijano, 2016; Chan-Quijano *et al.,* 2023a).

With the sustainable indicators that can be created with respect to contaminated soils, environmental public policies can be generated that help in the recovery and remediation of contaminated soils. In addition, strategies are generated to help the government and companies make better decisions for sustainable remediation and electroremediation of the affected area (Martínez-Alier and Roca-Jusmet, 2013; Lajous, 2014; Chan-Quijano *et al.,* 2023b). Thus, sustainability must be understood as an articulated discipline of knowledge and as a new holistic vision in the relationship of humans with nature, based on the integrality of the economic, governmental, social, environmental and value dimensions, which leads to an awareness and sensitivity with planet Earth and not only as a term that enjoys good social acceptance (Zarta-Ávila, 2018; Meli *et al.,* 2022).

Scope of sustainable electroremediation

In terms of sustainable electroremediation, this bioelectrochemical biotechnology is intended to support the recovery of the contaminant and, at the same time, the remediation of the soil and, in turn, a generator of clean energy with the technique of bioelectricity generated by the biogeochemical processes of microorganisms and their interaction with plant species; that is, electroremediation can be a good sustainable technique for harvesting energy derived from the use of low-power electronic devices that derive their energy from external sources, such as microbial fuel cells, solar energy, thermal and kinetic energy (Osorio-de-la-Rosa *et al.,* 2019; Valdez-Hernández *et al.,* 2022).

As part of this synergy, sustainable electroremediation seeks, within economic, social and environmental perspectives, effective processes in contaminated soils and, with this, an action towards green technology and environmental improvement of the affected areas by reducing the toxicity of contaminants (Yazdani and Asadollahfardi, 2020). In this sense, the United Nations Organization (UN, 1987) within the Brundtland report seeks that sustainable development can meet the needs of the present without compromising the ability of future generations to meet their own needs. However, it is necessary to understand the concept as part of the management of remediation and recovery of contaminated areas.

Sustainability in the remediation of contaminated soils that is often attempted to be presented is more apparent than real, therefore, an effective tripod (economic, social, environmental) must be guaranteed within the Earth-system, life-system and human-life-system that guarantees at least 80 % recovery of the ecosystems (Boff, 2013; Meli *et al.,* 2022). Prescott-Allen (1997) and Zarta (2018) highlight that the relationship between economic growth, social equity and environmental sustainability to give rise to an efficient and effective sustainable development of contaminated soils must be analyzed using the Nijkamp triangle or the sustainability barometer for a good guideline.

In addition, eight Millennium Development Goals were defined, one of which was environmental degradation, and it seeks to remedy areas affected by ecosystem pollution (UN, 2000), and the new universal agenda 2030 seeks to transform our world with 17 sustainable development goals, aiming to achieve sustainability (UN, 2015a; 2015b). In this same sense, with sustainable electroremediation, objectives 3, 6, 7, 13, 15 and 17 can be covered, that is, by reducing the negative effects of contaminated environments, it combines goods and services with remediation with clean technologies, non-destructive to nature and, in turn, will achieve the participation of citizens in decision-making before, during and after the sanitation process to achieve a healthy environment for the development and well-being of human rights (CNDH, 2016; Zarta-Ávila, 2018).

Likewise, the General Law on Ecological Balance and Environmental Protection (LGEEPA; DOF, 2023) seeks to establish competencies between the three levels of government (municipal, state and federal) through environmental, economic and social criteria and indicators for the improvement, productivity and quality of life of people. Likewise, it seeks new friendly biotechnologies, as well as public policies for the remediation and recovery of contaminated ecosystems. However, this has not been enough to advance decisively in the remediation of contaminated soils and towards sustainable development in Mexico. Hence, the need to promote an exchange that helps promote the best and most harmonious development for the country with the social, environmental and economic dimension, supporting with greater integrity responsible behaviors, empowering people to assume their leading role with their community and space in which they are located.

CONCLUSIONS

Sustainable electroremediation serves as an innovative, inter- and transdisciplinary alternative in decision-making for the recovery of contaminated soils, since it considers the social, environmental and economic axes within the remediation processes. At the same time, by considering indicators under the three axes of sustainability, a recovery of contaminated areas will be achieved from a sociocultural, socioenvironmental and socioeconomic perspective as part of the strategies of sustainable electroremediation. On the other hand, when there is a political, social and business will, transversal policies can be generated for the care of the environment; in order to integrate the different elements that characterize it: the environment, resources, social and economic aspects. In addition, with the legitimate environmental interest in sustainable electroremediation, important tools can be created from evidence-based policy for the recovery of socioecosystems affected by contamination and, in turn, scientific and technical evidence will be generated for multicriteria decision-making. The availability of innovative techniques for the recovery of contaminated soils affects human and environmental health and can generate a systematic analysis of legal instruments that support the remediation of contaminated soils since there will be social participation and, with it, strategies will be formulated for the planning and construction of public policies focused on contamination, following up on the government plans and programs of the different agencies and the various international commitments.

Funding. Part of this publication was funded as a review article under the project "Socio-environmental impact of contaminated soils in Tabasco, Mexico" by the Red de Soluciones Ambientales y Sociales, A.C. (REDSAS A.C.).

Conflict of interest. The authors declare no conflict of interest.

Compliance with ethical standards. Does not apply.

Data availability. If information is required, the corresponding author can be contacted.

Author contribution statement (CRediT). J.G. Chan-Quijano: conceptualization, formal analysis, writing, review, editing, visualization, **R. Bravo-Honorato**: writing- review and editing, **E.M. López-García**: formal analysis, writing, review, editing, visualization.

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