Environmental Footprint Analysis Tools of Electrokinetic Remediation (EKR): A Bibliometric View of The Literature

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Abstract. Electrokinetic remediation (EKR) technology has been applied in both lab and pilot scales to actual size since 1993. Recently, sustainable measures for EKR have been relatively considered a form of minimizing resource use during land restoration. This study aims to identify the environmental footprint assessment tools that arise during the EKR process according to the scale of the application. 284 scientific literature indexed by Scopus and the Web of Science during 2011-2021 was analyzed using the Systematic Literature Review (SLR) method, and the results were visualized using the VOSviewer application. The investigated parameters included the amount of scientific literature, year of publication, topics of scientific literature, authors of literature and their country of origin, names of reputable journals, and a number of citations. Research results from 43 scientific literature studies show that different environmental footprint analyses in EKR have been applied in various parts of the world. Most of environmental footprint assessment tools used by researchers include life cycle assessment (LCA) and green and sustainable remediation (GSR) tools. A recommendation is given to the GSR tools developed by the US EPA because known to have the simplest analytical method compared to other methods.

1. Introduction
The rapidly growing industrialization impacts the environment, such as waste that needs to managed appropriately. The waste produced as a by-product is generally organic or inorganic [1]. There are various technologies that act as physical-chemical and biological approaches to remove contaminated land and water bodies. However, the critical point for selecting the right technology depends on the characteristics of the pollutant, economic, and social aspects [2]. The technology that has existed since 1993 and has developed in the last decade is electrokinetic remediation (EKR). The advantages of this soil and water remediation technology include being more efficient in time, easy to operate, and can be applied in situ or ex-situ [3]. EKR operation involves an electric current to remove pollutants in the soil. The processes include (i) physics, conduction of electricity through electrodes into the ground, and (ii) electrochemical, oxidation-reduction processes along the electrode surface [1,4]. Electrochemical processes include electro-migration (movement of ions in the soil), electrophoresis (movement of...
charged particles), and electro-osmosis (movement of water in the ground due to the influence of an electric field) [4].

Pollutant removal activities using EKR technology have a weakness, i.e., promoting a negative impact on the environment. EKR activities require electrical energy, electrode materials, and supporting materials such as electrolytes for proper installation and operation [5]. The number of materials and chemical substances, the electrical energy used, and the consumption of natural resources cause gas emissions and pollution to the environment [6]. This negative impact on the environment leads the necessity to evaluate the environmental footprint.

Evaluation of the environmental footprint for sustainable remediation and EKR was initiated by the US EPA through the NICOLE project (1997) in the form of a life cycle analysis specifically for remediation [7]. Furthermore, in 2006, the Sustainable Remediation Forum (SuRF) was established in the USA as a milestone in developing standardized remediation tools. Until now, SuRF has already existed in several countries such as Australia, the UK, Netherlands, Brazil, Canada, Taiwan, and Italy. SuRF-UK assesses EKR as one of the green-remediation technologies that have the potential to be more environmentally friendly than other remediation technologies such as air sparging, natural attenuation, and pump-treat combinations [6]. EKR does not require further processing and additional costs for soil disposal. Previous studies show that replacing conventional electricity with solar panels can reduce operating costs, while delaying electrode replacement [8-11]. In addition to the tools initiated by SuRF, there are also other tools such as ISO 18504:2017 Soil Quality Sustainable Remediation, QUALICS, Green Remediation Japan/ GRAT-J, US EPA’s GSR Tool, and ASTM E2893d-16e1 Standard Guide for Greener Cleanups.

Before evaluating the environmental footprint on a remediation project, it is necessary to have a literature review related to the measurement tool for environmental footprint analysis. The purpose of this study is to identify the environmental tools for EKR activities based on a systematic literature review (SLR) and bibliometric analysis; also synthesize environmental footprint clusters in the EKR topic [12,15]. Visentin, one of the researcher, found 44 papers from 2007 to 2018 related to sustainable remediation. The EKR topic included as one of the literature evaluated the environmental impacts of remediation techniques. SLR and bibliometric analysis are used to identify environmental remediation tools, especially the environmental footprint in this study.

2. Methodology

2.1. Overview

The research period was between February and June 2021. In SLR and bibliometric analysis, a systematic classification of publications is crucial since it identifies theory development, type of journal, author’s name, and author’s origin [12,13,14]. After the identification process, the input obtained can fill the gap regarding the most suitable device for EKR.

Sources of information search come from reputable international journals and chapters in books. The criteria for articles to be reviewed include: (1). the scope of the research is limited to the topic of remediation of polluted soils, particularly EKR; (2). the relationship between research objectives and green remediation/sustainability/life cycle assessment; (3). the time span of articles published in the past ten years, namely 2011-2021; and (5). They were written in English. English is an essential criterion regarding article uniformity and ease of interpretation [15]. The indexes used in the search are the Scopus and the Web of Science (WoS). The two indexes feature completeness of abstracts and journal citations. The range of articles for both the Scopus and the WoS is also diverse, covering basic research, applied research, patents, conferences, and seminars [12].

2.2. Literature search procedure and analysis

The keywords used in searching the Scopus and the WoS databases include “Electrokinetic Remediation OR EKR OR (Electro KineticS Remediation) EKSR AND Green Remediation AND Sustainable Remediation AND Environmental Assessment.” The words "AND" and "OR" are Boolean operators to separate combinations in the search. For example, the search is done by submitting the comment "AND,"
then there are two terms that appear, namely "Electrokinetic Remediation" and "Green Remediation." When the word “OR” is used, there is a choice between “EKR” or “EKR.” Management of the collection of selected literature database lists using the Mendeley™ application and EndNote online.

The working system of the database is to match the combination of words in the title, abstract, and keywords, then search for the appropriate literature. The initial search results obtained 264 literature, consisting of 139 literature in the Scopus and 125 literature in the WoS. These results show equivalence between topics for the search for electrokinetic remediation, green remediation, sustainable remediation, and environmental assessment. The bibliographic-based search method, as shown in Figure 1, a bibliography-based selection process [16]. The literature was sorted, and 198 non-conforming literature were eliminated. The suitability of the literature with the title and abstract was then assessed, as a result 23 literature was eliminated. The final results of the literature to be reviewed in this study were 43 literature. The last step after getting the literature was data extraction, then synthesizing various things from the literature that have been chosen. The main objective of data synthesis was to analyze various research results, and to select the most appropriate method to integrate interpretation of the multiple findings [16].

![Figure 1. Selection of Bibliography-based literature referring to the keywords of EKR, green remediation, sustainable remediation, and environmental assessment.](image)

The 43 scientific literature titles were reviewed based on the year of publication, the author of scientific literature, the journal’s name and its reputation value, the country of origin of the principal author, and the topic of the journal. Data compilation was carried out by transferring .xml format from Mendeley™ and EndNote online into Ms. Excel spreadsheet, analysis of inter-author contributions, and inter-topic clustering were visualized using VOSviewer™ software. VOSviewer™ functions as a quantitative bibliographic data processing application. Furthermore, an entire bibliographic portfolio is obtained that displays device topics in the environmental footprint specific to EKR.
3. Results and Discussion

3.1. Development of study on environmental footprint process of EKR

The stage used in the elimination of literature sources from 264 to 66 was the screening stage. One hundred ninety-eight articles included in the proceedings and book chapters, not written in English, unclear methods, outside the topic of remediation were excluded at this stage. Furthermore, 23 articles that did not include EKR as a topic of discussion were banned at the eligibility stage. In 2011 to 2013 publications, there was no specific literature that discussed the environmental footprint of the EKR process (Figure 1). It is reasonable because the development of case studies was still limited to other remediation activities such as bioremediation. In 2009-2011, pilot-scale remediation land clean-up activities were recorded, and published for the first time by the US Environmental Protection Agency (US EPA) at Romic East Palo Alto, BP Wood River and Travis Air Force Base (https://cluin.org/greenremediation/footprintassessment). The US EPA developed a methodology called Spreadsheets for Environmental Footprint Analysis (SEFA) to analyze the environmental carbon footprint of remediation activities, piloted at accurate scale in 2014 at Williams Air Force Base, Site SR012, Mesa, Arizona. The development of working papers for further evaluation includes the Green Remediation Evaluation Matrix (GREM) by the CA Department of Toxic Substances Control (CA DTSC), the Greener Cleanups Matrix by the Illinois EPA, SiteWise™ by the US Navy, US Army Corps of Engineers, Battelle, and Sustainable Remediation Tools (SRT) by the Air Force Center for Engineering and Environment. In 2014, green remediation sustainability (GSR) tools based on SiteWise™ at the Janghan in-situ facility, South Korea is also discussed [5].

Throughout 2015, there was no literature discussing the sustainability of the EKR process because most EKR researchers were developing various EKR technologies and their combinations on a laboratory, pilot, or actual scale. EKR research, sustainability analysis, and the development of its tools take at least one year. It also affects the fluctuations in the amount of literature from 2016 to 2021. The number of publications in 2018 and 2021 increased along with the benefits of environmental footprint tools such as LCA, SURF-UK, QUALICS, and GRAT-J were also used for decision making before remediation work was carried out [7,12,17,18,19,20].

![Figure 2. Number of literature and publishing year.](image-url)
3.2. Researcher and Country of Origin

The analysis results, based on VOSviewer (Figure 2), show four authors who have in-depth research topics on EKR, environmental footprint tools, and its sustainability. Authors who have a strong network are Thomé et al. (2019-2020), Rodriguez-Maroto et al. (2017-2018), Ferro Sergio et al. (2017-2018), and Gill et al. (2014-2018). The environmental footprint research collaboration for EKR is still agglomerated within each continent, namely researchers from the Americas consisting of the US and Brazil; researchers from the European continent consisting of England, Spain, and Italy. There were also researchers from the Asian continent, namely China, Taiwan, South Korea and Japan. The trend of researchers from China has increased since Hou compiled ISO 18504:2017 and wrote book chapters with other researchers such as Wang. South Korean researcher Baek collaborated with researchers from China, Chen collaborating with researchers from the US, New Zealand to develop sustainability likelihood using gaming tools developed with other tools in remediation. The LCA tool also acts as a decision-making tool [12,22].

Braun explained more coherently the reasons for implementing sustainable remediation, the need to build perceptions among stakeholders, conducting risk management analysis, and developing multi-criteria decision analysis devices to justify sustainable remediation [23,24,25]. Da S Trentin and Reddy, specifically developed QUALICS, an environmental footprint tool to assist decision making that combines the analytical hierarchy process and integrates value model for sustainable assessment, along with sensitivity analysis [20]. Reddy himself is one of the originators of EKR technology originating from the US. He and colleagues recommended a life cycle sustainability assessment as an environmental footprint analysis tool to measure the effect of remediation on climate change [26,27].

SURF, started in the UK, has pioneered other countries in Europe such as Italy and Spain in environmental assessments of EKR. Gill, Harbottle, Smith, and Thornton from the UK recommended the EKR technique combined with bioremediation, using SURF-UK with 2 Tier [28,29]. Smith, later with Bardos developed SURF-UK based on multi-criteria considerations [19]. Rodriguez-Maroto from Spain, in collaboration with Gomez-Lahoz, Vereda-Alonso, Paz-Garcia, and Villen-Guzman, developed a mathematical model to predict energy demand based on the type of metal pollutant in the EKR process [30]. This energy demand can then help estimate the environmental footprint as well as decision-making [31]. While the researcher Ferro S. from Italy, together with Vociante, Bagatin, and Terruci in a row
during 2016-2021, examined the best EKR strategies so that the impact of EKR on the environment is reduced, one of the tools used is the GaBi LCA software [1,32 - 34].

3.3. Topic Categorization and Environmental Footprint Tool Recommendations for EKR

Research topics were categorized based on the relationship between words using VOSviewer (Figure 4) to obtain three clusters of environmental footprint tools that describe environmental footprint tools, the study of decision making in the EKR project, and the efforts made in the context of saving energy and natural resources. Efforts to save energy and natural resources are included in the scope of the environmental footprint for carbon reduction [1,18].

Figure 4. EKR network of cluster topics.

The red cluster (Figure 4) is the first cluster with the terms “contaminated site,” “sustainable remediation,” “assessment,” “sustainability,” and “life cycle assessment,” which means assessment of polluted soil using LCA analysis for sustainable remediation technology. The topic of remediation in the assessment was not limited to EKR alone but other remediation activities [17,18,19,20,27,36,37]. From thirteen literature, only six literature discusses LCA tools and GSR tools for EKR. However, the environmental footprint assessment tool also applies to the implementation of the EKR. The EKR study based on the ISO 18504:2017 Soil Quality Sustainable Remediation and ASTM E2893d-16e1 Standard Guide for Greener Cleanups that has not been carried out can be an opportunity in the future.

The green cluster containing the terms “environment,” “contaminant,” “groundwater,” “bioremediation,” “project,” and “combination” is closely related to the word “decision making,” so that this second cluster focuses on decision making for EKR technology and combined EKR-bioremediation. Scientists in Brazil analyzed decision-making for EKR using sustainability criteria, and input from stakeholders in the form of AHP analysis [23–25]. Ecological model, human health assessment approach, INSIDE management model, a predictive model of energy consumption and heavy metal movement in soil, and the sampling point estimate model was initiated to provide input for decision making on EKR activities on a field scale [2,30,31,32,38,39]. EKR project financing factors in the form of economic models and technical-economical were also considered as elements of decision making [38,40]. A widespread combination of decision-making tools is the LCA quantitative mechanisms that is applied with other tools [22,41].
The terms “soil”, “electrokinetic remediation,” “removal,” “contaminated soil,” “heavy metal,” and “treatment” are the third base cluster shown in blue. The third cluster is related to the EKR technology itself, which was developed towards green remediation to remove heavy metals in contaminated soil. Energy and resource efficiency efforts are carried out in the form of electrolyte effectiveness studies, a combination of EKR with bioremediation, the combination of EKR with bioremediation and soil flushing, soil profile considerations, and the application of renewable energy sources [6,29,33,42,43,44,45,46]. The development of a more environmentally friendly EKR is not limited to being studied in one strategy but can be applied to two or more strategies at once [1,47]. Utilization of materials such as bio-char specifically for EKR-bioremediation, its functioned to save energy while eliminating multi-contaminants in the soil [48].

The network between clusters is connected to each other to form a bibliographic profile [Table 1] which shows the decision making in the EKR, aiming to achieve a sustainable balance of the environment and economy. The most common methods used by researchers of the environmental footprint are LCA and GSR tools (SEFA, SiteWise™) [Table 1]. The GSR tools method is adopted in the East Asian region such as South Korea and Taiwan because it is simpler and does not require the operation of specific software, only in the form of working papers [5,49].

Table 1 Bibliographic profile of EKR for synthetic topic of carbon footprint and sustainability

| Literature Reference | Scope of the Study | Highlighted Point |
|----------------------|--------------------|-------------------|
| Amponsah, et al. (2018) | Carbon Footprint Tool' for EKR | LCA evaluation for GHGs or Global Warning Potential (GWP) emissions from six ex situ land remediation technologies. |
| Ayyanar & Thatikonda (2021) | Multi Decision Criteria Analysis | Study of the effectiveness of various electrolytes in the context of cost efficiency of EKR. |
| Bardos et al. (2018) | Efficient Effort for EKR' Sustainability | SURF-UK consists of 15 criteria, 5 of which are environmental criteria. The tools can be applied to all remediation techniques, successful case studies reported in the UK. The term sustainable remediation in developing countries, e.g., Brazil, is still relatively new. Risk management and stakeholder considerations are included as criteria for implementing sustainable remediation. |
| Braun et al. (2019a) | | There are 8 methods for sustainable remediation and 9 methods for decision making. The AHP method is applied as a weighting criterion for stakeholders. The Monte-Carlo simulation was applied to 4 case study areas in 3 different countries. In-situ applications are considered more sustainable than ex-situ applications. |
| Braun et al. (2019b) | | |
| Braun et al. (2020) | | |
| Chen et al. (2017) | | |
| da S Trentin et al. (2019) | | |
| Ferrucci et al. (2017) | | |
| Gill et al. (2014) | | |
| Gill et al. (2016) | | |

Application of Tier 2 in the SURF-UK method to remediate MTBE pollutants. Air sparging/ soil vapor extraction and EKR-Bio scenarios are better than pump & treat and monitoring natural attenuation.
## Scope of the Study

| Literature Reference | Carbon Footprint Tool' for EKR | Developing Multi Decision Criteria Analysis | Efficient Effort for EKR' Sustainability | Highlighted Point |
|----------------------|-------------------------------|---------------------------------------------|----------------------------------------|------------------|
| Huang et al. (2016)  | V                             |                                             |                                        | Application of the SEFA GSR toolkit issued by the US EPA for two remediation scenarios to eliminate total petroleum hydrocarbons (TPHs). |
| Istrate et al. (2018)| V                             |                                             |                                        | Health risk assessment for humans is carried out for EKR based on laboratory-scale research in the context of eliminating TPHs and PAHs. |
| Khan et al. (2021)   | V                             |                                             |                                        | Selection of an appropriate remediation strategy to eliminate toxic elements in the soil, so that it is safe for the environment and human health. |
| Kim et al. (2014)    | V                             |                                             |                                        | An environmental impact assessment was carried out on a field- scale EKR project using the SiteWise™ working paper based on the US EPA’s GSR toolkit. |
| Koteswara (2019)     | V                             |                                             |                                        | Preparation of contamination level and ecological index in the form of pollution index (PI), geo-accumulation index (GI), and potential ecological risk index (RI). |
| Koteswara et al. (2020)| V                       |                                             |                                        | Model of cost estimation needs to be applied in the implementation of the EKR conventional and EKR modification. |
| Kumar & Reddy (2020)| V                             |                                             |                                        | Application of life cycle sustainability assessment and analysis of uncertainty in climate change for remediation. |
| Lim et al. (2016)    | V                             |                                             |                                        | The application of technology EKR- bioremediation and efficiency electrolyte for remediation were environment friendly. |
| Lima et al. (2017)   | V                             |                                             |                                        | The application of sustainable renewable EKR technology when applied to contaminated soil. |
| López-Vizcaíno et al. (2019)| V                       |                                             |                                        | EKR study which considers the aspects of engineering-economic on a 4 scale projects EKR done as a guide for the further study of EKR. |
| Millán et al. (2020) | V                             |                                             |                                        | Energy efficiency in the EKR process through the use of solar panels. |
| Naseri-Rad et al. (2020)| V                       |                                             |                                        | Methods INSIDE as a method of decision-making and management of the management of the remediation of soil. |
| Prasad et al. (2018) | V                             |                                             |                                        | Sustainable remediation approach for Chromium removal in contaminated soil. |
| Ramadan et al. (2018)| V                             |                                             |                                        | Technology joint between the EKR, soil flushing and bioremediation (EKSF-Bio), and surfactant as a flushing agent rated effective in the provision for soil contaminated with hydrocarbons. |
| Reddy et al. (2018)  | V                             |                                             |                                        | Quantitative device of life cycle sustainability assessment was used as a device determinant of engineering remediation of the best. |
| Song et al. (2018)   | V                             |                                             |                                        | Analysis of LCA was used as an analysis of the environment, the results were evaluated by the social and economic use of multi-criteria decision analysis. Analysis was carried out in China, the largest remediation marketplace country right now. |
| Villen-Guzman et al. (2018a)| V                       |                                             |                                        | Energy demand prediction model at various EKR project scales. |
| Villen-Guzman et al. (2018b)| V                       |                                             |                                        | Prediction model of heavy metal movement in contaminated soil, useful for selecting the best EKR treatment. |
| Visentin et al. (2019)| V                             |                                             |                                        | LCA implemented together with other tools can be used as a sustainability tool. |
| Visentin et al. (2020)| V                             |                                             |                                        | LCA implemented together with other tools can be used as a sustainability tool as well as a decision-making tool. |
### Literature Reference

| Literature Reference         | Scope of the Study                                                                 |
|-----------------------------|-----------------------------------------------------------------------------------|
| Vocciante et al. (2016)     | V Carbon Footprint Tool' for EKR                                                  |
| Vocciante et al. (2017)     | V Developing Multi Decision Criteria Analysis                                      |
| Vocciante et al. (2021)     | V Efficient for EKR' Sustainability                                                |
| Vocciante et al. (2021)     | V Highlighted Point                                                                |
| Volchkho et al. (2014)      | V Assessment of EKR activities according to global warming potential (GWP) parameters of a polluted land using GaBI LCA software. |
| Wang et al. (2021)          | V Application of EKR together with soil flushing in order to optimize the use of water and electricity. |
| Wu et al. (2021)            | V Optimization of the EKR process can be done through optimization of electrolyte consumption and the use of renewable energy. |
| Xu et al. (2014)            | V EKR carbon footprint assessment based on LCA procedure on a 700 m² contaminated land in Tuscany, Italy. |
| Yasutaka et al. (2016)      | V Decision-making techniques based on polluted soil conditions.                   |
| Zhang et al. (2021)         | V The use of bio-char as a carbon source for microorganisms in optimizing EKR- bioremediation techniques. |
|                             | V Optimization EKR through a combined placement of cathode-anode and the type of electrolyte that is appropriate to the allowance for Chromium. |
|                             | V EKR efficiency strategy based on energy expenditure and soil type.             |
|                             | V The GRAT-J method is an LCA -based spreadsheet to assess environmental performance during the remediation process. |
|                             | V Combination of LCA, EIA, analysis of cost-benefit and multi-criteria decision to analyze the technology remediation. |

### 4. Conclusion

A total of 43 literature were obtained based on the bibliographic selection method. The number of literature in 2011-2015 was minimal but showed a fluctuating increase throughout 2016-2021. There is a tendency to group researchers based on their respective continents, the Americas, the European continent, and the Asian continent. Several new tools have emerged and developed in developed countries that have field-scale EKR projects. The environmental footprint cluster in the EKR topic is divided into three, namely: environmental footprint tools, the study of decision-making in the EKR project, and efforts made to save energy and natural resources. The environmental footprint tools commonly used are LCA & its modifications and GSR Tools. The selection of these tools depends on the project objectives, economics, project scale, and stakeholder commitment. Stakeholder commitment, technical design, and adequacy of financing are considered for EKR project decision-making, while the decision-making method itself is developed based on the principle of sustainability. As a future opportunity, the environmental footprint for EKR based on ISO and ASTM standards can be studied in developing countries, especially the Southeast Asia region.

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