Sustainable Remediation: A New Way of Thinking the Contaminated Sites Management

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Abstract. Within the evolution in the remediation field, the traditional approach to contaminated sites management, based almost exclusively on the risk, time, cost, and decontamination efficiency, is gradually being replaced by the concepts of sustainability. The most recent focus is the incorporation of the term "sustainable remediation (SR)", taking into account that application of a remediation technique can have its own impacts. Thus, this paper aims to present and analyze the characteristics and trends on the knowledge developed in the field of SR and its incorporation in the contaminated sites management context. Firstly, the background to the SR approach is presented. This discussion was carried out through a contextualization of the main changes that occurred in the contaminated sites management with insertion of SR. After that, the main characteristics and concepts of SR are presented and analyzed, and the different stakeholders involvement in this process is discussed. Finally, the main elements present in sustainability evaluation of remediation processes are discussed. It can be concluded that a consensus on the increasingly solid incorporation of a sustainable approach in remediation projects is emerging on the global scene with a view to reducing the process impacts and maximizing the long-term benefits of the contaminated site.

Keywords: environmental remediation, literature review, stakeholders involvement, sustainability evaluation, triple bottom line.

1. Introduction

Environmental issues for a long time did not receive due attention. Anthropogenic activities, such as inadequate and unregulated industrial and waste discharges, have resulted in contaminated sites around the world. These actions have led to a rapid increase in pollutant loads in air, water and soil, limiting the environment ability to absorb such contamination without causing adverse effects on natural ecosystems and human health. Thus, for the many contaminated sites that emerged and could no longer be corrected by natural processes alone, and thus generated some kind of risk, they needed to be managed, generally undergoing some remediation and rehabilitation process (Van Liedekerke *et al.*, 2014; Reddy & Adams, 2015).

The most important factor of a remediation process conduction is the fact that contaminated sites can bring serious consequences for human health and the environment (Bardos *et al.*, 2002; Hou *et al.*, 2017). The main goal of remediation is to reduce the harmful risks that contaminated sites may bring, in order to protect human health and the environment (Petruzzi, 2011; Anderson *et al.*, 2018; O'Connor & Hou, 2018). However, there is already a broad understanding that remediation is not inherently sustainable. The very implementation of remediation technology can result in other environmental, economic, and social secondary impacts both in the short and long term, and can even overcome the benefits of its application, producing a negative effect or reducing the overall net benefit of the remediation process (Forum, 2009; Petruzzi, 2011; Adams & Reddy, 2012; Hou *et al.*, 2014a; Bardos *et al.*, 2016a; Vidonish *et al.*, 2016; Yasutaka *et al.*, 2016; Favara & Gamlin, 2017; Anderson *et al.*, 2018; O'Connor & Hou, 2018).

Therefore, while society can benefit from new land use opportunities such as residences and recreation by contaminated site remediation, corrective actions can result in unintended consequences. These include atmospheric emissions of harmful pollutants, waste generation, significant natural resources consumption including fossil fuels and energy, materials using, ecosystems disruption and risks to workers and the community, among other negative impacts (Petruzzi, 2011; Harclerode *et al.*, 2015a; Rosén *et al.*, 2015). So, a tension comes up between protecting people from the environmental pollution risk and potentially damaging side effects from remediation activities, which may be associated with global damage (O'Connor & Hou, 2018).

In this sense, the approach, decision-making and how the management of contaminated sites is carried out has

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been marked by some changes in recent years (Pollard *et al.*, 2004). Since the early 2000s, the interest in incorporating sustainability in this context of remediation has increased, through the dissemination of the term "sustainable remediation (SR)". Its inclusion and dissemination are recent but gradually increasing, because it reflects the perception that remediation activities can bring positive and negative environmental, social and economic impacts, and that considering these aspects in isolation is no longer enough. It is necessary to establish effective balances between the benefits of remediation and the harmful emission of secondary pollutants (Rizzo *et al.*, 2016; O'Connor & Hou, 2018). Therefore, SR is intended to consider in a balanced way the three pillars of sustainability, and to implement sustainable measures and practices during the development of the entire remediation process (Forum, 2009).

However, although SR corresponds to a new paradigm shift within the management of contaminated sites, it is still an emerging approach in this context, and has evolved gradually over the past few years (Bardos *et al.*, 2011; Pollard *et al.*, 2004; Reddy & Adams, 2015; Hou *et al.*, 2016). This indicates there is scope for studies that review and deepen the knowledge of SR main characteristics, in order to assist researchers and professionals in the field of contaminated sites management and remediation to choose the best solutions available.

In view of the above considerations, this paper aims to present and analyze the characteristics and trends of the knowledge developed in the field of SR in contaminated sites management context. This discussion includes the background of the SR inclusion in the contaminated sites management field, as well as a contextualization of SR with the main concepts, the different stakeholders involvement approach and in what form the sustainability evaluation is carried out in the remediation.

2. Background and Contextualization of the Sustainability Insertion in the Management of Contaminated Sites

Corrective action selection systems created over 30 years have represented the best knowledge and practices available (Forum, 2009). Historically, contaminated land management has relied heavily on preventing unacceptable risks to human health and environment to ensure that a site is suitable for reuse (Bardos *et al.*, 2011; Hou & Al-Tabbaa, 2014).

Likewise, the decision-making process to select the contaminated site remediation technique has traditionally focused on the cost and ease of implementation of the remediation process, on the availability and viability of the technologies, on the time needed for remediation and on the efficiency for remediation to achieve decontamination goals and compliance with existing laws (Vik *et al.*, 2001; Pollard *et al.*, 2004; Forum, 2009; Harclerode *et al.*, 2015a).

Although these considerations are critical components in a conventional remedial options assessment, over the years practitioners and researchers have become aware that in many cases the contamination was not being destroyed but only transferred to a different environment (Adams & Reddy, 2012). Moreover, this traditional remediation approach does not assess atmospheric emissions, natural resource consumption, energy use, and worker safety during the remediation process, in addition to not fully balancing the environmental, social, and economic impacts of a project, since they generally focus on "internalities" of a project (correction objectives, system performance, and local impacts) and devote minor attention to its "externalities" (impacts at local, regional, and global level) (Forum, 2009).

Therefore, research in this context needs to go beyond simply determining the effect of treatment on contaminants and whether contaminant removal has been achieved (SuRF-UK, 2010; Vidonish *et al.*, 2016). A variety of other environmental factors, as well as economic and social aspects, play an increasing role in decision-making in contaminated sites management (Reinikainen *et al.*, 2016). The increase in the recognition of secondary adverse effects associated with remediation operations was one of the main driving forces that helped to change the context of managing contaminated sites (Forum, 2009; Huysegoms & Cappuyns, 2017).

Thus, the remediation industry has shown interest in including sustainability as a criterion of decision-making during the application of a remediation process (Bardos *et al.*, 2011; Rizzo *et al.*, 2016). The first perspectives for the insertion of sustainability in the remediation contexts arose through the dissemination of the green remediation concepts. At the beginning, a great deal of concern was focused on the primary impacts due to the contaminated sites and the environmental impacts of the remediation processes (Søndergaard *et al.*, 2017).

In this sense, green remediation is generally described as the practice that takes into account all the environmental effects and aspects of the remediation techniques application, seeking to use more ecological options and alternative/renewable sources of energy whenever possible, in order to maximize the environmental benefit (USEPA, 2008; Bardos *et al.*, 2013; Hadley & Harclerode, 2015). In addition to energy, green remediation relies on four other key elements to achieve its environmental objectives, such as: water; air and atmosphere; materials and waste; and land and ecosystems (USEPA, 2011). Therefore, green remediation is intended to improve environmental performance, reducing environmental impacts and conserving natural and ecological resources during remediation actions (Bardos *et al.*, 2013).

Green remediation was adopted by USEPA, in the United States, to regulate sustainability assessments in remediation projects. Some authors consider green remediation as a variant for SR (Hou *et al.*, 2014b). Others consider that SR can mean green remediation, when it is considered that reduced energy consumption minimizes greenhouse gas emissions; that lower environmental impacts are associated with cost reductions; and that green practices can lead to better and faster social acceptance, since stakeholders generally agree that the remediation process should be driven by the selection of green and environmentally friendly techniques (Baker *et al.*, 2009; Fortuna *et al.*, 2011).

However, most authors point out that the terms are not equivalent and there are differences in its approaches, since the application of green remediation may not achieve the sustainability goals, because alone it does not represent a complete and comprehensive approach, whereas it considers only the environmental aspects (Bardos *et al.*, 2013; Hadley & Harclerode, 2015; Bardos *et al.*, 2016a). Thus, with a view to a broader and holistic approach to sustainability, the two concepts are sometimes considered together as Green and Sustainable Remediation (GSR), addressing a range of environmental, social and economic impacts during all stages of remediation (Reddy & Adams, 2015). Yet, more recently and broadly, the term "sustainable remediation" has been used to express the balanced incorporation of the "Triple Bottom Line" in the context of contaminated sites management and remediation, as shown in Fig. 1, looking beyond the focus solely on risk control, but considering the overall environmental, economic and social benefits and impacts of remediation (Hou & Al-Tabbaa, 2014).

3. Characteristics and Concepts of SR

Sustainability and sustainable development represent complex, subjective and ambiguous concepts. The most commonly sustainability definition quoted internationally and widely accepted is that of the Report of the World Commission on Environment and Development - Brundtland Commission of 1987. Sustainable development is defined as meeting the needs of present generations without compromising the capacity of future generations to meet their own needs (Brundtland, 1987).

Since then, many have promoted adaptations and derivations of this definition to the most different fields, organizations, and specific sectors. SR applies the principles of sustainable development, since the latter has in essence the objective of promoting the balance between considerations of social, environmental and economic aspects, as well as between local and global needs (Bardos *et al.*, 2011; Virkutyte & Varma, 2014; Nathanail *et al.*, 2017).

Sustainable Remediation is an emerging study field and the growing interest and development of its concepts represent the advancement and maturity of contaminated sites remediation industry (Hou *et al.*, 2014b; Hadley & Harclerode, 2015). The understanding of what SR means as a whole has evolved in recent years, largely driven by the work of agencies and organizations working in the context, as well as studies developed by the scientific community (Hou *et al.*, 2014b), and different definitions are linked to the term (Cundy *et al.*, 2013). Table 1 provides the most common definitions used to represent the concept behind SR.

There is a high level of consensus among the definitions given in Table 1. It is clear the broad purpose of SR to reduce environmental, economic, and social impacts and to optimize and/or maximize long-term benefits of remediation projects, in a balanced decision-making process (Cundy *et al.*, 2013; Rizzo *et al.*, 2016). Therefore, the definitions tend to emphasize decision-making in a proportional and balanced way across all three elements/pillars of sustainability; the optimization of process benefits; the search

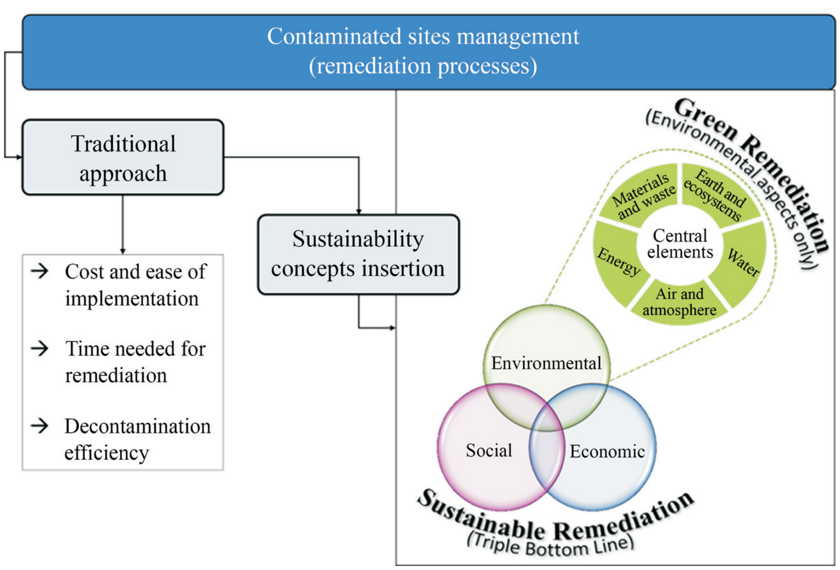

Figure 1 - Evolution of sustainability considerations in the context of contaminated sites remediation.

Table 1 - Examples of defining SR.

Reference	Definition
NICOLE (2010)	A SR project is one that stakeholders agree to represent the best solution considering environmental, social and economic factors, and where the benefits achieved outweigh the impacts.
SuRF-UK (2010)	SR is the practice of demonstrating, in terms of environmental, economic and social indicators, that the benefit of remediation is greater than its impact, and where the optimal solution is selected through a balanced decision.
ITRC (2011a, b)	SR refers to an integrated assessment of the environmental, economic and social impacts of corrective activities.
SuRF-US (Holland *et al.*, 2011)	SR can be defined as an alternative or combination of alternatives whose practice is to protect human health and the environment while maximizing the net environmental, social and economic benefits throughout the life cycle of the remediation project.
ISO (2017)	The practice of SR consists in eliminating and/or controlling the unacceptable risks of the remediation process in a safe and timely manner, optimizing the environmental, social and economic value of work.
Bardos (2014)	SR is a process of finding the ideal means to manage the risks associated with the remediation process. Therefore, in a generic sense it aims to achieve a global net benefit in the face of a series of environmental, economic and social concerns that are considered representative of sustainability.
Holland (2011); Hou *et al.* (2014c); Hadley & Harclerode (2015)	SR seeks to maximize benefits and reduce the overall environmental, economic and social impacts of remediation actions to ensure the protection of human health and the environment.
Bardos *et al.* (2016b)	SR is the process of effectively managing the risks to human health and the environment associated with the contaminated site and remediation processes, so as to minimize environmental footprint, maximize social benefits, and minimize the costs of such remediation activities. In addition, SR is the process that seeks to optimize the selection of remediation activities, promoting the use of more sustainable practices.

for the ideal means to find sustainable solutions; the management of risks and protection of human health and environment in general; the long-term vision; the identification of the best option among those available; the use of indicators to assess sustainability; and stakeholder involvement in the process (Rizzo *et al.*, 2016).

The balance between the three elements of the sustainability tripod has been a key factor in the approach to SR. Environmental elements go beyond soil and groundwater quality, but also include the use of non-renewable resources and the production of waste and air pollutants, for example by adopting *in situ* options that prevent truck driving through a neighborhood, producing exhaust smoke, consuming fuel and energy (Slenders *et al.*, 2017). Social elements are related to the deeper assessment of how the local community and global society are affected in a beneficial way and adversely by remediation activities, such as the nuisance due to dust, odor and noise from remediation work and the overall risk to human health, as well as the risk resulting from physical accidents to workers (Harclerode *et al.*, 2015b; Slenders *et al.*, 2017). The economic elements are associated with the full cost of the short- and long-term life cycle of the remediation process execution, and these must be evaluated in terms of risk reduction, increase in the site value and the resulting use, and improvement of ambience in general (Slenders *et al.*, 2017).

The net benefit has also been a central element of discussion in the conceptualization of SR. Reaching the net benefit is related to choosing alternatives, not only to reduce the risk to the health of site users but also to minimize costs, including both detrimental direct environmental, social and economic impacts during the remediation operation. Besides, this considers indirect harmful impacts during, for example, the acquisition of materials and energy and waste disposal associated with remediation (Forum, 2009; Hou *et al.*, 2017).

The SR approach also encourages the remediated sites reuse in order to achieve sustainable benefits from the entire system, including the brownfields redevelopment. SR in the context of site reuse involves finding the best balance between remediation and reuse options. SR increases value when associated with feasible reuse and increases long-term financial returns for investments. Locations can be reused in a conventional way (*e.g.*, for commercial, industrial or residential use), or require innovative forms of reuse (*e.g.*, for interim or ecological uses) (Bardos *et al.*, 2011; Holland, 2011; Holland *et al.*, 2013; Bardos, 2014; Mobbs *et al.*, 2019).

In general, the main mission of SR continues to be the reduction of the contamination risk, but its concept has brought greater attention to the side effects and contradictions often neglected in contaminated sites management and remediation (Hou & Al-Tabbaa, 2014; Anderson *et al.*, 2018). SR requires not only the identification of a technical solution, but an informed debate, discussion, negotiation and transparent decision-making (Mobbs *et al.*, 2019).

Sustainable Remediation provides a specific context to find the best solution by comparing different corrective alternatives, since there is no definitive sustainable solution (Hou *et al.*, 2018). In view of this, there is a variety of criteria which determine a SR process, and such criteria may include: that future benefits outweigh the cost of remediation; the environmental, social and economic impacts of implementing the remediation process are less than the impact of leaving the site untreated; the remediation process impacts are minimal and measurable; the time scale over which the consequences occur is part of the decision-making process; and the decision-making process includes an appropriate level of involvement of all stakeholders (Al-Tabbaa *et al.*, 2007).

As such, the adoption of SR presents specific benefits that make it an important approach and increasingly necessary in this environment, as well as clear drivers for its realization and fundamental objectives and characteristics (Forum, 2009; Bardos *et al.*, 2011; Fortuna *et al.*, 2011; Kalomoiri & Braida, 2013; Martino *et al.*, 2016; Slenders *et al.*, 2017), as can be seen in Fig. 2.

The importance of sustainability considerations in contaminated sites management is already prominent in political, organizational and business frameworks around the world. In recent years, a growing number of agencies and

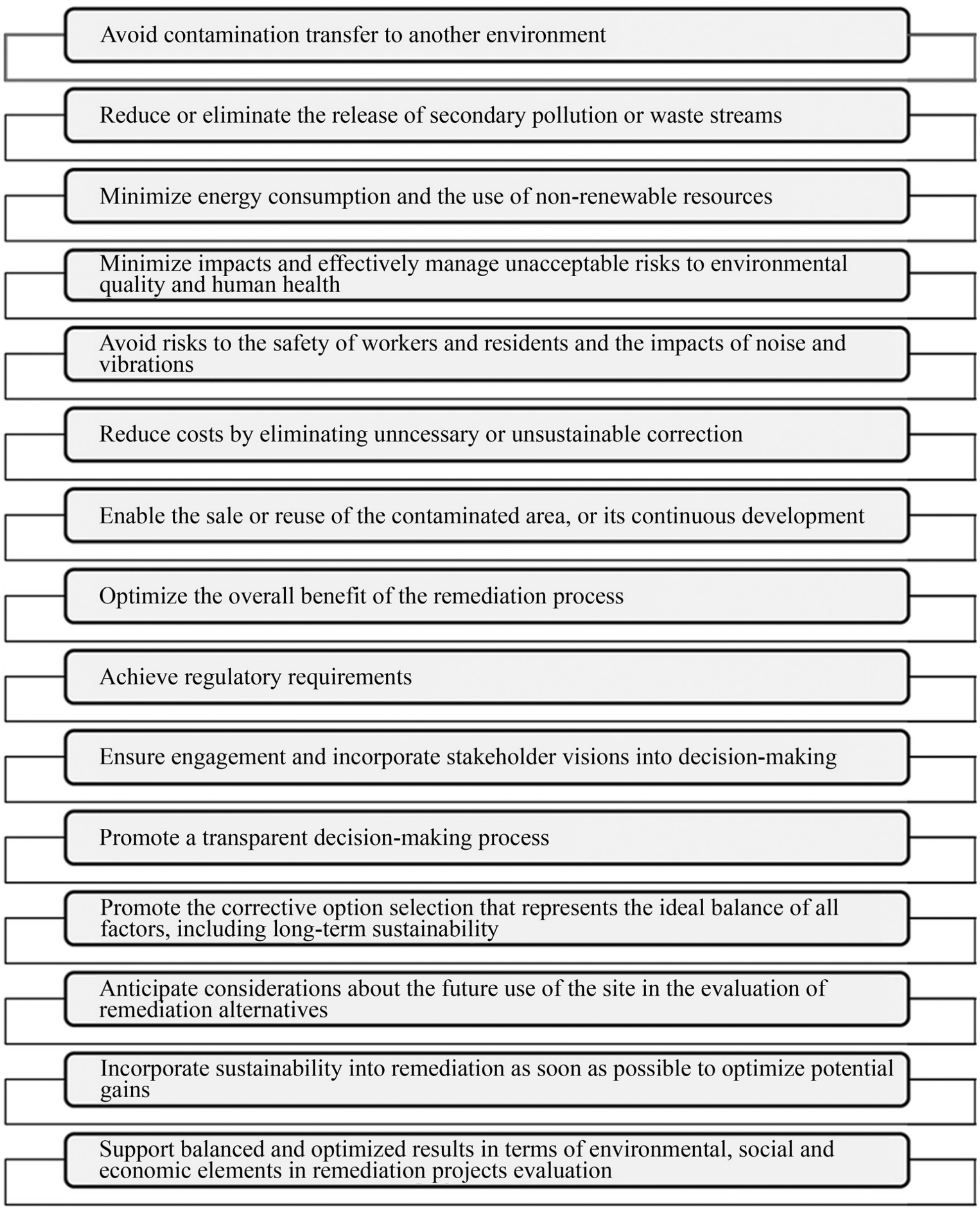

Figure 2 - Main objectives and characteristics of SR.

organizations from different countries have been debating SR and its approach in regulatory contexts (Hou & Li, 2018). These debates are followed by the adoption of SR procedures, publishing technical and normative guidelines, as well as guiding documents with structures, methods and tools to support evaluation and decision making (Holland, 2011; Sparrevik *et al.*, 2011; Huysegoms & Cappuyns, 2017; Anderson *et al.*, 2018; Song *et al.*, 2018).

The Sustainable Remediation Forum (SuRF), which began in the United States and was created in 2006 by professionals involved in remediation projects, researchers and industries, is the first coalition dedicated specifically to the promotion and application of remediation concepts (Bardos *et al.*, 2013; Hadley & Harclerode, 2015). Currently SuRF has partner organizations and groups also in the United Kingdom (SuRF-UK), Brazil (SuRF-Brazil), the Netherlands (SuRF-NL), New Zealand and Australia (SuRF-ANZ), Canada (SuRF-Canada), Italy (SuRF-Italy), China (SuRF-Taiwan), Japan (SuRF-Japan), and Colombia (SuRF-Colombia). These SuRFs share the progress, learning and work each group is carrying out in their different countries towards SR.

In addition to the SuRFs, other organizations are dedicated to developing initiatives for SR, including the United States Environmental Protection Agency (USEPA), the American Society for Testing and Materials (ASTM), the Interstate Technology & Regulatory Council (ITRC), the Network for Industrially Contaminated Land in Europe (NICOLE) and the United Kingdom Institution of Contaminated Land: Applications In Real Environments (CL:AIRE) (Bardos *et al.*, 2013; Hadley & Harclerode, 2015). The United Kingdom, where sustainability is widely recognized in regulation and used in practice, plays a leading role in promoting SR through the dynamic actions of CL:AIRE and SuRF-UK organizations (Hou *et al.*, 2014c; Rizzo *et al.*, 2016; Hou & Li, 2018).

These organizations produce several publications covering recommendations, guidelines, frameworks, standards and tools for evaluating SR, which fit in the context of different countries and regions and assist in its implementation in remediation activities (Hou *et al.*, 2016; Huang *et al.*, 2016). In the last decade, several events have been highlighted with the objective of promoting SR, some of which are presented in Fig. 3. One of the highlights is the publication of ISO 18504 in 2017, which is the first document with global coverage in the field of SR, consolidating the international state of practices on the approach and evaluation of sustainability in the context of remediation options (Rizzo *et al.*, 2016; ISO, 2017; Nathanail *et al.*, 2017; Bardos *et al.*, 2018).

This evolution in the approaches, orientations, structures and case studies focused on the discourse of sustainability in the contaminated sites remediation can also be perceived in the scientific production scenario. A survey of the Institute for Scientific Information (ISI) Scopus database indicates that the number of publications pertaining to SR has grown exponentially over the last decade (Fig. 3). According to Fig. 3, the first publications began in 1999, and since 2008 the total number of articles published began to grow, reaching its peak in 2014 and 2016. Besides this, according to our latest survey of the Scopus database (March 18, 2019), in 2019 there are already 29 publications, surpassing the year 2017 and with only two publications less than 2018. This shows that the concerns in this

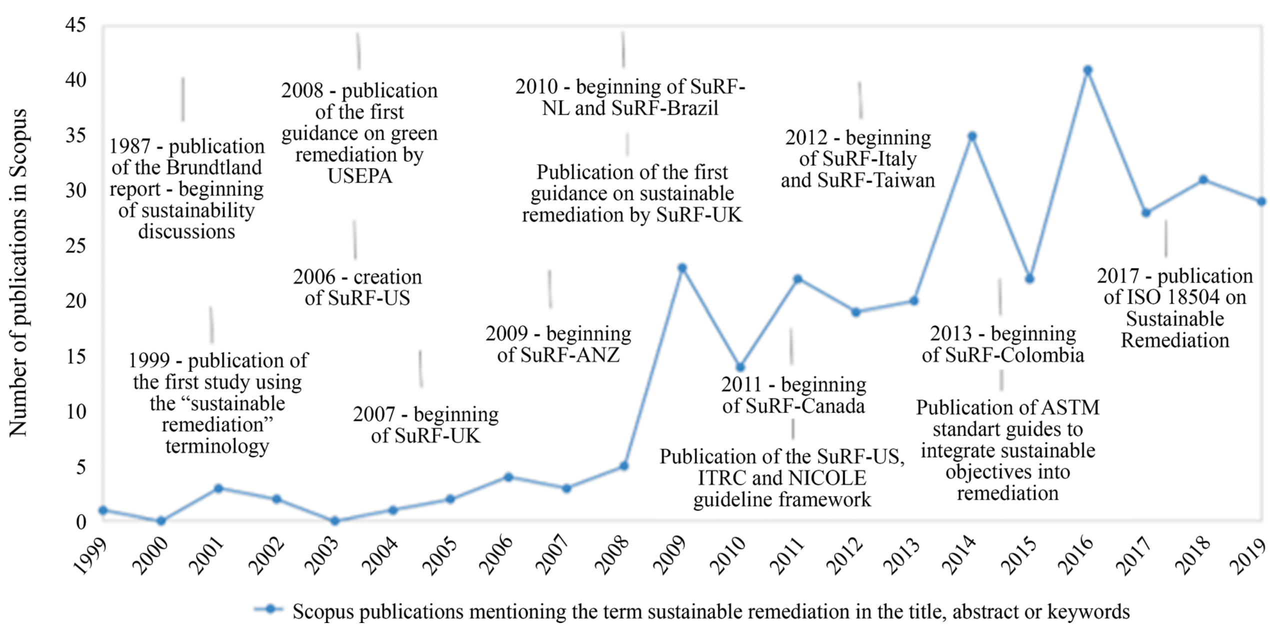

Figure 3 - Exponential growth of publications on SR and historical events. Source: Elaborated by the authors based on Bardos *et al.* (2013); Bardos (2014); Bardos *et al.* (2016b); Scopus (2018).

context tend to grow increasingly, since sustainability is at the peak of global discussions.

In this context, Brazil has only seven publications related to the subject. A situation that is due in large part to the fact that Brazil still does not have a concise approach towards SR in its regulatory context on the management of contaminated sites.

Taking into account all these approaches to SR, their incorporation can occur at all stages of the remediation processes life cycle, involving project stakeholders, principles, indicators, metrics, tools and methods to support the evaluation of potential sustainable correction alternatives (Petruzzi, 2011), as can be seen in Fig. 4.

3.1. Stakeholders involvement in SR processes

Involvement of stakeholders is an important practice of SR. It is widely recognized that decision-making and successful management and remediation of contaminated sites depends to a large extent on the interaction of a variety of stakeholders, each with its unique demand (Hou *et al.*, 2014a; Hou & Al-Tabbaa, 2014; Hou, 2016).

Stakeholders correspond to an organization, group or person that may potentially be directly or indirectly affected by some of the remediation project stages, or those that have an interest in solving the problem (Cundy *et al.*, 2013). Among the stakeholders who have the strongest influence on the sustainable practices adoption are: the owner of the site; federal, state, and local regulatory agencies; primary planners or consultants; the workers; local residents and neighboring sites affected by remediation actions; and researchers (Forum, 2009; Cundy *et al.*, 2013; Kalomoiri & Braida, 2013; Hou *et al.*, 2014a; Hou & Al-Tabbaa, 2014).

Site owners manage the costs of remediation and long-term administration of the property's environmental issues. Regulators, however, balance regulatory requirements with SR and reuse approaches. And finally, the involvement of the resident community and society in general increases their awareness of the risks associated with contamination and related remediation activities, and thus seeks to protect the environment and economic and quality-of-life improvements (Holland *et al.*, 2013; Harclerode *et al.*, 2016).

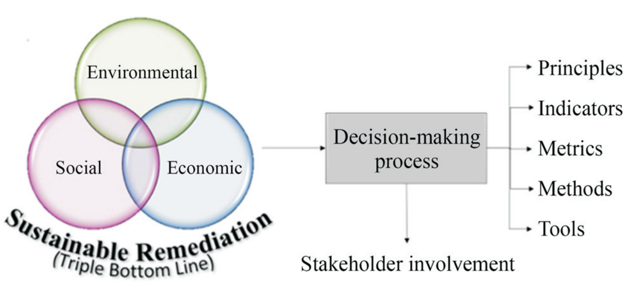

Figure 4 - Forms and stages of incorporation and evaluation of SR.

For the involvement of these stakeholders in remediation projects, some basic principles should be considered, such as: identifying and involving all stakeholders at the outset of the process; adopting a proactive approach; involve stakeholders at all stages of the process; planning long-term engagement; developing effective communication structures to enable reciprocal dialogue; ensuring that involvement is transparent and registered; recognizing that the criteria for assessing indicators may be subjective or objective; defining all assumptions clearly at the beginning of each step; and following a logical and gradual approach to avoid circular discussions and clearly address subjective issues (Cundy *et al.*, 2013). In addition, in order for this involvement to take place satisfactorily, stakeholders need to be aware of the limits of the remediation process and the objectives of SR (Kalomoiri & Braida, 2013).

Understanding the concepts of SR may not be the same for all these groups. O'Connor *et al.* (2019) observed that, on average, primary consultants gave higher scores for the environmental and social impacts analyzed than those given by regulators. However, across different perspectives, through transdisciplinary processes and communication or negotiation among stakeholders, consensus can be reached on a mutually beneficial and project-specific definition of sustainability and driving the adoption of sustainable practices (Forum, 2009; Hou, 2016). In addition, regulatory agencies play one of the most important roles among all stakeholders as they lead oversight of remediation activities and can act as mediators in disseminating sustainability concepts to other stakeholders in the process, as well as providing technical guidance to stakeholders. (Hou & Al-Tabbaa, 2014).

In general, stakeholder engagement is a vital SR practice to obtain useful feedback and identify the needs of all stakeholders and society at large (Harclerode *et al.*, 2016). In addition, it ensures that the uncertainties of sustainability assessment are minimized by allowing stakeholders to provide a balance of potential impacts and benefits (Cappuyns, 2016; NICOLE, 2010). Also, according to Harclerode *et al.* (2015b), stakeholder contributions already at the beginning of a remediation project can prevent conflicts, reduce unnecessary corrective measures, and help define the appropriate sustainability indicators acceptable to the context and acceptable to stakeholders.

However, since SR is still an emerging concept, stakeholders may not have enough knowledge to proactively stimulate and encourage sustainable practices, leading to divergent views and perceptions (Hou *et al.*, 2014a; Hou, 2016). In addition, dissemination and public engagement in remediation projects are still very limited, especially in developing countries, and greater incentives and improvements are needed to overcome these obstacles (O'Connor *et al.*, 2019). In this way, Hou *et al.* (2014a) have observed that although the involvement of different stakeholders affects behavior towards sustainability, their greatest influence is exerted through institutional forces, that is, in most cases, the institutionalization of specific environmental practices still precedes the influence stakeholders.

4. Sustainability Evaluation in Remediation

The sustainability evaluation in remediation is a key component of integrating diverse information to support decision making on SR (Rosén *et al.*, 2015). According to Hou *et al.* (2014d), the main objective of sustainability assessment in remediation is to collect information so that decision makers and stakeholders can manage complex systems with a holistic view. For Gibson *et al.* (2005), assessing sustainability while pursuing a general approach to sustainability contributes to defining the specificities of sustainability in particular circumstances.

Alternatively, assessing the sustainability of remediation is quite complex and usually involves a great deal of information from different sources, such as concrete data from on-the-spot investigations, environmental footprint analyzes, economic and social analyzes, as well as information that reflects views and preferences between those involved (Rosén *et al.*, 2015). Thus, the sustainability evaluation in remediation is a process that requires a set of individual criteria to be agreed upon by those who carry out the evaluation, defining what is relevant to the project perspectives and stakeholders (Bardos *et al.*, 2018).

The sustainability evaluation seeks to identify the impacts and benefits of a remediation project (Song *et al.*, 2018); to address and balance both local and regional/global dimensions, and to cover both short-term and long-term prospects (Hou *et al.*, 2014d; Hou *et al.*, 2018); and to manage, inform, compare, select, verify performance, and optimize appropriate remedial solutions and processes (Bardos *et al.*, 2018).

In general, the sustainability evaluation in remediation is facilitated by the use of principles, indicators, metrics, methods, and tools that can be used to ensure the practicality of SR.

The principles usually address a number of common issues, such as ecological integrity, social equity, the sustainability tripod, immediate and long-term sufficiency, and democratic processes (Ridsdale & Noble, 2016). The six principles of SR listed by SuRF-UK are often cited and used in this context (SuRF-UK, 2011). However, a number of agencies and organizations already provide lists of SR principles, new and/or complementary to those listed by SuRF-UK, to guide decision-makers (Department of Defence, 2010; ITRC, 2011a; NICOLE, 2012; ISO, 2017).

An indicator is a unique feature or a specific observable measure that expresses an environmental, social or economic aspect and results in a sustainability effect. These indicators can be measured to monitor and compare the performance of different remediation options according to criteria in question and to a specific site (NICOLE, 2012; Beames *et al.*, 2014; Virkutyte & Varma, 2014). In general, the indicators can be objective or subjective, with qualitative or quantitative approaches (Reddy & Adams, 2015; Tilla & Blumberga, 2018). And in this context, although there is no set of indicators standardized, the list of indicators for SR presented by SuRF-UK is the most well-known and frequently used in studies (SuRF-UK, 2011).

Indicators may not be easily measurable, requiring metrics to be integrated, so that they can be evaluated objectively and accurately. Sustainability metrics are numerical values that can be used to assess or determine the degree of success, performance or progress that a particular project or alternative can achieve in relation to sustainability dimensions (Reddy & Adams, 2015). As for indicators, there is also no commonly accepted set of metrics. SuRF presents an extensive list of metrics for SR in its metrics toolbox, which tabulates metrics for each phase of the remediation process. However, for the purpose of evaluating SR, the ITRC set provides a compilation of reasonably complete SR metrics, built from reputable sources and which can therefore be used as a basis in this context (ITRC, 2011a).

The methods or frameworks are conceptual and systematic forms of decision making that assist in the sustainability evaluation of a remediation project regarding environmental, social and economic aspects. In addition, they help evaluate the indicators and sustainability metrics of a remediation project (Reddy & Adams, 2015). A standardized and universally accepted method has not yet been developed. However, agencies and organizations in many countries have been active in developing structures to facilitate the sustainability assessment in contaminated sites remediation. This is especially perceived in regions where discussions on SR are in a more advanced process, such as the United States and Europe (Reddy & Adams, 2015; Ridsdale & Noble, 2016; Rizzo *et al.*, 2016; Slenders *et al.*, 2017).

In the world scenario, the developed methods correspond to: USEPA (US Environmental Protection Agency) (USEPA, 2012); ASTM (American Society for Testing and Materials) (ASTM, 2013); ITRC (Interstate Technology and Regulatory Council) (ITRC, 2011b); NICOLE (Network for Industrially Contaminated Land in Europe) (NICOLE, 2010); and four groups associated with the SuRF (Sustainable Remediation Forum) - United States (Holland *et al.*, 2011), United Kingdom (SuRF-UK, 2010), Australia and New Zealand (Smith & Nadebaum, 2016), and Taiwan (Huang *et al.*, 2016). At the Brazilian level, there are some initiatives aimed at SR, such as SuRF-Brazil and NICOLE Brazil, but the approach to sustainability issues and effective actions is still very limited. Therefore, no methods developed for the sustainability analysis in remediation are identified in the country.

The methods, as they are consisting in decision-making processes, often use tools during its stages to assist in the remediation project sustainability analysis. The Decision Support Tools (DSTs) comprise step-by-step approaches, which include qualitative, semi-quantitative or fully quantitative analyzes of remediation processes (Smith & Kerrison, 2013; Reddy & Adams, 2015; Anderson *et al.*, 2018).

In recent years a number of sustainability assessment tools have become available. These tools, of varying type and scope, may be in the public domain, sold as software for profit, or limited to use within a particular organization, which offer different levels of comprehensiveness, complexity and analysis (Holland *et al.*, 2011; Beames *et al.*, 2014; Reddy & Adams, 2015). In addition, tools can range from simple decision trees or spreadsheets, tables or graphs in Excel, to full life cycle assessments (Reddy & Adams, 2015; Huang *et al.*, 2016).

Many agencies, organizations, and studies categorize, list, and define the existing set of tools (Bardos *et al.*, 2002; Harclerode *et al.*, 2015b; Reddy & Adams, 2015; Cappuyns, 2016). Other studies aim to develop structures for sustainability evaluating of remediation projects, incorporating in decision-making the different tools already available (Halog & Manik, 2011; Kalomoiri & Braida, 2013; Yasutaka *et al.*, 2016; Hou *et al.*, 2017; Zheng *et al.*, 2019). In a more practical context, a considerable number of studies have already been carried out using different tools to analyze the impacts of remediation techniques, evaluating them and classifying for sustainability (Hou *et al.*, 2014b; Anderson *et al.*, 2018).

Therefore, there are already several evaluation and decision support tools for choosing more SR alternatives. However, more and more flexible instruments are needed to address the full range of indicators and metrics in the three dimensions of sustainability and to be applicable from project design to project reuse (Huysegoms & Cappuyns, 2017).

5. Conclusions

It is recognized in the academic world that sustainable remediation (SR), unlike traditional remediation and green remediation, presents a broader vision, bringing the incorporation of sustainability concepts in the management and remediation projects of contaminated sites. It may be noted that the main objective of SR is to consider both environmental, social and economic impacts and benefits that the application of a remediation technique can generate, always with a view to selecting the most sustainable option among those considered.

Great advances are observed in the SR field, especially with the creation of the Sustainable Remediation Forum (SuRF) in 2006 in the United States, in addition to the efforts of Agencies and Organizations in several countries to disseminate guidelines for the objective application of SR. In addition, the ISO 18504 publication, which comes to standardize the main outstanding issues regarding the orientation and implementation of SR concepts, represented a huge advance.

However, the practical application of SR in the remediation processes still needs to be improved. The concepts of SR are still very new in much of the world, as in the case of Brazil. The principles, indicators, metrics, methods and tools do not yet have standardization for worldwide use. In this way, the inclusion of sustainability in remediation should start from the dissemination of knowledge about SR, favoring the involvement of stakeholders in the decision-making processes.

Also, it is noted that, in order for the SR approach within the management of contaminated sites to continue to move forward, the SR should be seen as a new way of thinking about contaminated sites remediation, where the integration of economic, environmental, and social variables must be considered a fundamental factor in decision making.

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