Cleaner Environmental Systems 21 (2026) 100431

Contents lists available at ScienceDirect

Cleaner Environmental Systems

journal homepage: www.journals.elsevier.com/cleaner-environmental-systems

Circularity indicators for remediation activities: assessing circularity at the *ex-ante* and *ex-post* phases in compliance with the latest standards

A. Sellitri [a,b], L. Pizzol [b,**], A. Bonfà [c], G. Meneghin [c], M. Menegaldo [b,c], P. Scanferla [c], A. Zabeo [b], G. Schileo [c], S. Devecchi [a,b], S. Breda [c], P. Bardos [d], E. Semenzin [a,*]

[a] *Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Scientific Campus, via Torino 155, 30172, Mestre, VE, Italy*
[b] *GreenDecision srl, Cannaregio 5904, 30121, Venezia, VE, Italy*
[c] *Fondazione Università Ca' Foscari, Ca' Dolfin – Calle Larga Ca' Foscari, Dorsoduro 3859/A, 30123, Venezia, Italy*
[d] *r3 Environmental Technology Ltd, 37 St Peter's Ave, Caversham, Reading, RG4 7DH, UK, England*

ARTICLE INFO

Keywords:
Circularity assessment
Sites remediation
Expert evaluation
Circularity indicators

ABSTRACT

The sector of contaminated soils and groundwater remediation is a critical and complex one, that requires targeted interventions and integrated strategies to reduce and mitigate the health and environmental risks posed by contamination, while adhering to principles of sustainability and circularity. The objective of this paper is to provide a set of suitable indicators for assessing circularity in the context of contaminated sites remediation both in the *ex-ante* and the *ex-post* remediation phases. Indicators have been selected from those provided in the latest standards for circularity assessment, specifically UNI/TS 11820:2022 and ISO 59020:2024. The selection process involved an in-depth analysis of the indicators included in the aforementioned standards and their data requirements, which serve as the knowledge base for a working group of experts with interdisciplinary expertise in remediation technologies design, Life Cycle Assessment, and Multi-Criteria Decision Analysis, which selected the circularity indicators suitable for application in contaminated sites remediation processes. The selected indicators follow the SMART model of criteria, which requires that they all are specific, measurable, achievable, relevant and time-bound. This selection procedure identified a total of 24 circularity indicators applicable in the *ex-ante* and the *ex-post* phases. These indicators cover the key dimension of material, energy, and water resource efficiency and aim to support informed decision-making and monitoring, with a structured and measurable basis for the integration of circularity aspects into contaminated sites remediation.

1. Introduction

Within the European Union, the environmental policy context aims to steer the economy towards a circular model, characterised by waste reduction, material regeneration and reuse, and optimization of resource efficiency (Fetting, 2020). This transition is supported by regulatory instruments such as the European Green Deal (European CommissionDirectorate-General for Research and Innovation, 2021) and the Circular Economy Action Plan (European CommissionDirectorate-General for Communication, 2020). The circular economy (CE) is regarded not only as an environmental imperative but also as an opportunity to stimulate industrial innovation, to foster the creation of green jobs, and to strengthen the EUs global competitiveness (Ossewaarde and Ossewaarde-Lowtoo, 2020; Sabato and Fronteddu, 2020; Kuci and Fogarassy, 2021). Within this political and economic framework, actions are also envisaged to expand the scope of eco-design, strengthen consumer rights and awareness, increase circularity in production processes, and reduce the impact of waste generation and waste-related markets at European level (Farmer, 2020).

Among the industrial sectors in which these principles and actions can be effectively integrated, the remediation of contaminated sites emerges as an important area of intervention posing critical and complex challenges. These includes the need for targeted interventions and integrated strategies to reduce and mitigate the environmental and health impacts associated both with the presence of pollutants and with the impacts caused by the remediation processes themselves. Contaminated sites arising from past industrial activities, inadequate disposal practices or prolonged urban decay (Ashraf et al., 2014), typically exhibit complex contamination profiles, including organic compounds,

---

* Corresponding author.
** Corresponding author.

E-mail addresses: lisa.pizzol@greendecision.eu (L. Pizzol), semenzin@unive.it (E. Semenzin).

https://doi.org/10.1016/j.cesys.2026.100431
Received 21 August 2025; Received in revised form 23 March 2026; Accepted 27 March 2026

Acronyms list

CE	circular economy
CSM	Conceptual Site Model
ESRS	European Sustainability Reporting Standard
LCA	Life Cycle Assessment
MCDA	Multi-Criteria Decision Analysis
SMART	specific, measurable, achievable, relevant, time-bound
WG	working group

heavy metals, and inorganic substances, among others (Aparicio et al., 2022). In many cases, contamination affects both soil and groundwater, which constitute interconnected yet distinct environmental media, characterised by different contaminant mobility, spatial distribution, and exposure pathways (National Research Council, 1994; Nathanail and Bardos, 2004). Accurate identification of contamination sources and site hydrogeological conditions represents a prerequisite for the selection of appropriate remediation technologies, particularly in groundwater systems (Liu et al., 2024). Building on this compartmentalised understanding, contaminated site assessment typically relies on the development of a Conceptual Site Model (CSM). The CSM provides a structured and site-specific representation of contamination sources, affected environmental media, transport mechanisms, and potential receptors, thereby supporting the interpretation of site data and risk assessment (ASTM International, 2017; International Organization for Standardization, 2019; Ciampi et al., 2024). This complexity is particularly apparent in remediation contexts influenced by legacy contamination, as a result of cumulative interaction of historical activities and site evolution (Swartjes, 2011). In parallel, increasing attention is being paid to emerging contaminants, whose complex environmental behaviours are not yet fully understood and properly addressed by conventional assessment frameworks (Singh et al., 2024). These conditions challenge static interpretation of site characteristics, highlighting the need for adaptive assessment processes in which remediation strategies, CSMs, and related decisions are iteratively refined based on monitoring outcomes and evolving site knowledge (Price et al., 2017). In response to this complexity, remediation activities now encompass a wide range of strategies, covering different technologies and implementation modalities. Remediation approaches are commonly categorised as physical/chemical or biological treatments, which may involve *in situ* or *ex situ* technologies. The choice of specific interventions – including containment, removal, or treatment-based solutions – depends on site-specific contamination patterns, environmental settings, and risk management objectives, as no single remediation technology can be considered universally applicable across different site and contaminant conditions (UNEP, 2021; Khan et al., 2004). Remediation efforts typically involve a combination of strategies to address the multifaceted nature of contaminated sites, considering that integrated and hybrid approaches have been shown to improve effectiveness across heterogeneous contamination scenarios (Zheng et al., 2022). Accordingly, remediation planning increasingly relies on integrated approaches that combine multiple complementary technologies, implemented in a phased or adaptive manner, to improve effectiveness and resilience under uncertainty.

Remediation interventions play a strategic role in land-use transformation processes, contributing to the transition of contaminated sites from liabilities into resources. These activities aim not only at the protection of human health, but also at the restoration of environmental functions, potentially enabling the redevelopment of previously degraded areas and their reintegration into the urban and territorial fabric (Ferber et al., 2006; Holland et al., 2013). Nevertheless, remediation is not a neutral activity.

The implementation of remediation technologies may entail environmental, economic, and social impacts, including energy consumption, greenhouse gas emissions, waste generation, disturbance to local communities, and substantial financial costs. Increasing attention has been directed towards the adoption of more sustainable remediation approaches, which explicitly account for environmental, social, and economic impacts alongside risk management objectives (Ellis and Hadley, 2009; Hodson, 2010). Within such contexts, remediation planning requires structured decision-making processes capable of balancing technical performance, environmental impacts, and broader sustainability considerations (Aparicio et al., 2022; Khan et al., 2004). Over the past decades, a gradual shift in remediation approaches has emerged, strongly influenced by international exchange within professional networks such as ICCL, ISRA, COMMON FORUM, NICOLA, and NICOLE (Smith, 2019; Grifoni et al., 2022; Rizzo et al., 2016). Early remediation practices were focused on containment measures or on excavation and off-site disposal. These approaches were progressively complemented by treatment-oriented solutions aimed at reducing contaminant mass and toxicity rather than merely isolating polluted materials. In parallel, risk assessment has evolved from a supporting analytical tool to a central framework guiding decision-making. More recently, this evolution has culminated in the explicit incorporation of sustainability principles into remediation practice, reflecting a shared understanding that contaminated land management should integrate both risk-based reasoning and sustainability considerations (NICOLE and COMMON, 2013). Among the various aspects to be considered when assessing the sustainability of remediation technologies, Life Cycle Assessment (LCA) plays a crucial role in estimating the environmental impacts of remediation options across their life cycles. LCA is an internationally recognised and standardised method according to ISO 14040:2006 and, when complemented by PCR 2012:09 “Site remediation and clean-up services, soil and groundwater” represents a key methodological framework for evaluating the environmental performance of remediation technologies and supporting the comparison and prioritisation of remediation alternatives (Lemming et al., 2010; Owsianiak et al., 2013). However, the selection of remediation technologies typically involves multiple, often conflicting criteria that extend beyond environmental performance alone, including technical feasibility and site-specific constraints. A structured integration of heterogeneous evaluation criteria is commonly achieved through Multi-Criteria Decision Analysis (MCDA), which provides a transparent decision-support framework (Abrams et al., 2024). MCDA is a sub-discipline of operations research that provides a formal framework for evaluating multiple conflicting criteria in decision-making to identify the most preferred alternative (Lamprou and Vagiona, 2025).

The combined use of LCA- and MCDA-based perspectives provides a coherent analytical basis for the evaluation and adaptation of circularity indicators to the remediation context. This evolution has led to the standardisation of sustainable remediation activities (Nathanail et al., 2017), and to the development of dedicated frameworks (Favara et al., 2019; Bardos et al., 2020) and indicator sets (Braun et al., 2021) for sustainability assessment. The aim of these tools is to support informed remediation planning by enabling the evaluation of alternatives beyond compliance with safety objectives, while explicitly accounting for the environmental, social, and economic impacts of applied technologies. Consequently, the design and implementation of effective remediation require thorough assessment and careful planning, as well as collaboration and coordination between different scientific disciplines (Okx et al., 1996), stakeholders, and administrative agencies.

Despite the conceptual and methodological maturity of sustainable remediation, the circularity dimension remains largely implicit or entirely absent within assessment frameworks and decision-support tools. To date, circularity assessment has become a standardised and regulated topic (see Section 1.1); however, this regulatory advancement is not yet reflected in the evaluation of remediation interventions.

A consensus on the origin of the concept of CE has not been reached. Emerging from early environmental and system-thinking discourse

(Meadows et al., 1972), the CE concept aims at countering the linear *take-make-dispose* model. However, CE principles and actions have evolved over time (Suárez-Eiroa et al., 2019) and are currently interpreted and implemented in diverse ways across sectors and actors. This diversity reflects the rapid expansion of CE research and practice, encompassing scientific contributions, independently developed methodologies and standards, as well as policy-driven interpretations (Reike et al., 2018; Sassanelli et al., 2019). Consequently, a universally recognised and authoritative definition of CE is still lacking. For the sake of this work, the definition provided by Kircherr (Kirchherr et al., 2017) was adopted. It describes CE as *an economic system that is based on business models which replace the "end-of-life" concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*. Circularity is conceptualised as the extent to which CE principles and actions are integrated (or aligned) within a business model, an organization, or an economic system. The assessment of circularity is, for organizations, a fundamental requirement for the implementation of concrete actions and for attaining measurable outcomes (Ente Italiano di Normazione, 2022), facilitating a more effective pursuit of sustainable development goals. In recent years, numerous circularity metrics have been proposed to support circular management of material flows and resource efficiency (Corona et al., 2019; Walzberg et al., 2021). This proliferation highlighted the for standardisation, resulting in the development of standards for measuring circularity performance, including the international standard ISO 59020:2024, the Italian standard UNI/TS 11820:2022, and the European standard ESRS E5, which are briefly described below, while detailed information can be found in the text of the standards.

The ISO 59020:2024 "Circular Economy – Measuring and assessing circularity" standard provides a framework of environmental, social, and economic indicators to assess the circularity performance of a selected system. The results of this assessment are intended to be used to support the transition towards a circular economy. The methodology can be used across different levels of an economic system, spanning regional, inter-organizational, organizational, and product levels. The framework also relies on inputs from a variety of complementary methods.[1] The framework consists of three main steps: (i) the *boundary settings* step, which includes the definition of the system in focus, the circularity aspects to be measured, data quality requirements and the pre-selection of complementary methods of assessment; (ii) the *data acquisition* step, where general circularity indicators are used for data collection (they can serve as a basis to form more detailed, sector specific measurement methods, when required); (iii) the *circularity assessment and reporting* step, in which the results of the circularity measurement are evaluated in a comprehensive statement about the circular outcomes of the examined system. The standard provides a set of core circularity indicators that can be supplemented by additional ones (also derived from complementary methods) to meet the goal and the scope of the circularity measurement and assessment.

The UNI/TS 11820:2022 "Measuring circularity – Methods and indicators for measuring circular processes" standard defines a set of indicators suitable for assessing the circularity performance at the micro level (i.e. single organization) and meso level (i.e. inter-organizations, industrial clusters, supply chains, etc.). The assessing methodology is developed on a 100-base rating system that considers environmental, economic, and social aspects. The circularity indicators that provide the main information for data acquisition are grouped into six categories, which are: material resources and components; energy and water resources; waste and emissions; logistics; product/service; human resources, assets, policies, and sustainability. The indicators are further divided, based on the type of assessment they are suitable for (indicators related to goods, indicators related to services, and indicators related to both) and on classes (core, specific, and rewarding indicators). The calculation of each indicator is given by a ratio, so that a normalised circularity index value between 0 and 1 can be obtained. The preliminary steps to the assessment involve the definition of the system boundaries, the data quality requirements and the type of assessment (and the relative indicators set). After collecting data and evaluating the indicators, the circularity performance can be calculated for each indicator category. The results can be visualised on a radar chart encompassing all 6 categories.

The Corporate Sustainability Reporting Directive introduces a requirement for companies listed on regulated EU market, including small and medium-sized enterprises (SMEs), to focus on sustainability reporting in line with the principle of double materiality. Accordingly, companies must disclose information both on financial materiality (i.e. how environmental, social, and governance factors affect their economic performance), and on impact materiality (i.e. how their activities affect the environment and society). These disclosures must follow the European Sustainability Reporting Standards (ESRS), promoted by the European Financial Reporting Advisory Group and in force from December 2023 (European Commission, 2023). Within this framework, ESRS E5 "Resource use and circular economy" requires companies to disclose information on their actions to decouple economic growth from resource use and to align their business models to the CE principles.[2] The standard focuses on resource inputs, product durability and reparability, and waste management without prescribing specific methodologies or indicators for measuring circularity performance. Although ESRS E5 is not applied in this paper, it is briefly introduced here as a reference framework, as the ISO and UNI standards can be considered operational tools that companies may use to comply with ESRS E5 disclosure requirements. In line with their main objective of assessing companies' circularity performances, these standards, by their nature, are more aligned with an *ex-post* assessment of a specific process or organisation rather than to the *ex-ante* phase, where different options need to be compared and prioritised.

1.1. Objective of the paper

The absence of research and studies specifically exploring how to integrate CE principles into remediation practices represents a significant knowledge gap in the scientific literature. A study focused on this topic could provide valuable insights for developing more sustainable and effective strategies and guidelines for remediation, thereby contributing to a more holistic and integrated approach to managing contaminated sites.

In the context of this study, two phases of the remediation process are distinguished: an *ex-ante* phase and an *ex-post* phase. The *ex-ante* phase is the one preceding the start of decontamination activities and concerns the operations planning. Specifically, during this phase the selection of the remediation technology takes place, based on factors such as the reclamation objective(s), the characteristics of the contaminated site, the expected costs and timescale, and the interests of the involved stakeholders. The *ex-post* phase, on the other hand, concerns ongoing and completed remediation activities. Monitoring is carried out during and on completion of the remediation activities. The resulting data can be used to support the sustainability report of the organisation carrying out the remediation activities.

---

[1] Environmental Life Cycle Assessment, Life Cycle Sustainability Assessment, Social LCA, Life Cycle Costing, Material Flow Analysis.

[2] Including, but not limited to, minimizing waste, maintaining the value of products, material, and other resources at their highest value and enhancing their efficient use in production and consumption.

The objective of this study is to provide two sets of indicators for assessing the circularity of remediation in both the *ex-ante* and *ex-post* phases, also compliant with the ISO 59020:2024 and the UNI/TS 11820:2022 standards.

2. Methods

This section describes the methodology for evaluating and selecting which of the circularity indicators provided by the ISO 59020:2024 and the UNI/TS 11820:2022 standards are applicable and relevant to the contaminated sites remediation sector and specifically to the circularity assessment of remediation technologies. The evaluation process was structured around a Delphi-inspired approach (Hsu and Sandford, 2007) articulated in two iterative phases as reported in the methodological framework described in Fig. 1.

To operationalise this methodological framework, experts were selected through a nomination process requiring (i) demonstrated expertise in one or both approaches, together with (ii) deep competences in remediation of contaminated sites and sustainability assessment of remediation technologies. The nominated figures have been selected among a pool of experts who contributed to the development of previous international and Italian national projects on sustainability assessment of contaminated sites, including policymakers involved in contaminated site management. Of the invited experts, only two declined, resulting in a working group (WG) of 10 participants. Their professional experience in the sector ranges from 3 to 25 years, intentionally including individuals with different levels of seniority. This heterogeneity of the group was considered functional to capturing a diverse range of perspectives and sensitivities towards sustainability issues. Technical experts provided insights on practical feasibility and remediation alternatives, such as dig-and-dump, thermal desorption, capping, containment barriers, soil washing, pump-and-treat, low-input techniques (*in situ* stabilisation, electro-remediation), and biopile (see Section 3.3); LCA/MCDA specialists ensured robust assessment of environmental and multi-criteria impacts; policymakers contributed an understanding of regulatory and management considerations. This combination of competences was deemed essential to inform the evaluation and prioritisation of circularity indicators to be adapted to the specific context of contaminated sites remediation. Summary information on the characteristics of the WG experts is shown in Table 1.

In the first phase, each member of the WG was invited to independently review all the indicators from both standards, assessing their relevance and applicability to the remediation context. To guide the evaluation process, a mission was formulated and shared with all experts, requesting them to contribute to the assessment of circularity indicators. Specifically, they were asked to evaluate each indicator based on their professional experience and knowledge of remediation processes and circular economy principles, with particular attention to the representativeness and availability of the required data. The evaluation did not aim to compare or select remediation technologies, nor to assess sustainability performance, but rather to examine the suitability of existing indicators for conducting circularity assessments of remediation interventions. Each expert independently assessed the indicators using the SMART criteria (Doran, 1981) as a guiding framework. These criteria were used to evaluate whether each indicator could be considered suitable for application in the remediation context. The assessment evaluated whether the data required by the indicator were: specific, i.e. clearly defined and referring to identifiable elements of the remediation process, or to information associated with them (e.g. quantities of excavated materials, or material and energy inputs required by remediation technologies); measurable, i.e. quantifiable using data typically available from design and planning documents, or site reports; achievable, i.e. realistically collectible within the boundaries of remediation projects (based on information routinely generated during site investigation, technology design, set-up, and operation phases); relevant, i.e. able to inform key circularity-related aspects of remediation interventions (e.g. management of excavated materials, use of secondary resources, reduction of off-site disposal); time-bound, i.e. referable to a defined phase of the remediation process. Additionally, the experts were asked to identify what they considered to be the priority topics – that is, thematic domains deemed crucial when assessing the circular performance of remediation intervention. Priority topics were defined as key areas within the remediation process where the application of CE principles can have a significant impact, and where the use of tailored circularity indicators is essential to ensure a meaningful assessment process. To facilitate the evaluation process, a standardised Excel template was provided, allowing experts to document their assessments in a structured manner. The evaluation was carried out for both the *ex-ante* and the *ex-post* phases. A qualitative evaluation approach led to the classification of each indicator into one of three categories. An indicator was marked “Y” (YES) if it was deemed suitable for assessing the circularity of a remediation technology. Conversely, it was marked “N” (NO), if it was deemed unsuitable for this purpose. In cases where the relevance or applicability of and indicator raised critical issues requiring

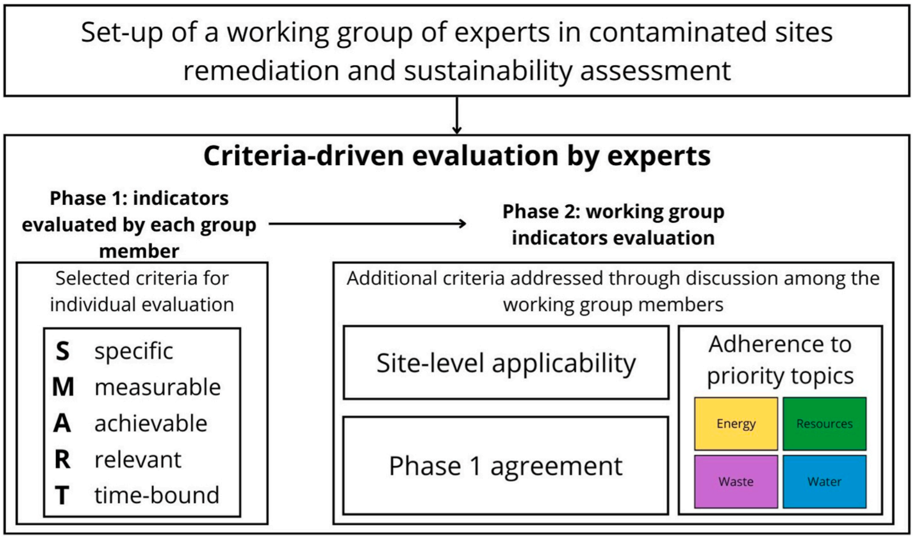

Fig. 1. Methodological framework for the selection of circularity indicators applicable and relevant to the contaminated sites remediation sector. Source: personal elaboration by the authors.

Table 1

Summary of the WG experts' characteristics, including identification code (expert ID), educational level, field of expertise, current occupation, sector of origin, and years of professional experience.

Expert ID	Educational level	Field of expertise	Occupation	Sector of origin	Years of experience
E1	BSc	Remediation of contaminated sites	Practitioner in the field of remediation activities	Private	20
E2	PhD	Remediation of contaminated sites	Consultant for a remediation company	Private	15
E3	BSc	Sustainability assessment/LCA	Researcher on sustainability assessment	Academia	5
E4	BSc	Sustainability assessment/LCA	Researcher on sustainability assessment	Academia	8
E5	BSc	Remediation of contaminated sites	Practitioner in the field of remediation activities	Private	4
E6	PhD	Sustainability assessment/MCDA	Consultant on sustainability assessment	Private	20
E7	PhD	Sustainability assessment/MCDA	Practitioner in the field of remediation activities	Private	25
E8	BSc	Sustainability assessment/LCA	Consultant on sustainability assessment	Private	3
E9	PhD	Sustainability assessment/MCDA	Consultant on decision analysis	Private	20
E10	BSc	Land quality and materials management	Director	Private	20

further discussion, it was classified as "M" (MAYBE).

Building on the outcome of the first phase of the process, Phase 2 was conducted through an online meeting moderated by the first author of this paper, who also acted as facilitator of the discussion. A structured agenda was circulated in advance, and the discussion followed the sequence of indicators for which no agreement had previously been reached, starting with those most frequently rated as "MAYBE". These indicators were reviewed one by one, and each participant was invited to justify their previous ratings and elaborate on concerns or preferences. During this phase, three additional criteria were introduced to support and structure the discussion among the WG members on the selection of circularity indicators. The first criterion concerns site-level applicability, i.e. the ability of an indicator to be applied at the scale of a single remediation site and, more importantly, to discriminate between different remediation alternatives. Indicators estimated at broader levels – such as the organisational scale (e.g. "Has the organisation invested in circular design of its assets in years n and/or n-1 and/or n-2?") – were not considered suitable, as they equally affect all remediation alternatives and therefore do not provide added value for comparative assessment. The second criterion reflects the correspondence between the data requirements of each indicator and the priority topics previously identified by the WG members. These topics, which emerged from the collective suggestions provided by individual members during Phase 1, include resources, energy, water and waste – key dimensions also recognised in the literature (Hou and Al-Tabbaa, 2014). The third criterion refers to the level of agreement reached during Phase 1 for each indicator. Agreement was considered "positive" or "negative" based on the prevailing number of "YES" (Y) or "NO" (N) ratings. A full or near-full convergence – such as all WG members agreeing, or eight giving the same rating out of nine with one uncertain ("MAYBE") – was considered sufficient for agreement. In cases where "YES" or "NO" responses coexisted, or where "MAYBE" prevailed, no agreement was considered to have been reached, requiring further discussions among the WG members.

A number of useful considerations for the selection of indicators emerged from the discussion, leading to the identification of further discriminating criteria, such as the reference to industrial symbiosis practices (i.e. as mentioned in the UNI indicators from 47 to 55, which were deemed not applicable in the field of remediation) or the presence of indicators relevant for the assessment of the implementation of circular economy principles in a process, but not for comparing different remediation technologies (i.e. indicators that assess organization-level choices, like the UNI indicator 19 "Did the organisation perform its carbon footprint assessment according to UNI EN ISO 14064-1 in year n and/or n-1 and/or n-2?"). In addition to the criteria already established and described above, another observation emerged during the discussion. According to the reference jurisprudential discipline (which has expressed itself, for example, on the subject of resources such as vegetal material mowings, e.g. DGEC Interpretation Veneto Region dated August 8, 2023; or MASE circular no. 51657 dated May 14, 2021), reclaimed soil and water cannot be considered products/by-products of the remediation activities as they do not derive from an original creative process. However, according to the definition provided by the UNI standard, they can be considered secondary material resources.

3. Results and discussion

3.1. Scoring of the UNI/TS 11820:2022 assessed indicators

The methodology presented above has been applied to the indicators available in the UNI/TS 11820:2022 standard as shown in Table 2, where the number and the description of the indicators are provided, followed by the number of Y, N, M ratings acquired as applicability in the *ex-ante* and *ex-post* assessments. Table 2 only shows the assessment results of the selected indicators, while the full set of indicators is available in the supplementary materials. The complete description of the indicators is reported in the UNI/TS 11820:2022 standard.

The reasoning developed by the WG for the exclusion of certain circularity indicators from the set of those suitable for assessing the circularity of remediation activities is here detailed. Indicators from 7 to 10, 19 to 21, 26, 27, 32, 36 to 38, 40, 49, 51 to 55, 57 and 58 were excluded because they received mostly – if not all – negative (i.e. "N") evaluations. The most agreed upon motivations behind the overall negative evaluation of these indicators include: (i) the lack of relevance to the remediation field of the topics covered by some indicators (e.g. packaging in indicator 7, critical raw materials in indicator 8, complex articles and mixtures in indicator 9, employee habits in indicator 26, and products with no market in indicator 27); (ii) misalignment with the nature of remediation activities (e.g. indicators 32, 36, 37, 38, and 40 investigate on some aspects of the outputs of a production system, while remediation does not generate products; indicators from 47 to 55 focus on industrial symbiosis, which is rarely applicable in this context; indicators 57 and 58 address topics related to organisational assets, not relevant for the assessment and comparison of remediation activities); (iii) limited applicability (e.g. indicator 10 refers to input-residue differentials, that were not considered useful for the assessment of remediation activities); (iv) closer alignment with general sustainability assessment rather than circularity in remediation (e.g. indicators 19, 20, and 21 address carbon footprint reporting). Indicators from 42 to 45, 56, 59, 60, 62, 63, and 66 to 71 were excluded because they focus on aspects related to the overall organisation management; therefore, assessing these indicators was not considered relevant for the purposes of comparing the circularity performance of different remediation technologies (in the *ex-ante phase*) or monitoring the development of a remediation site (in the *ex-post* phase). Indicators 5, 6, 17, 23 to 25, 28, and 29 were excluded because the WG considered them to be not informative for assessing circularity in the context of remediation activities. Lastly, some indicators were excluded by the WG for specific reasons: Indicator 3 because the data for its calculation would not be available in the *ex-ante* phase and that, in the *ex-post* phase, no aspect of circularity relevant to remediation would be valorised; Indicator 18 because it was considered useful for circularity assessment only if the

Table 2
Assessment results for the circularity indicators of the UNI/TS 11820:2022 standard. In bold, the indicators selected for both the *ex-ante* and *ex-post* phases. In italic, the indicators selected for the *ex-post* phase only. The original descriptions of the indicators are provided in Italian, while the English translations are an original elaboration by the authors. Further details on the indicators are available in the text of the standard.

Indicator number	Description	Y *ex-ante*	N *ex-ante*	M *ex-ante*	Y *ex-post*	N *ex-post*	M *ex-post*
	1. Indicators related to material resources and components						
1	**Self-produced secondary material resources, compared to total raw and secondary material resources**	2	2	6	8	0	2
2	**Raw materials and secondary material resources purchased and/or acquired from local suppliers compared to total raw materials purchased and/or acquired**	1	3	6	7	1	2
4	**By-products and/or secondary material resources (input) compared to total material resources (input)**	1	4	5	7	0	3
	2. Indicators related to energy and water resources						
11	**Self-produced electrical energy from renewable sources and/or recovery processes compared to total electrical energy consumed**	7	2	1	8	2	0
12	**Self-generated thermal energy from renewable sources and/or recovery processes, compared to total thermal energy consumed**	7	2	1	8	2	0
15	**Amount of water from recovery and/or recycling compared to total water demand**	8	0	2	10	0	0
	3. Indicators related to waste and emissions						
16	**Municipal and/or special waste sent to landfill compared to total waste produced**	6	0	4	9	0	1
	4. Indicators related to logistics						
22	**Waste treated at local recovery plants compared to total treated waste**	7	0	3	9	0	1
	5. Indicators related to product/service						
30	**Value of supplies from suppliers with product and/or service and/or organisational sustainability and/or circularity certifications compared to the total value of supplies**	0	5	5	5	2	3
31	**By-products generated compared to total production residues generated**	1	7	2	3	2	5
34	**Value of procured products and services related to circular business models compared to total procured products and services**	1	5	4	3	1	6
41	*Value of products and services (excluding raw materials) procured from local suppliers in year n compared to the total value of products and services (excluding raw materials)*	1	2	7	7	0	3
46	*R&D investments related to circular economy principles in years n and/or n-1 and/or n-2 compared to total R&D investments in years n and/or n-1 and/or n-2*	0	4	6	4	2	4
	6. Indicators related to human resources, assets, policies, and sustainability						
64	*Goods and infrastructure (e.g. computers, vehicles, furniture, buildings, land) purchased by the organisation based on the lowest life-cycle cost criterion in relation to the total purchased goods and infrastructure*	4	2	4	4	1	5
65	*Goods and infrastructures with circular end-of-life management solutions compared to the organisation's total goods and infrastructures*	7	0	3	7	0	3

soil is completely recovered and does not end up in landfill (an outcome considered too specific). Indicators 33 and 35 because they are not applicable at site-level. Indicator 39 because the product life extension is not a service that can be fulfilled by remediation activities.

The analysis of the scoring reveals important insights into the applicability and representativeness of the UNI/TS 11820:2022 indicators in the context of remediation activities. The exclusion of a substantial number of indicators stresses critical limitations regarding their operational relevance and contextual appropriateness.

Table 3 shows the relevance percentage of each indicator category of the UNI/TS 11820:2022 standard for both the *ex-ante* and the *ex-post* phases. It represents the proportion of indicators within a category that have been selected for the circularity assessment of remediation technologies.

Table 3

Relevance percentages of each indicator category of the UNI/TS 11820:2022 standard.

Indicator category	Relevance percentage for the *ex-ante* phase	Relevance percentage for the *ex-post* phase
01. Indicators related to material resources and components	3/10 = 30%	3/10 = 30%
02. Indicators related to energy and water resources	3/5 = 60%	3/5 = 60%
03. Indicators related to waste and emissions	1/6 = 16.6%	1/6 = 16.6%
04. Indicators related to logistics	1/6 = 16.6%	1/6 = 16.6%
05. Indicators related to product/ service	3/28 = 10.7%	5/28 = 17.8%
06. Indicators related to human resources, assets, policies, and sustainability	0/16 = 0%	2/16 = 12.5%
Average relevance percentage	22.3%	25.6%

3.2. Scoring of the ISO 59020:2024 assessed indicators

The methodology presented in Section 2 - Methods has been applied to the indicators available in the ISO 59020:2024 standard, as shown in Table 4. The table includes the description of each indicator, followed by the number of Y, N, M ratings assigned by the experts of the WG for their applicability in the *ex-ante* and *ex-post* assessments. Table 4 only shows the assessment results of the selected indicators, while the full set of indicators is available in the supplementary materials. The complete description of each indicator can be found in the Annex A (core indicators) and in the Annex B (additional indicators) of the ISO 59020:2024 standard.

Table 4

Assessment results for the circularity indicators of the ISO 59020:2024 standard. In bold, the indicators selected for both the *ex-ante* and *ex-post* phases. In italic, the indicators selected for the *ex-post* phase only. Further details on the indicators are available in the text of the standard.

Indicator category	Circularity indicator	Y *ex-ante*	N *ex-ante*	M *ex-ante*	Y *ex-post*	N *ex-post*	M *ex-post*
Resource inflow	**Average percent reused content of an inflow (X)**	8	0	2	9	0	1
	Average percent recycled content of an inflow (X)	9	1	0	9	1	0
Resource outflow	*Percent actual reused content derived from outflow (X)*	1	3	7	8	1	2
	Actual % recycling rate of outflow (X)	0	4	6	6	1	3
Energy	**Average percent of energy consumed that is renewable energy**	9	0	1	10	0	0
Water	*Percent water withdrawal from circular sources*	2	0	8	9	0	1
	Percent water discharged in accordance with quality requirements	2	3	5	8	2	0
	Ratio (onsite or internal) water reuse or recirculation	3	2	5	9	0	1
ADDITIONAL CIRCULARITY INDICATORS (FROM ANNEX B)							
Additional energy indicators	**Percent energy recovered from residual, non-renewable and non-recoverable resource outflow**	9	1	0	9	1	0

The reasoning developed by the WG for the exclusion of certain circularity indicators from the set of those suitable for assessing the circularity of remediation activities is here summarised. The "Economic indicators" and the "Additional economic indicators" were excluded because they pertain to organisational-level financial performance. Consequently, assessing these indicators was not considered relevant for the purposes of comparing the circularity performance of different remediation technologies (in the *ex-ante* phase) or monitoring the development of a remediation site (in the *ex-post* phase). The "Average percent renewable content of an inflow" indicator was excluded due to the nature of inputs in remediation, where soil – a non-renewable resource – is predominant; while phytoremediation may involve biomass, this was considered a too specific case to validate broad applicability. Indicators such as "Average lifetime of product or material relative to industry average" and "Percent actual recirculation of outflow in the biological cycle" were deemed inapplicable because remediation activities do not generate outflows that re-enter resource cycles. Finally, the indicators "Energy intensity" and "Nutrient extraction from discharged water" were excluded due to their limited relevance in the context of remediation activities.

Table 5 shows the relevance percentage of each indicator category of the ISO 59020:2024 standard for both the *ex-ante* and the *ex-post* phases.

3.3. Discussion of the results

In the context of environmental remediation, the concept of circularity differs from its conventional application in industrial production systems, as remediation activities do not generate marketable products, but primarily manage flows of soil, water, energy, and residual materials at the site level. Accordingly, circularity in remediation is primarily associated with the reduction of primary resource extraction and waste generation, on-site and off-site reuse of excavated materials, and the minimization of disposal, rather than with product life extension or closed-loop manufacturing processes. Indicators related to material resources (i.e., UNI 1, UNI 4, UNI 31, and indicators from ISO category "Resource inflow") assume a central role in remediation, as they capture circular strategies for the potential reuse of excavated soils (Nwaogu et al., 2025). This includes uncontaminated soil removed to access deeper contamination layers, which, depending on the applied technique (e.g. excavation and off-site disposal or on-site treatment, thermal desorption, or the installation of capping or containment barriers) may be identified as a by-product and subsequently reused, for instance through on-site backfilling. Soil washing has been proven to allow for on-site reuse of excavated and cleaned soil and for the recovery and recycling of valuable metals (such as lead, copper, and zinc) (Gusiatin

Table 5

Relevance percentages of each indicator category of the ISO 59020:2024 standard.

Indicator category	Relevance percentage for the *ex-ante* phase	Relevance percentage for the *ex-post* phase
Resource inflow	2/3 = 66.7%	2/3 = 66.7%
Resource outflow	0/4 = 0%	2/4 = 50%
Energy	1/1 = 100%	1/1 = 100%
Water	0/3 = 0%	3/3 = 100%
Economic	0/3 = 0%	0/3 = 0%
Additional energy indicators	1/2 = 50%	1/2 = 50%
Additional water indicators	0/1 = 0%	0/1 = 0%
Additional economic indicators	0/1 = 0%	0/1 = 0%
Average relevance percentage	27.8%	45.8%

et al., 2020). *In situ* stabilisation may show strong circularity performance with the incorporation of waste-derived amendments, such as biochar or bone char derived from agricultural or agro-industrial residues, which has been investigated for the remediation of heavy-metal-contaminated soils (Chen et al., 2022; Mei et al., 2022) or fluorine-contaminated water (Quan et al., 2022). Permeable reactive barriers can be constructed from secondary or renewable materials (Bardos et al., 2026), thereby limiting dependence on virgin raw materials. Water-related indicators (i.e., UNI 15 and ISO category "Water") capture circular practices linked to the management of water flows during remediation activities, such as the reuse of treated groundwater (Lenker et al., 2014) or process water within remediation systems, the reduction of freshwater withdrawals, and the control of water losses during treatment operations. In remediation contexts, water is both a treatment medium and a potentially contaminated matrix, making its recirculation and controlled reuse a key aspect of circular performance. Energy-related indicators reflect the significant energy demand of remediation technologies, including excavation, pumping, treatment, and material handling operations. The retained indicators (i.e., UNI 11, UNI 12, and ISO category "Energy") primarily address the sustainable energy supply, a critical aspect for reducing the environmental footprint of remediation interventions, particularly in energy-intensive technologies. These indicators can address energy supply from sustainable sources for low-input technologies such as photovoltaic-powered systems for low current electro-remediation (Hassan et al., 2015; Souza et al., 2016). Indicators related to waste generation and management (i.e., UNI 16, UNI 22) address the residue flows produced during remediation activities, mostly being excavated materials identified as waste. Circular strategies in this domain focus on minimizing the quantity of waste requiring final disposal, promoting recovery or reuse pathways, or even the possibility to label excavated materials as non-waste wherever technically and legally feasible. A representative example of a technology allowing for soil reuse is provided by biopile treatment, which enables the valorisation of soil that would otherwise be managed as waste (McWatters et al., 2016). The indicators addressing economic aspects (i.e., UNI 31, UNI 34, UNI 41, UNI 46, UNI 64, and UNI 65) reflect strategic and operational choices that can influence the circular performance of remediation activities, such as the selection of suppliers, technologies, and services aligned with circular principles, or investments aimed at improving material recovery and reuse pathways. While these indicators can generally be more informative in the *ex-post* assessment phase – where financial and procurement data are available and consolidated – they also provide insight into the organisational capacity to support circular remediation practices over time.

To date, literature provides no evidence of the direct evaluation of circularity in environmental remediation using standardised indicators. When circularity is considered, it is typically addressed as a secondary aspect within sustainability assessment (Diwan et al., 2024). Studies focus primarily on how the application of specific remediation techniques or materials may enable recovery, recycling, and reuse of treated matrices or derived by-products (Thamarai et al., 2025). As a result, circularity is most often framed as a contextual or supporting perspective, rather than as a foundation for operational decision-making (Nalladiyil and Babu, 2024; Dervash et al., 2024). While a number of studies highlight the potential circular benefits of individual technologies or practices (Povedano-Priego et al., 2025), there is no systematic approach to evaluate whether and how standard circularity indicators can quantify the degree to which remediation interventions implement CE principles. This represents a knowledge gap that the present study addresses: by critically assessing standardised indicators in the context of actual remediation activities, this work aims to determine if there are meaningful, context-appropriate, and operationally useful indicators to support decision-making and performance monitoring in remediation activities. The work moves beyond conceptual frameworks, providing a quantitative and comparative perspective on the applicability of circularity assessment in real remediation scenarios. In order to illustrate the operational applicability of the selected indicators, a hypothetical remediation scenario was developed. A hydrocarbon-contaminated site was assumed to be remediated using one of the following three alternative remediation technologies: excavation and off-site disposal (dig & dump), capping, and biopile treatment. Tables 6 and 7 present examples of how the retained UNI circularity indicators can be operationalised, respectively, in an *ex-ante* (i.e. during the technology screening and decision-making phase) and an *ex-post* (i.e., during the monitoring of an ongoing remediation project) context. Tables 8 and 9 present the same examples for the retained ISO circularity indicators. Table 6, Table 7, Tables 8, and Table 9 identify the main circularity elements that would be valorised for each technology, including material reuse, waste generation and recovery pathways, energy and resource use, and procurement-related aspects. However, the effective valorisation of the identified circularity elements depends on data availability and quality. In the *ex-ante* phase, this is primarily constrained by the availability of sufficiently detailed site-specific documentation from which the required information can be derived. In the *ex-post* phase, it depends on the efficiency and consistency of the data collection process implemented during the monitoring of the ongoing remediation intervention.

The present study evaluates standardised circularity indicators in terms of their operational relevance, contextual appropriateness, and practical applicability within environmental remediation. This analysis clarifies which indicators can potentially support circularity assessment and decision-making, with circularity understood as a component that reinforces broader sustainability objectives in environmental remediation. The assessment of the UNI/TS 11820:2022 and ISO 59020:2024 indicators highlight a series of common challenges in applying general circularity assessment frameworks to the specific context of environmental remediation. In both cases, a substantial number of indicators were excluded due to issues of operational relevance, contextual appropriateness, or limited data availability.

For the UNI/TS 11820:2022 standard, the most represented category in both assessment phases was "02. Indicators related to energy and water resources", while the least represented was "06. Indicators related to human resources, assets, policies, and sustainability". The average relevance percentage was 22.3% for the *ex-ante* phase and 25.6% for the *ex-post* phase, reflecting a modest retention aligned with the original focus of the standard on sustainability reporting.

For the ISO 59020:2024 standard, the most represented indicators category was "Energy" (despite having only one indicator), while the least represented categories were "Economic", "Additional water indicators", and "Additional economic indicators". Here, the average relevance percentage was 27.8% for the *ex-ante* phase and 45.8% for the *ex-post* phase, confirming a greater alignment with post-intervention monitoring and non-financial reporting rather than early-stage planning.

Inter-expert agreement was assessed using Krippendorff's alpha.[3] For the UNI group, alpha values were 0.25 for the *ex-ante* assessment and 0.28 for the *ex-post* assessment, indicating weak concordance among experts. For the ISO group, alpha values were 0.38 for the *ex-ante* assessment and 0.38 for the *ex-post* assessment, reflecting weak-to-moderate concordance. These results suggest that, despite the selection of relevant indicators, substantial differences in expert judgements exist, highlighting potential ambiguities in the interpretation of indicators requirements. This underscores the need to test the selected indicators in a real case study, in order to modify the set or adapt the indicators to the remediation context, thereby developing a framework specifically tailored to environmental remediation.

The modest proportion of retained indicators point to a significant gap between the full sets and the specific information and practical needs of the remediation domain. This observation underlines a shared

---

[3] The complete R code used for the Krippendorff's alpha analysis is provided in the supplementary material.

Table 6
Possible characteristic elements of three remediation technologies (dig & dump, capping, and biopiles) that can be assessed using UNI circularity indicators in *ex-ante* phase.

UNI INDICATORS	Technology- and site-specific elements for circularity indicators valorisation		
	DIG & DUMP	CAPPING	BIOPILES
1. Self-produced secondary material resources/ total material resources	Quantity of excavated soil that can be reused on site for backfilling after treatment. This indicator measures the ratio between the quantity of backfill generated on site and the quantity of clean soil and other material resources sourced externally.	This technology does not generate secondary material resources, since the contaminated soil remains sealed.	Quantity of excavated and biologically treated soil that can be reused on site for backfilling. This indicator measures the quantity of backfill generated on site and the quantity of material resources sourced externally.
2. Raw materials and secondary material resources from local suppliers/ total purchased materials	Quantity of materials for stabilisation and containment, geosynthetics, drainage materials, and surface restoration materials that can be locally sourced.		
4. By-products or secondary material resources/ total material input	Quantity of uncontaminated soil excavated to access the contaminated soil layer.	Quantity of uncontaminated soil generated during excavation and grading activities required for the installation of the capping system.	Quantity of uncontaminated soil excavated during the preparation of biopile treatment.
11. Self-produced renewable electrical energy/total electrical energy	The valorisation of this indicator is operational-dependent rather than technology-dependent, as it is not directly related to the intrinsic characteristics of the remediation technologies, except for differences in their energy demand. Instead, it reflects site-specific choices regarding energy supply during remediation works. For example, part of the electricity required for on-site operations can be provided by renewable energy systems installed directly at the site, such as photovoltaic panels.		
12. Self-generated renewable thermal energy/total thermal energy	The valorisation of this indicator is operational-dependent rather than technology-dependent, since it is not directly related to the intrinsic characteristics of the remediation technologies, except for differences in their energy demand. Instead, it reflects site-specific choices regarding energy supply during remediation works. For example, part of the heat required on-site can be provided by solar thermal systems or heat pumps installed directly at the site.		
15. Water from recovery or recycling/ total water demand	Quantity of process water for site operations and dust suppression that is collected, treated and reused or safely discharged.		
16. Waste sent to landfill/ total waste produced	Quantity of contaminated soil that is excavated and sent to landfill; quantity of fine contaminated fractions.	Quantity of vegetation residues; quantity of geosynthetic offcuts.	Quantity of non-treatable contaminated fractions (if present); quantity of residual contaminated technical materials.
22. Waste treated at local recovery plants/total treated waste	Quantity of contaminated soil sent to a local soil treatment plant; quantity of inert waste sent to a local recovery plant. The valorisation of this indicator depends on local availability of recovery or treatment plants.	Quantity of vegetation residues sent to a local composting or green waste treatment plant; quantity of residual technical materials sent to a local plastic waste recycling plant.	Quantity of organic residues that are not reused on site and are sent to a local composting plant; quantity of residual technical materials sent to a local recycling plant.
30. Supplies from certified sustainable or circular suppliers/ total supplies value	Economic value of mineral materials (natural or recycled aggregates) supplied by suppliers certified according to ISO 14001 or provided with an Environmental Product Declaration (EPD).	Economic value of geosynthetic materials supplied by suppliers certified according to ISO 14001 or provided with a Product Environmental Footprint (PEF).	Economic value of soil conditioners and organic materials (e.g., compost, organic soil conditioners, bulking agents) supplied from suppliers certified according to ISO 14001 certification or provided with an EPD.
31. By-products generated/ total production residues	Quantity of uncontaminated soil removed during site preparation activities; quantity of topsoil removed before excavation; quantity of coarse uncontaminated mineral fractions separated from contaminated soil.		
34. Procured circular business model products or services/ total procurement	Quantity or economic value of rented equipment (instead of purchased equipment); quantity or economic value of secondary aggregates supplied by recovery plants.		

structural limitation: many indicators in both standards are designed with broader industrial or organisational contexts in mind and therefore struggle to address specific operational and site-level related aspects of remediation activities. For example, indicators related to product output or industrial symbiosis appear poorly transferable as remediation projects typically lack ongoing production processes and rarely operate within interconnected production networks. Similarly, indicators focused on organisational strategies or broad economic aspects offer limited value in site-specific assessments. At the same time, the greater representation of resource-related indicators (such as those covering material resources, energy and water use) across both standards confirms that resource efficiency remains a core, transversal component of circularity within remediation contexts. These indicators were also considered among the most informative and actionable for evaluating how specific technologies contribute to circular and sustainable outcomes. Notably, the set of selected indicators focuses predominantly on environmental and economic sustainability dimensions, with little to no coverage of social aspects. Economic indicators tend to be more commonly included in the *ex-post* phase assessment, while being underrepresented in the *ex-ante* phase assessment. This asymmetry reflects the WG members' assessment that there is a lack of reliable and specific data sources with data suitable for supporting the evaluation of economic indicators in the *ex-ante* phase. Importantly, the lower *ex-ante* relevance observed in both standards signals a gap in the ability to support strategic and comparative evaluations in the planning phase, where sustainability considerations should ideally be embedded. This suggests that, while both standards offer a useful reference framework, their effective application to the remediation sector requires critical selection, sector-specific adaptation, or even the development of tailored indicators to ensure operational value and compliance with

Table 7
Possible characteristic elements of three remediation technologies (dig & dump, capping, and biopiles) that can be assessed using UNI circularity indicators in *ex-post* phase.

UNI INDICATORS	Technology- and site-specific elements for circularity indicators valorisation		
	DIG & DUMP	CAPPING	BIOPILE
41. Value of products and services (excluding raw materials) procured from local suppliers / total value of products and services (excluding raw materials)	Economic value of local environmental monitoring services; economic value of local project supervision and site management services; value of machinery rental.		
46. R&D investments related to circular economy principles / total R&D investments	Economic value of investments for studies aimed at reducing the amount of excavated soil classified as waste and increasing reuse or recovery pathways.	Economic value of investments for design optimization and development of containment solutions based on recycled or low-impact materials.	Economic value of investments for the development of biological treatment strategies based on waste-derived amendments and maximization of soil reuse.
64. Goods and infrastructure (e.g. computers, vehicles, furniture, buildings, land) purchased by the organisation based on the lowest life-cycle cost criterion / total purchased goods and infrastructure	Economic value of purchased operational equipment, vehicles, and reusable containers selected based on life-cycle cost criteria.	Economic value of purchased monitoring systems and technical equipment selected based on life-cycle cost criteria.	Economic value of purchased aeration, irrigation, and monitoring systems selected based on life-cycle cost criteria.
65. Goods and infrastructures with circular end-of-life management solutions / organisation's total goods and infrastructures	Economic value of reusable containers, monitoring equipment, and temporary site infrastructures designed for repeated use in other remediation projects.	Economic value of monitoring systems and temporary technical infrastructures designed for reuse.	Economic value of aeration systems and irrigation systems, monitoring equipment, and temporary infrastructures designed for dismantling and reuse in other remediation projects.

Table 8
Possible characteristic elements of three remediation technologies (dig & dump, capping, and biopiles) that can be assessed using ISO circularity indicators in *ex-ante* phase.

ISO INDICATORS	Technology- and site-specific elements for circularity indicators valorisation		
	DIG & DUMP	CAPPING	BIOPILES
Average percent reused content of an inflow	Quantity of excavated soil that can be reused for on site backfilling after treatment; quantity of uncontaminated soil excavated to access the contaminated soil layer that can be reused on site; quantity of coarse uncontaminated mineral fractions separated from contaminated soil that can be reused on site.	Quantity of uncontaminated soil generated during excavation and grading activities required for the installation of the capping system that can be reused on site.	Quantity of excavated and biologically treated soil that can be reused for on site backfilling; quantity of uncontaminated soil excavated during the preparation of biopile treatment that can be reused on site.
Average percent recycled content of an inflow	Quantity of recycled aggregates and recycled granular materials for site restoration after excavation.		Quantity of compost and recycled organic materials used as amendments.
Average percent of energy consumed that is renewable energy	The valorisation of this indicator is operational-dependent rather than technology-dependent, as it is not directly related to the intrinsic characteristics of the remediation technologies, except for differences in their energy demand. Instead, it reflects site-specific choices regarding energy supply during remediation works.Quantity of energy required for site operations provided by renewable energy systems installed directly at the site, such as photovoltaic panels.		
Percent energy recovered from residual, non-renewable and non-recoverable resource outflow	Quantity of residual contaminated or uncontaminated fractions, technical materials, and non-recoverable waste that are sent to energy recovery treatment.		

legal and environmental constraints. Ultimately, the comparative assessment carried out in this study helps to clarify not only which indicators are more robust and meaningful, but also where circularity metrics need refinement to become fully operational within the environmental remediation domain.

4. Conclusions

This paper presents an expert-based methodology for selecting circularity indicators applicable to contaminated site remediation, in both *ex-ante* (screening and prioritisation) and *ex-post* (monitoring and reporting) phases. A total of 24 suitable circularity indicators were identified from ISO 59020:2024 and UNI/TS 11820:2022 standards: 15 from UNI/TS 11820:2022 (11 for both phases and 4 only for the *ex-post* phase) and 9 from ISO 59020:2024 (4 for both phases and 5 only for the *ex-post* phase). All indicators for the *ex-ante* assessment phase are also valid *ex-post*, while additional indicators apply only once remediation activities have started.

The selected indicators focus on the environment and economic domains, aligning with the identified priority thematic areas of resources, energy, water and waste, with the "resources" theme being the most articulated. The proposed approach highlights the opportunity to systematically measure circularity contributions to sustainability, with the aim of enabling more informed technology choices during the *ex-ante* phase and a reliable monitoring framework during the *ex-post* phase. The prospective application to real case studies aims to evaluate the extent to which circular economy principles are integrated into remediation technologies, thereby guiding decision-making from a circularity perspective in support of sustainability. From an operational standpoint, this approach can enable the assessment of circular management of material and water resources, the recovery and reuse of excavated materials, the minimization of waste generation, and the economic aspects associated with implementing circular practices.

Future work will test the indicators through a real case study application, allowing evaluation of their operational feasibility and the extent to which available data can support their calculation and use in practice, drawing information documented in remediation project plans,

Table 9
Possible characteristic elements of three remediation technologies (dig & dump, capping, and biopiles) that can be assessed using ISO circularity indicators in *ex-post* phase.

ISO INDICATORS	Technology- and site-specific elements for circularity indicators valorisation		
	DIG & DUMP	CAPPING	BIOPILES
Percent actual reused content derived from outflow	Quantity of clean or treated soil, aggregates, and inert materials thar can be reused for off-site backfilling.		
Actual % recycling rate of outflow	Quantity of excavated uncontaminated aggregates and metallic materials that are sent to a recycling plant.	Quantity of aggregates and granular materials from demolition ed excavation activities and geosynthetic offcuts that can be recycled.	Quantity of excavated uncontaminated aggregates, and organic materials that can be recycled.
Percent water withdrawal from circular sources	Quantity of collected rainwater, collected and treated process water that is reused for site operations (e.g. cleaning and dust suppression).		
Percent water discharged in accordance with quality requirements	Quantity of process water for site operations that is collected, treated and safely discharged.		
Ratio (onsite or internal) water reuse or recirculation	Quantity of process water from reuse against total site water consumption.		

site investigation reports, feasibility studies, progress and monitoring reports, waste management sheets, and procurement records. Since the selected indicators cover environmental and economic dimensions, future research could explore the integration of social aspects. One possible approach could be to consider the reduction of negative externalities associated with remediation technologies that enable on-site reuse of excavated materials, thereby lowering emission from transport and reducing reliance on landfills, which would capture a social relevant dimension of circularity performance.

CRediT authorship contribution statement

A. Sellitri: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **L. Pizzol:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **A. Bonfà:** Methodology. **G. Meneghin:** Methodology. **M. Menegaldo:** Methodology. **P. Scanferla:** Writing – review & editing, Project administration, Methodology. **A. Zabeo:** Methodology. **G. Schileo:** Methodology. **S. Devecchi:** Methodology. **S. Breda:** Methodology. **P. Bardos:** Writing – review & editing. **E. Semenzin:** Writing – review & editing, Funding acquisition.

Funding sources

This work has been supported by a PhD scholarship funded by the European Commission Next-Generation EU Plan through its Italian implementation: PNRR (National Recovery and Resilience Plan) DM 352/2022 CUP H73C22000350004; by the RETURN Extended Partnership and received funding from the European Union Next-Generation EU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 August 2, 2022, PE 0000005); the Horizon Europe ISLANDR Project, funded by the European Union (under Grant Agreement 1001112889), UKRI, and the Swiss Government. This work took place within the framework of the DoW 2023-2027 (MUR, AIS.DIP.ECCELLENNZA2023_27.FF) project.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2026.100431.

Data availability

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

References

Abrams, F., Hendrickx, L., Turcanu, C., Sweeck, L., Van Orshoven, J., 2024. Multi-criteria decision analysis to support the remediation of polluted soils: a review of case studies. Land 13 (6). https://doi.org/10.3390/land13060887.

Aparicio, J.D., Raimondo, E.E., Saez, J.M., Costa-Gutierrez, S.B., Alvarez, A., Benimeli, C., Polti, M.A., 2022. The current approach to soil remediation: a review of physicochemical and biological technologies, and the potential of their strategic combination. J. Environ. Chem. Eng. 10 (2), 107141. https://doi.org/10.1016/j.jece.2022.107141.

Ashraf, M.A., Maah, M.J., Yusoff, I., 2014. Soil contamination, risk assessment and remediation. Environmental risk assessment of soil contamination 1, 3–56. https://doi.org/10.5772/57287.

ASTM International, 2017. Standard Guide for Developing Conceptual Site Models for Contaminated Sites, E1vols. 689–95. ASTM. https://doi.org/10.1520/E1689-95.

Bardos, P., Lai, J., Pizzol, L., Sellitri, A., Couto, N., Derycke, V., Cundy, A., 2026. Low input remediation techniques for contaminated site management. Environmental Sciences: Advances 5, 567–590. https://doi.org/10.1039/D5VA00242G.

Bardos, R.P., Thomas, H.F., Smith, J.W., Harries, N.D., Evans, F., Boyle, R., Haslam, A., 2020. Sustainability assessment framework and indicators developed by SuRF-UK for land remediation option appraisal. Remed. J. 31 (1), 5–27. https://doi.org/10.1002/rem.21668.

Braun, A.B., Visentin, C., da Silva Trentin, A.W., Antônio, T., 2021. List of relevant sustainability indicators in remediation processes and their validation by stakeholders. J. Clean. Prod. 317. https://doi.org/10.1016/j.jclepro.2021.128440.

Chen, Q., Zhang, Z., Wang, Y., Mu, G., Wu, X., Liu, Y., Wen, X., 2022. Remediation of soil contaminated by heavy metals using biochar: strategies and future prospects. Pol. J. Environ. Stud. 32 (1), 27–40. https://doi.org/10.15244/pjoes/153912.

Ciampi, P., Felli, G., Feriaud, D., Esposito, C., Petrangeli Papini, M., 2024. 3D GeoRemediation: a digital Hydrogeophysical–Chemical clone and virtual hydraulic barrier with groundwater circulation Wells (GCWs) for groundwater remediation. Sustainability 16 (5216). https://doi.org/10.3390/su16125216.

Corona, B., Shen, L., Reike, D., Carreón, J.R., Worrell, E., 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. 151, 104498. https://doi.org/10.1016/j.resconrec.2019.104498.

Dervash, M., Yousuf, A., Bhat, M., Ozturk, M., 2024. Soil remediation: biological approaches, regulatory frameworks, and circular economy. Soil Organisms 107–117. https://doi.org/10.1007/978-3-031-66293-5_10.

Diwan, H., Sreeraman, B., Yadav, G., 2024. Circularity assessment through LCA approach. In: Kumar, A., Kumar, S., Ratna, S. (Eds.), Nature-Based Wastewater Treatment Systems. Taylor & Francis Group.

Doran, G.T., 1981. There's a SMART way to write managements's goals and objectives. Management review 70 (11). Retrieved from. https://web.p.ebscohost.com/ehost/detail/detail?vid=0&sid=2d9c3912-6a84-4dd9-910f-ed3b57aa8e28%40redis&bdata=JnNpdGU9ZWhvc3QtbGl2ZQ%3d%3d#db=bsu&AN=6043491.

Ellis, D.E., Hadley, P.W., 2009. Sustainable remediation white paper - integrating sustainable principles, practices, and metrics into remediation projects. Remed. J. 19 (3), 5–114. https://doi.org/10.1002/rem.20210.

Ente Italiano di Normazione, 2022. Measuring Circularity - Methods and Indicators for Measuring Circular Processes in Organizations. Retrieved from. https://store.uni.com/en/uni-ts-11820-2022.

European Commission, 2023. Commission delegated regulation (EU) 2023/2772 of 31 July 2023 supplementing Directive 2013/34/EU of the European Parliament and of the Council as regards sustainability reporting standards. Retrieved from. https://eur-lex.europa.eu/eli/reg_del/2023/2772/2023-12-22.

European Commission, Directorate-General for Communication, 2020. Circular Economy Action Plan - for a Cleaner and More Competitive Europe. Publication Office of the European Union. https://doi.org/10.2779/05068.

European Commission, Directorate-General for Research and Innovation, 2021. European Green Deal - Research & Innovation Call. Publication Office of the European Union. https://doi.org/10.2777/33415.

Farmer, A., 2020. Developing the circular economy in the European Union. In: Circular Economy: Global Perspective. Springer, Singapore, pp. 389–412. https://doi.org/10.1007/978-981-15-1052-6_20.

Favara, P., Raymond, D., Ambrusch, M., Libera, A., Wolf, G., Simon, J.A., Howard, L., 2019. Ten years later: the progress and future of integrating sustainable principles, practices, and metrics into remediation projects. Remed. J. https://doi.org/10.1002/rem.21612.

Ferber, U., Grimski, D., Millar, K., Nathanail, P., 2006. Sustainable Brownfield Regeneration. University of Nottingham, Nottingham.

Fetting, C., 2020. The European Green Deal. ESDN Office, Vienna: ESDN.

Grifoni, M., Franchi, E., Fusini, D., Vocciante, M., Barbafieri, M., Pedron, F., Petruzzelli, G., 2022. Soil remediation: towards a resilient and adaptive approach to deal with the ever-changing environmental challenges. Environments 9 (18). https://doi.org/10.3390/environments9020018.

Gusiatin, Z.M., Kulikowska, D., Klik, B., 2020. New-Generation washing agents in remediation of metal-polluted soils and methods for washing effluent treatment: a review. Int. J. Environ. Res. Publ. Health 17 (17). https://doi.org/10.3390/ijerph17176220.

Hassan, I., Mohamedelhassan, E., Yanful, E.K., 2015. Solar powered electrokinetic remediation of Cu polluted soil using a novel anode configuration. Electrochim. Acta 181, 58–67. https://doi.org/10.1016/j.electacta.2015.02.216.

Hodson, M.E., 2010. The need for sustainable soil remediation. Elements 6 (6), 363–368. https://doi.org/10.2113/gselements.6.6.363.

Holland, K., Karnis, S., Kasner, D., Butler, P., Hadley, P., Nathanail, P., Wice, R., 2013. Integrating remediation and reuse toAchieve whole-system SustainabilityBenefits. Remed. J.

Hou, D., Al-Tabbaa, A., 2014. Sustainability: a new imperative in contaminated land remediation. Environ. Sci. Pol. 39, 25–34. https://doi.org/10.1016/j.envsci.2014.02.003.

Hsu, C.-C., Sandford, B.A., 2007. The Delphi technique: making sense of Consensus. Practical Assess. Res. Eval. 12. https://doi.org/10.7275/pdz9-th90.

International Organization for Standardization, 2019. Soil Quality - Conceptual Site Models for Potentially Contaminated Sites. *ISO 21365:2019*.

Khan, F.I., Husain, T., Hejazi, R., 2004. An overview and analysis of site remediation technologies. J. Environ. Manag. 71 (2), 95–122. https://doi.org/10.1016/j.jenvman.2004.02.003.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kuci, A., Fogarassy, C., 2021. European green deal policy for the circular economy opportunities and challenges. Hungarian Agricultural Engineering 39, 65–73. https://doi.org/10.17676/HAE.2021.39.65.

Lamprou, A., Vagiona, D., 2025. The Application of Multicriteria Decision Making/Analysis Methods (MCDM/MCDA) for the evaluation of Project Success: a State-of-The-Art Survey. Annals of Social Sciences & Management studies 11 (5), 1–17. https://doi.org/10.19080/ASM.2025.11.555825.

Lemming, G., Hauschild, M., Bjerg, P., 2010. Life cycle assessment of soil and groundwater remediation technologies: literature review. Int. J. Life Cycle Assess. 15 (1), 115–127. https://doi.org/10.1007/s11367-009-0129-x.

Lenker, c., Harclreode, M., Aragona, K., Fisher, A., Jasmann, J., Hadley, P., 2014. Integrating groundwater conservation and reuse into remediation projects. Remed. J. 24 (2), 11–27. https://doi.org/10.1002/rem.21389.

Liu, Y., Fei, Y.Y.L., Bao, X., Zhang, P., 2024. Pollution source identification methods and remediation technologies of groundwater. China Geol. 7 (1), 125–137. https://doi.org/10.31035/cg2022080.

McWatters, R.S., Wilkins, D., Spedding, T., Hince, G., Raymond, B., Lagerewskij, G., Snape, I., 2016. On site remediation of a fuel spill and soil reuse in Antarctica. Sci. Total Environ. 571, 963–973. https://doi.org/10.1016/j.scitotenv.2016.07.084.

Meadows, D.H., Meadows, D.L., Randers, J., Behrens III, W., 1972. The Limits to Growth. A Report for the Club of Rome's Project on the Predicament of Mankind. Universe Books. Retrieved from. https://donellameadows.org/the-limits-to-growth-now-available-to-read-online/.

Mei, H., Huang, W., Wang, Y., Xu, T., Zhao, L., Zhang, D., Pan, X., 2022. One stone two birds: bone char as a cost-effective material for stabilizing multiple heavy metals in soil and promoting crop growth. Sci. Total Environ. 840, 156–163. https://doi.org/10.1016/j.scitotenv.2022.156163.

Nalladiyil, A., Babu, G., 2024. Dumpsite remediation through landfill mining and rehabilitation: a circular economy perspective. J. Indian Inst. Sci. 104, 489–518. https://doi.org/10.1007/s41745-024-00445-5.

Nathanail, C.P., Bardos, R.P., 2004. Geology for contaminated land. In: Reclamation of Contaminated Land. John Wiley & Sons, Ltd, pp. 34–48. https://doi.org/10.1002/0470020954.ch4.

Nathanail, C.P., Bakker, L.M., Bardos, R.P., Furukawa, Y., Nardella, A., Smith, G., et al., 2017. Towards an international standard: the ISO/DIS 18504 standard on sustainable remediation. Remed. J. 28 (1), 9–15. https://doi.org/10.1002/rem.21538.

National Research Council, 1994. Alternatives for Ground Water Cleanup. The National Academies Press, DC. https://doi.org/10.17226/2311.

NICOLE; COMMON FORUM, 2013. Risk-Informed and sustainable remediation. NICOLE and COMMON FORUM. Retrieved from https://nicole.org/documents/.

Nwaogu, C., Minasny, B., Field, D., Cherubin, M., 2025. Conceptualizing core aspects of circular economy in soil: a critical review and analysis. Crit. Rev. Environ. Sci. Technol. 55 (11), 805–835. https://doi.org/10.1080/10643389.2025.2454689.

Okx, J.P., Hordijk, L., Stein, A., 1996. Managing soil remediation problems. Environ. Sci. Pollut. Control Ser. 3, 229–235. https://doi.org/10.1007/BF02986966.

Ossewaarde, M., Ossewaarde-Lowtoo, R., 2020. The EU's green deal: a third alternative to green growth and degrowth? Sustainability 12 (23), 9825. https://doi.org/10.3390/su12239825.

Owsianiak, M., Lemming, G., Hauschild, M.Z., Bjerg, P., 2013. Assessing environmental sustainability of remediation technologies in a life cycle perspective is not So easy. Environmental Science & Technology 47 (3). https://doi.org/10.1021/es305279t.

Povedano-Priego, C., Jroundi, F., Lopez-Fernandez, M., Ruiz-Fresneda, M., Newman-Portela, A., Hlavackova, V., Cundy, A., 2025. From waste to resource: a review on biological and physicochemical metal remediation and recovery in the light of the circular economy. J. Hazard Mater. 498. https://doi.org/10.1016/j.jhazmat.2025.139991.

Price, J., Spreng, C., Hawly, E.L., Deeb, R., 2017. Remediation management of complex sites using an adaptive site management approach. J. Environ. Manag. 204 (2), 738–747. https://doi.org/10.1016/j.jenvman.2017.04.009.

Quan, W., Wang, A., Gao, C., Li, C., 2022. Applications of Chinese Camellia oleifera and its By-Products: a review. Front. Chem. 10. https://doi.org/10.3389/fchem.2022.921246.

Reike, D., Vermeulen, W.J., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0?—exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour. Conserv. Recycl. 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027.

Rizzo, E., Bardos, P., Pizzol, L., Critto, A., Giubilato, E., Marcomini, A., Smith, G., 2016. Comparison of international approaches to sustainable remediation. J. Environ. Manag. 184 (1), 4–17. https://doi.org/10.1016/j.jenvman.2016.07.062.

Sabato, S., Fronteddu, B., 2020. A socially just transition through the European Green Deal? ETUI Research Paper-Working Paper. https://doi.org/10.2139/ssrn.3699367.

Sassanelli, C., Rosa, P., Rocca, R., Terzi, S., 2019. Circular economy performance assessment methods: a systematic literature review. J. Clean. Prod. 229, 440–453. https://doi.org/10.1016/j.jclepro.2019.05.019.

Singh, S., Sivaram, N., Dhanjal, D.S., Assefa, H., Singh, J., Ramamurthy, P.C., 2024. Navigating the complexity of emerging contaminants: sources, impacts, and remediation strategies. J. Indian Inst. Sci. 104, 519–533. https://doi.org/10.1007/s41745-024-00446-4.

Smith, J.W., 2019. Debunking myths about sustainable remediation. Remediation 29 (2), 7–15. https://doi.org/10.1002/rem.21587.

Souza, F.L., Saéz, C., Llanos, J., Lanza, M.R., Cañizares, P., Rodrigo, M.A., 2016. Solar-powered electrokinetic remediation for the treatment of soil polluted with the herbicide 2,4-D. Electrochim. Acta 190, 371–377. https://doi.org/10.1016/j.electacta.2015.12.134.

Suárez-Eiroa, B., Fernández, E., Méndez-Martínez, G., Soto-Oñate, D., 2019. Operational principles of circular economy for sustainable development: linking theory and practice. J. Clean. Prod. 214, 952–961. https://doi.org/10.1016/j.jclepro.2018.12.271.

Swartjes, F.A., 2011. Dealing with Contaminated Sites - from Theory Towards Practical Application. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-9757-6.

Thamarai, P., Deivayanai, V., Ragini, Y., Kamalesh, R., Saravanan, A., Vickram, A., 2025. Recent advances in carbon nanomaterials: pioneering sustainable environmental contamination remediation and advancing circular economy practices. Rev. Environ. Contam. Toxicol. 263 (19). https://doi.org/10.1007/s44169-025-00094-4.

UNEP, F.a., 2021. Global Assessment of Soil Pollution. FAO and UNEP. https://doi.org/10.4060/cb4894en.

Walzberg, J., Lonca, G., Hanes, R.J., Eberle, A.L., Carpenter, A., Heath, G.A., 2021. Do we need a new sustainability assessment method for the circular economy? A critical literature review. Front. Sustain. 1. https://doi.org/10.3389/frsus.2020.620047.

Zheng, W., Cui, T., Li, H., 2022. Combined technologies for the remediation of soils contaminated. A review. Environ. Chem. Lett. 20, 2043–2062. https://doi.org/10.1007/s10311-022-01407-y.