The impacts of remediation techniques on soil functions: a review

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Literature review strategy

A structured, narrative literature review (Snyder, 2019) was performed by searching the Scopus database for scientific studies that have measured the impacts of remediation techniques on specific soil functions or indicators. First, a broad, simple search for combinations of “remediation techniques”, “impacts”, “soil function”, “soil health”, and “soil quality” were tested, which resulted in many hits (945) but few relevant papers after a cursory review of titles and abstracts (6). Following this search, combinations of primary (remediation techniques) and secondary (soil function-related) keywords were used to collect a representative (i.e., non-exhaustive) sample of the literature to make the assessment (Table S1), which followed the same general search strategy for all remediation techniques: 1) primary keywords – conventional and low-impact remediation techniques considered in the review including related terms and abbreviations, e.g., “chemical remediation” OR “ISCO” OR “ISCR”; AND 2) search terms related to soil functions and specific indicators, e.g., “soil function”, “soil functionality”, “soil health”, “soil quality”, “soil properties”, “organic matter”, “enzyme”, “biodiversity”, etc. Titles and abstract were screened for relevance, followed by a full-text review of shortlisted articles (131). Studies were included if they reported measurable changes in soil properties or indicators associated with soil functions following remediation but were excluded if they focused solely on contaminant removal efficiency without reporting changes in other soil parameters. The search was conducted for studies published up to 2026, without restriction on publication year. Note that not all secondary keywords were used for each remediation technique but were explored until a sufficient number of studies were collected to perform the assessment or a knowledge gap was identified.

Table S1. Primary and secondary keywords for narrative literature review.

Primary Keywords	Secondary Keywords
Chemical remediation OR ISCO OR ISCR	Soil function OR soil functionality
Thermal treatment OR thermal desorption	Soil properties
Electrokinetic remediation	Soil health
Soil washing OR soil flushing	Soil parameters
Multi-phase extraction OR MPE	Soil quality
Air sparging	Soil impacts
Soil containment OR capping OR barrier	Organic matter OR SOM OR SOC OR organic carbon

Stabilization solidification OR stabilisation OR S/S	Enzyme activity
Immobilization Or immobilisation OR stabilization OR stabilisation AND inorganic amendments	Microbial biomass
Immobilization Or immobilisation OR stabilization OR stabilisation AND organic amendments OR biochar OR compost	Soil fauna
Monitored natural attenuation OR MNA OR natural source zone depletion OR NSZD	Earthworm
Bioremediation OR biostimulation OR bioaugmentation	Respiration OR carbon mineralization OR carbon mineralization
Phytoremediation OR phytomanagement	Soil mesofauna
	Biodiversity
	Functional diversity
	Functional genes
	Soil texture
	Water holding capacity OR water retention
	Ecotoxicological
	Nitrification
	Bulk density
	Microbial activity
	Nutrient availability
	Porosity
	Aggregate stability OR aggregation

Impacts of conventional remediation techniques on soil functions

Table S2. Expected impacts of conventional remediation techniques on the six main soil functions, sub-functions and indicators/descriptors.

Remediation techniques / **Soil functions**		***Conventional remediation techniques***							
Function	**Sub-functions & -** *indicators/descriptors*	**Thermal treatment (in-situ/ex-situ*)[a]**	**Soil washing (ex-situ*) or flushing (in-situ)[b]**	**ISCR/ISCO (in-situ)[c]**	**Electrokinetic remediation (in-situ)[d]**	**Multi-phase extraction (in-situ)[e]**	**Air sparging (in-situ)[f]**	**Containment/ capping/barriers (in-situ)[g]**	**Stabilisation/ solidification (S/S, in-situ/ex-situ*)[h]**
Organic matter storage, transformation and recycling	**Decomposition**								
	-soil microbial biomass	– or +/-	– or +/-	– –	– or +/-		+ or +/-	– –	– –
	-invertebrate feeding activity						+	– –	– –
	-organic matter mineralization in soil	+/-			– or +/-		-	– –	– –
	Resource reallocation								
	-soil organic carbon (SOC)	– –	–	– –	+/-		– or +/-	– –	– –
	Biochemical transformation								

	-soil organic carbon (SOC)	– –	–	– –	+/-		– or +/-	– –	– –
	-microbial basal respiration (carbon mineralization)		– or +/-	– or +/-	– or +/-			– –	– –
	-microbial catabolic activities (MSIR, enzymes)	– or +/-	– –	–	– or +/-		+	– –	– –
	-functional diversity/genes				– or +/-			– –	– –
	Water retention								
	-soil texture	– –	– or +/-	+/-			+ or -	– or +/-	+ or -
	-water holding capacity (retention)	– –	–	–			-	– or +/-	— —
Water regulation, retention and release	*-soil organic carbon (SOC)*	– –	–	– –			– or +/-	--	– –
	Infiltration and percolation								
	-infiltration/permeability	–				+/-	+ or +/-	--	– –
	-bulk density	+/-	+/-			+/-	+ / -	+ / -	+ / -
	-effects on macrofauna (earthworms)	– or +/-		– –			+ / -	--	
	Nutrient transformation								
Nutrient cycling	*-total nitrogen content*	– or +/-	–	–	+/-		+/-	+/-	
	-Assimilable/extractable phosphorous content	+ or +/-	–	+ or +/-	+ or +/-			+/-	

	-pH	+/-	+/-	– –	– –		-	+/-	+/-
	-microbial catabolic activities (MSIR, enzymes) - and respiration?	–	– –	–	+/-		-		
	-soil microbial biomass	– or +/-	– or +/-	– –	–		+ or +/-		
	Nutrient reallocation								
	-CEC		+/-	–					
	-microbial catabolic activities (MSIR, enzymes)	– or +/-	– –				+		
	Nutrient assimilation (plants)								
	-available nitrogen (NO2, NO3)			+ or +/-	+ or +/-		–		
	-microbial activities (denitrification)	– –					–		
	-functional diversity/genes				– –				
Contaminants retention, transformation and degradation	**Retention**								
	-soil organic carbon (SOC)	– –	–				– or +/-		
	-pH	+/-	+/-	– –	– –				+/-
	-soil texture (clay content)	– –		+/-					+/-

	-total/bioavailable concentrations of metals and organics	+/-	+/-	–	–		–	
	Transformation & Degradation							
	-microbial catabolic activities (respiration, enzymes)	– or +/-	– or +/-		–			
	-soil microbial diversity							
	-biodegradation of organic chemicals					+	++	– –
Physical stability	**Inherent soil stability and evolution**							
	-soil texture	– –	– or +/-					
	-soil microbial biomass	– or +/-	– or +/-	– –	–		+	
	-change in pore networks (compaction, etc.)	– or +/-	– or +/-	–			– or +/-	
	-aggregation	– or +/-	– or +/-				+ / -	
	-soil organic carbon (SOC)	– –	–	– –			– or +/-	
	-effects on macrofauna (earthworms)	– or +/-	+/-	– –			+ / -	
	-salinity (electrical conductivity)	–	+/-	+/-				
	-CEC		+/-					
	-soil erosion rate	–					+ / -	
	-bulk density (plant rooting)	–	+/-				– or +/-	

	-geotechnical properties	+	– or +/-	– or +/-	+	+ / -	
Habitat provision	**Habitat quality**						
	-soil texture	–	– or +/-			– or +/-	– or +/-
	-pH	+/-	+/-	– –	– –	– or +/-	– or +/-
	-soil organic carbon (SOC)	– –	–	– –			– or +/-
	-soil microbial biomass	– or +/-	– or +/-	– –	–	+	– –
	-plant biomass production	–	+/-	– or +/-			
	-ecotoxicological quality (effects on macro-/meso-/microfauna and microbes) - density, abundance, reproduction, etc.	– or +/-	– or +/-	– –	–		– –
	Harbouring biodiversity						
	-microbial diversity (indices, genetic sequencing)	– or +/-	– or +/-	–	–		– –
	-invertebrate diversity (indices, genetic sequencing)	– or +/-					--

[a](Biabani et al., 2023; Lee et al., 2021; Liao et al., 2025; O'Brien et al., 2017, 2018; Pape et al., 2015; Rehman et al., 2023; Ren et al., 2020; Yi et al., 2016; Zhao et al., 2026)
[b](Biabani et al., 2023; Epelde et al., 2008; Gluhar et al., 2021b, a; Guo et al., 2018; Jelusic et al., 2013; Jelusic and Lestan, 2014; Kaurin et al., 2020, 2021; Kaurin and Lestan, 2018; Kwak et al., 2019; Lee et al., 2021; Rehman et al., 2023; Wang et al., 2016, 2018)

[c](Azadpour-Keeley et al., 2004; Huang et al., 2024; Liao et al., 2014; Liu et al., 2019; O'Brien et al., 2017; Polli et al., 2018; Rehman et al., 2023; Romero et al., 2011; Sahl and Munakata-Marr, 2006; Sirguey et al., 2008; Sutton et al., 2014; Usman et al., 2022; Venny and Ng, 2014; Wu and Lu, 2021)

[d](Cang et al., 2007, 2012; Crognale et al., 2020; Hamdi et al., 2025; Kim et al., 2010; Lear et al., 2004, 2007; Lima et al., 2017; O'Brien et al., 2017; Pazos et al., 2012; Rehman et al., 2023)

[e]*No relevant studies found*

[f](Bass et al., 2000; Benner et al., 2002; Clayton et al., 1996; Lee et al., 2002; Lim et al., 2016; Malina et al., 2002; Nguyen et al., 2023)

[g](Bhattacharyya et al., 2010; Meuser, 2013; Padhye et al., 2023; Roy et al., 2023; Tobias et al., 2018)

[h](Caravaca et al., 2017; Dermatas and Meng, 2003; Mao et al., 2023; Paria and Yuet, 2006; Zhao and Wong, 2025; Zhou et al., 2024)

Impacts of low-impact remediation techniques on soil functions

Table S3. Expected impacts of low-impact remediation techniques on the six main soil functions, sub-functions and indicators/descriptors.

Soil functions / **Remediation techniques**		*Low-impact remediation techniques*				
Function	**Sub-functions &** *-indicators/descriptors*	**Bioremediation (in-situ/ex-situ)[a]**	**Phytoremediation (all, in-situ)[b]**	**Monitored natural attenuation (in-situ)[c]**	**Immobilisation with amendments (organic, in-situ)[d]**	**Immobilisation with amendments (inorganic, in-situ)[e]**
Organic matter storage, transformation and recycling	**Decomposition**					
	-soil microbial biomass	+ or +/-	++	+	+	+ or +/-
	-invertebrate feeding activity		+	+	+	
	-organic matter mineralization in soil	+	+	+/-	+	
	Resource reallocation					
	-soil organic carbon (SOC)	+ or +/-	++	+	++	+ or +/-
	Biochemical transformation					
	-soil organic carbon (SOC)		++	+	++	
	-microbial basal respiration (carbon mineralization)	+ or +/-	+	+	+	+/-
	-microbial catabolic activities (MSIR, enzymes)	+ or +/-	+	++	++	
	-functional diversity/genes	–	+		+	+/-
	Water retention					

Water regulation, retention and release	*-soil texture*		+/-	– or +/-		
	-water holding capacity (retention)	+	+	+ or +/-	+	+/-
	-soil organic carbon (SOC)		++		++	
	Infiltration and percolation					
	-infiltration/permeability	+	+		+	+/-
	-bulk density	+	+/-		+	+
	-effects on macrofauna (earthworms)		+	-	+	+/-
Nutrient cycling	**Nutrient transformation**					
	-total nitrogen content	+/-	+/-	+/-	+	
	-Assimilable/extractable phosphorous content	+/-	+/-	+/-	+	+/-
	-pH	+/-	+/-		+/-	+/-
	-microbial catabolic activities (MSIR, enzymes) - and respiration?		+		++	+/-
	-soil microbial biomass		+	+	+	
	Nutrient reallocation					
	-CEC		+/-		+	+

	-microbial catabolic activities (MSIR, enzymes)		+	+	+	
	Nutrient assimilation (plants)					
	-available nitrogen (NO2, NO3)	+/-	+/-	+/-	+ or +/-	
	-microbial activities (denitrification)		+	+/-	+	
	-functional diversity/genes	–	+	+	+	
Contaminants retention, transformation and degradation	**Retention**					
	-soil organic carbon (SOC)		+		+	
	-pH	– or +/-	+/-		+	+
	-soil texture (clay content)			+ / -		
	-total/bioavailable concentrations of metals and organics	+/-	+	– or +/-	+/-	++
	Transformation & Degradation					
	-microbial catabolic activities (respiration, enzymes)	+ +	+	++	+	
	-soil microbial diversity		+	++	+	
	-biodegradation of organic chemicals	++	+	++	+	+/-
Physical stability	**Inherent soil stability and evolution**					

	-soil texture			+/-		+
	-soil microbial biomass		+	+	+	
	-change in pore networks (compaction, etc.)	+	+	+/-	+	+
	-aggregation	+	+	+/-	+	+
	-soil organic carbon (SOC)	+ or +/-	+	+/-	++	
	-effects on macrofauna (earthworms)		+	+/-	+	
	-salinity (electrical conductivity)			+/-	+	+/-
	-CEC			+/-	+	+
	-soil erosion rate?		+	+/-		
	-bulk density (plant rooting)		+	+/-	+	+
	-geotechnical properties	+ or +/-	– or +/-	+/-	+/-	+
Habitat provision	**Habitat quality**					
	-soil texture		+/-	+/-		
	-pH	+/-	+/-	+/-	+/-	+/-
	-soil organic carbon (SOC)	+ or +/-	+		++	
	-soil microbial biomass	+ or +/-	+	+	++	
	-plant biomass production				++	+/-

	-ecotoxicological quality (effects on macro-/meso-/microfauna and microbes) - density, abundance, reproduction, etc.	+/-	+		+	+/-
	Harbouring biodiversity					
	-microbial diversity (indices, genetic sequencing)	+ or +/-	+	+	+	+/-
	-invertebrate diversity (indices, genetic sequencing)		+		+	

[a](Cui et al., 2020; Lacalle et al., 2020; Militon et al., 2010; O'Brien et al., 2017; Polyak et al., 2018; Salimnezhad et al., 2021; Shen et al., 2016; Wolf et al., 2019)

[b](Adl, 2008; Anza et al., 2019; Burges et al., 2016, 2017, 2021; Ciadamidaro et al., 2014; Epelde et al., 2008, 2009; Fiorentino et al., 2018; Garaiyurrebaso et al., 2017; Gómez-Sagasti et al., 2012; Ju et al., 2019; Kumpiene et al., 2009; Lacalle et al., 2018; Macci et al., 2013, 2016; Marchand et al., 2016; Mench et al., 2023; Míguez et al., 2020; O'Brien et al., 2017; Quintela-Sabarís et al., 2017; Rehman et al., 2023; Touceda-González et al., 2017a, b)

[c](Balland-Bolou-Bi et al., 2023; Chapelle et al., 2007; Declercq et al., 2012; Meuser, 2013; Smith et al., 2022; Song et al., 2023; Wozney et al., 2022)

[d](Abou Jaoude et al., 2020; Bai et al., 2018; Bera et al., 2016; Bielská et al., 2018; Brtnicky et al., 2021; Drenning et al., 2024; Epelde et al., 2014; Galende et al., 2014; Garaiyurrebaso et al., 2017; Godlewska et al., 2021; Gómez-Sagasti et al., 2018; Kidd et al., 2015; Kumpiene et al., 2009, 2019; Lacalle et al., 2018; Lwin et al., 2018; Marchand et al., 2016; Míguez et al., 2020; Rehman et al., 2023; Rijk et al., 2024; Schröder et al., 2018; Touceda-González et al., 2017)

[e](Baragaño et al., 2020, 2021; Bert et al., 2012; Cui et al., 2017, 2023; Kumpiene et al., 2019; Lacalle et al., 2018b, a; Lebrun et al., 2019; Liu et al., 2021, 2022; Lwin et al., 2018; Nandillon et al., 2019; Rehman et al., 2023)

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