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Subject review

Review of Life Cycle Assessment Studies of Sediment Stabilisation/Solidification Treatment

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Abstract: The aim of this paper is to review life cycle assessment studies on the stabilisation/solidification treatment of freshwater or marine sediments. First, the life cycle assessment studies on stabilisation/solidification treatment of sediments were reviewed on the Web of Science platform and eleven studies were selected. Secondly, the standardised phases of life cycle assessment were used as review criteria: Goal and Scope, Inventory Analysis, Life Cycle Impact Assessment, and Interpretation. The results of the review systematically showed information about the life cycle assessment phases and provided the similarities and differences. All studies reviewed had system boundaries from cradle to gate, but six studies did not include sediment dredging in the upstream life cycle stages. Ten of eleven studies used life cycle inventory databases to model background processes, and six studies reported the names of the datasets used. For the life cycle impact assessment methods, all studies used the CML, ReCiPe, and IMPACT 2002+ methods. In the interpretation phase, all studies included hotspot, contribution and scenario analyses, while sensitivity and uncertainty analyses were used in six out of eleven studies. The results of the review provide information that can be a good starting point for new research in this area.

Keywords: life cycle assessment; sediment; solidification; stabilisation

1 INTRODUCTION

In addition to binding regulations, environmental management instruments contribute to the protection of all environmental areas [1]. The growing awareness of the environmental impact of production has led to the development of methods for assessing this impact. One important tool is the life cycle assessment (LCA), also known as life cycle analysis. LCA assesses the environmental impact of products throughout their life cycle, from raw material extraction to end-of-life treatment [2-4]. It assesses energy and material consumption as well as the impact on human health and ecosystems. Unlike other analyses such as environmental impact assessments or risk assessments, LCA considers impacts at all stages of a product's life cycle [4] and is widely used in various sectors. It plays an important role in identifying opportunities to reduce the environmental impact of products throughout their life cycle. In industry, LCA supports decision-making at both strategic and operational levels and helps to prioritize actions in planning, design and production [5-7]. It also helps to identify key indicators for the efficiency of environmental protection. LCA is crucial for environmental labelling programs, product declarations and sustainability claims. In addition, LCA helps to integrate environmental aspects into the design process when developing new products or redesigning existing ones in accordance with the ISO/TR 14062 standard [8].

Contaminated sediments contain hazardous substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), pesticides and other pollutants that can accumulate over time and damage aquatic ecosystems and human health [9, 10]. The extent of sediment pollution is considerable: more than half of European dredged material is contaminated [11]. Depending on the type of pollution, the sediment and the environmental conditions, different remediation techniques are used [12]. These techniques are divided into ex-situ and in-situ methods. In-situ methods treat contaminated sediments on site without removing them. In-situ methods are less invasive, cost effective and suitable for ongoing monitoring, but are often slower and less effective for heavy contamination. These include: Capping, bioremediation, phytoremediation, electrokinetic remediation, chemical oxidation/reduction, etc. Ex-situ treatment methods treat contaminated sediments after off-site removal (after dredging). They offer more control and better treatment of highly contaminated sediments, but are associated with higher costs and disruption. Ex-situ methods include: Dredging and disposal, sediment washing, thermal desorption, stabilisation/solidification (S/S), bioremediation, chemical oxidation/reduction, dewatering and disposal, etc. [11].

One of the most promising remediation methods is S/S, which can be used to convert contaminated sediments into valuable building materials. Instead of treating the dredged sediments as waste, this approach reuses them, in particular by utilizing their mineral content in construction materials. This reduces landfill waste and the need for new raw materials, contributing to a more sustainable cycle [11, 13]. S/S immobilizes pollutants with chemical reagents such as cementitious or pozzolanic materials that bind pollutants through adsorption, precipitation and encapsulation [14]. This technique is effective against heavy metals [15] and some organic pollutants [16], reduces leachability and prevents the release of pollutants into the environment [17, 18]. Ongoing research aims to refine binder formulations, incorporate sustainable materials and improve durability. Advances in predictive modelling and LCA are improving the accuracy of S/S processes and helping to align them with broader sustainability goals [19, 20].

Although most research on the application of LCA has been conducted for S/S treatments, the application of LCA to other methods of sediment treatment has also been investigated. Some studies [21-27] have shown that certain remediation strategies, alone or in combination, have a significantly lower environmental impact compared to the conventional method - landfilling. Soleimani et al. [28] combined an economic analysis, an LCA and laboratory experiments to evaluate phytoremediation with *Arundo donax* for the treatment of chloride-rich dredged sediments and to investigate the utilization of biomass. The LCA showed that phytoremediation with or without biomass utilization had lower costs and environmental impacts than landfilling. Choi et al. [29] compared the environmental impacts of three methods for remediation of sediments contaminated with hydrophobic pollutants using LCA and found that capping with a geomembrane layer had lower impacts than dredging and filling, with recycled or wood-based activated carbon further reducing environmental impacts compared to charcoal-based activated carbon. Todaro et al. [30] used LCA and multi-criteria decision analysis to evaluate reactive capping solutions for the remediation of contaminated sediments. The results showed that the covers consistently met environmental standards, with activated carbon and zero-valent iron providing the most effective chemical isolation and degradation, although zero-valent iron had the highest environmental impact. Dong et al. [31] combined a field revegetation experiment with a LCA to evaluate the use of dredged sediments as a soil additive for post-mining reclamation. They concluded that this not only promotes plant growth and stabilizes heavy metals, but also offers significant environmental and economic advantages over alternative disposal methods, with lower environmental impacts and lower costs compared to the production of cement or unfired bricks. Microwave heating has been evaluated for the remediation of hydrocarbon contaminated sediments [32]. The LCA confirmed that microwave heating is a better environmental option, with 75,74% less environmental impact than electrokinetic treatment. In the study by Hernández et al. [33], an LCA was carried out to evaluate the environmental impact of using port sediments as a culture medium for lemon trees. Ninety lemon trees were grown in three different substrates containing 25%, 50% and 75% port sediment. The results showed that with increasing the amount of port sediment (75%) the environmental impact increased due to lower fruit production. The mixture of 50% peat and 50% port sediment had the least impact. Most of the environmental impacts were related to management rather than sediment content. In the LCA study by Legua et al. [34], the environmental impact of using dredged port sediments as a growing medium for food crops was assessed. The sediments had previously been phytoremediated. Strawberry plants were grown on three substrates: 100% peat, 100% dredged sediment and a 50% peat/sediment mixture to assess the impact on plant growth. Eighteen impact categories were considered, with marine eutrophication, human toxicity and freshwater ecotoxicity being the most important. The results showed that the use of 100% sediment increases the environmental impact compared to 100% peat, mainly due to lower fruit production. However, mixing sediment with peat (less than 50%) reduced both environmental impact and fruit yield. Co-composting is an effective method for recycling dredged sediments and green waste, which are often limited by contamination and different compositions. In order to optimize the process, the green waste content was varied in the study by Macci et al. [35]. A LCA was carried out to evaluate the environmental impact and the potential as a peat substitute. Overall, increasing the proportion of green waste in co-compost piles improves sustainability and compliance with fertilizer regulations. Nicese et al. [36] tested jointly composted dredged sediments and green waste in different ratios (1:3, 1:1 and 3:1) as sustainable alternatives to peat for growing two ornamental shrubs. The results showed no significant difference in plant growth, except for the belowground biomass of *V. tinus*. The LCA revealed that replacing peat with these co-composted mixtures reduced greenhouse gas emissions by 11,56% to 23,13%. The cultivation phase caused the most emissions (0,9 kg CO_2-eq./plant). Overall, the alternative substrates led to a reduction in greenhouse gas emissions of 28,1% to 59,6% compared to peat-based substrates.

Growing environmental awareness has led to a push for sustainable sediment management based on circular economy principles [37], focusing on the reuse of dredged sediments in construction materials to reduce waste and raw material consumption [11, 13]. To fully integrate circular economy principles, LCA is crucial to improve the reliability of processes such as S/S, where contaminated sediments are processed into construction materials.

The previous research on LCA of sediment management analysed case studies or evaluated LCA studies, but none of these studies addressed the LCA of S/S treatment of sediments according to the LCA phases with the analysis of specific criteria in each LCA phase. The aim of this review is to provide systematic information on the LCA of sediment treatment, analysing the LCA information according to the LCA phases: Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. The importance of this review lies in the information provided on each LCA phase, which can be used for future studies on the LCA of S/S treatment of sediments.

2 METHODOLOGY

The methodology for the review of LCA studies on sediment S/S treatment is shown in Fig. 1 and consists of three steps. In the first step, the studies, i.e. scientific research articles published in international journals, were searched on the Web of Science platform if they contained the following keywords in the title, abstract or key words: 'life', 'cycle', 'assessment' and 'sediment'. The search included the following document types: Article, Review Article, Early Access (excluding preceding paper, editorial material and data paper). In a second step, the LCA studies on sediment S/S treatment processes were manually selected for review by reading the title, abstract, keywords and full article if the information was of interest.

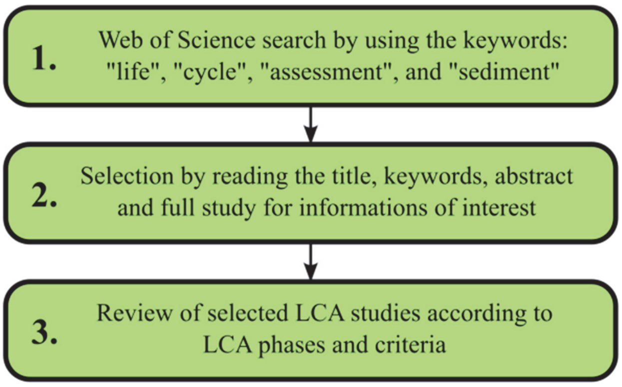

Figure 1 Methodology for the review of LCA studies on sediment stabilisation/solidification treatment

Finally, in the third step, standardised LCA phases according to ISO 14040 and ISO 14044 [2, 3] were used as a starting point for the analysis of previous research on S/S sediment management treatment processes: Goal and Scope, LCI, LCIA and Interpretation. Within the LCA phases, the following criteria were considered to review previous research:

- Goal and Scope: type of S/S treatment output, goal, functional unit, type of sediment, system boundaries and included life cycle stages, assumptions and constraints, cut-off rules, allocation rules, geographic coverage, temporal coverage (when the LCA data is collected), and system modelling;
- LCI and LCI tools: Database, tool (software), specified datasets, percentage of sediment in product;
- LCIA methods and impact categories: Reason for selection of LCIA method or impact categories, mean impact categories, normalisation, endpoint impact categories;
- Interpretation: hotspot and contribution analysis, scenarios, sensitivity and uncertainty analysis.

3 RESULTS

The first review step, the search in the Web of Science platform, was conducted in December 2024 and 556 results were obtained. The second review step, the selection of studies containing information of interest, yielded 11 results published between 2018 and 2024. The results that were excluded in the second review step did not contain information on LCA phases according to ISO 14040; freshwater (river or lake) or marine dredged sediment, such as construction and engineering wastes (e.g., study by Zhou et al. [38]), wastewater treatment waste sediment; and S/S sediment treatment, such as in situ capping of sediments (e.g., studies by Choi et al. [29], Sparrevik et al. [39], Todaro et al. [30]) and other treatment options.

- The results of the third review step are presented in the following figures and tables:
- Tabs. 1 and 2 and Figs. 2 and 3 provide an overview of the aim and scope,
- Tab. 3 provides an overview of the LCI and the LCI tools,
- Tab. 4 provides an overview of the LCIA methods and impact categories,
- Tab. 5 contains an overview of the interpretation elements.

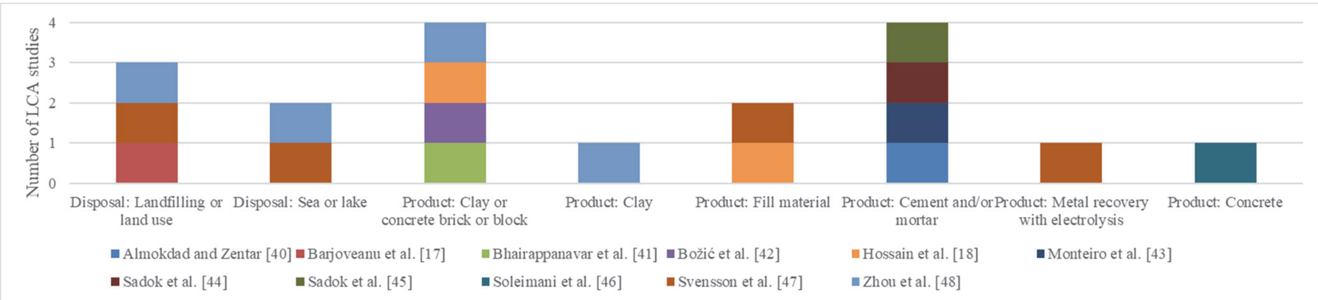

Figure 2 Type of sediment S/S treatment output

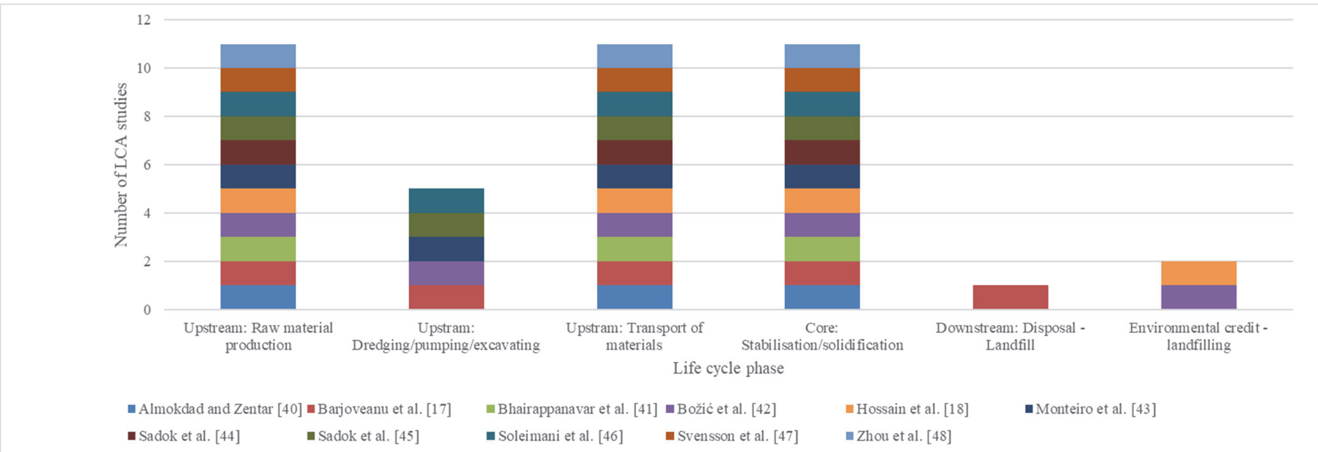

Figure 3 Review of the life cycle phases included in the system boundaries

Table 1 Review of goal and scope based on goal, functional unit, system boundaries, type of extracted sediment, assumptions and limitations

Goal	Functional unit	System boundaries	Type of extracted sediment	Assumptions and limitations	Reference
To comprehensively evaluate the environmental implications of incorporating sediments in cement and mortar application, with and without flash calcination, and at different substitution rates for ordinary Portland cement.	The primary functional unit was the production of 1 ton of CEM I 52.5 equivalent cement packed in 20 bags. The secondary functional unit was 1 square meter of mortar bed with 30 mm thickness and using CEM I 52.5 equivalent cement.	Cradle to gate (for primary functional unit) and cradle to use (for secondary functional unit)	Polluted marine sediment	ND[3)]	Almokdad and Zentar [40]
To investigate the environmental impacts associated to the current situation in Mar Piccolo (primary impacts), the impacts	One square meter of sea bed in Mar Piccolo from	Cradle to gate	Contaminated marine sediment	ND[3)]	Barjoveanu et al. [17]

Goal	Functional unit	System boundaries	Type of extracted sediment	Assumptions and limitations	Reference
associated to the S/S options (secondary impacts), and the potential impacts that appear during the post-treatment phases (tertiary impacts).	which the top layer of 50 cm was considered				
To understand the embodied energy (EE) and embodied carbon (EC) emission associated with the production of DM-CB as compared to the conventional bricks. 1)	ND	Cradle to gate	Potentially contaminated river sediment	Assumptions are declared	Bhairappanavar et al. [41]
To analyse the environmental impacts associated with the industrial production of bricks made from two different brick-making mixtures, i.e. original or traditional brick-making mixture and mixture of river sediment and traditional brick-making material.	ND	Cradle to gate	The sediment from the Drava River contaminated with heavy metals 2)	ND 3)	Božić et al. [42]
To comparatively evaluate the environmental performance of S/S technologies for managing two types of hazardous wastes such as contaminated dredged sediment and municipal solid waste incineration fly ash using LCA technique according to ISO guidelines.	1 tonne of products	Cradle to gate	Contaminated marine sediment	Assumptions and limitations are declared	Hossain et al. [18]
Evaluation of geopolymer mortars based on dredged sediments. 1)	1 m^3 of mortar having a compressive strength of at least 4 MPa at 28 days.	Cradle to gate	Untreated Garonne River sediment (quantity of pollutant below the thresholds)	Limitation declared and transport assumptions	Monteiro et al. [43]
To set up a system to low energy consumption for the treatment of calcined dredged sediments, taking into consideration the environmental impacts throughout the life cycle of this process, and to reduce the emissions of the outflows to the atmosphere (releases in to water, air and soil)	Treatment of one (1) ton of calcined dredged sediment that will be used in the partial substitution of cement (for fineness greater than 3000 cm^2/g)	Cradle to gate	Calcined sediments from the Chorfa dam (Mascara, Algeria)	ND 3)	Sadok et al. [44]
To quantify environmental impacts for cementitious materials production. 1)	Production of one (1) ton of CEM I 42.5 cement with a partial substitution of calcined sediments in the Zahana cement plant.	Cradle to gate	Calcined sediments from the Chorfa II dam (Mascara, Algeria)	Limitation are declared 3)	Sadok et al. [45]
Comparative attributional LCA - to find a viable and sustainable solution for the valorization of the dredged sediment in concrete (sand substitution by sediment in concrete). 1)	One cubic meter (1m^3) of concrete at the gate of the concrete plant	Cradle to gate	Non-hazardous marine sediment without the need for treatment	ND 3)	Soleimani et al. [46]
To evaluate differences in GHG emissions between the investigated treatment approaches for contaminated dredged sediment (comparative LCA).	100 m^3 dredged sediment	Cradle to gate	Polluted marine sediment	Assumptions are declared	Svensson et al. [47]
LCA of four typical dredged-sludge treatment technologies 1)	One tone (1 t) dry dredged-sludge	Cradle to gate	Polluted sediment from Baiyangdian Lake	ND 3)	Zhou et al. [48]

ND - not declared
1) Goal and scope of the LCA is not explicitly declared but as goal of the research.
2) Concentrations are in the range that allows for a direct use of the sediment for the production of building materials without the need for pre-treatment of sediment.
3) Assumptions and limitations are not explicitly declared, but some information can be found in the study.

Table 2 Review of goal and scope based on cut-off rules, allocation rules, geographic location, temporal coverage and system modelling

Cut-off rules	Allocation rules	Geographical coverage (case study location)	Temporal coverage	System modelling	Reference
ND	ND	Dunkirk port (England)	ND	Attributional	Almokdad and Zentar [40]
ND	ND	Mar Piccolo in Taranto (Southern Italy)	ND	ND	Barjoveanu et al. [17]
ND	ND	Cuyahoga River, Lake Erie, Cleveland, the state of Ohio	ND	ND	Bhairappanavar et al. [41]
ND	ND	Western Slovenia	ND	Consequential	Božić et al. [42]
ND	Economic allocation for upstream impacts of the commonly used industrial by-products as supplementary cementitious materials, such as ground-granulated blast-furnace slag, pulverized fuel ash and silica fume	Hong Kong	ND	ND	Hossain et al. [18]
ND	ND	Garonne River	ND	ND	Monteiro et al. [43]

ND	ND	Chorfa dam (Algeria)	ND	ND	Sadok et al. [44]
ND	ND	Chorfa II dam in Mascara (Algeria)	ND	ND	Sadok et al. [45]
ND	No allocation (allocation at the point of substitution LCI datasets used)	Port of Camargue (PC) and Perols (PP), South of France, region of Occitanie	ND	Attributional	Soleimani et al. [46]
ND	ND (allocation at the point of substitution LCI datasets were used)	Port of Gothenburg (lowpoll), Port of Oskarshamn (highpoll). (Sweden)	ND	ND	Svensson et al. [47]
ND	ND	Anxin County, Baoding City, Hebei Province (China)	ND	Attributional	Zhou et al. [48]
ND - not declared					

Table 3 Review of LCI and LCI tools

LCI Database or source of LCI data	LCI tool (software)	LCI provided with datasets	Percentage of sediment in product	Reference
Ecoinvent v. 3.7.1, cut-off by classification	SimaPro v. 9.2.0.2	Available in appendix with specific LCI datasets declared	0, 5, 10, 15, 20, 30% volume in cement and 0, 10, 20, 30% volume in mortar.	Almokdad and Zentar [40]
Ecoinvent v. 3.3	ND	Available in appendix with specific LCI datasets declared	15 and 20 % of mass (weight) of dry sediment in cement and clay.	Barjoveanu et al. [17]
Literature sources.	Without LCA software	ND	92%, 90% and 88%, weight	Bhairappanavar et al. [41]
Ecoinvent v. 3.8	GaBi Professional	Available in appendix without the LCI datasets declared	20 % dry sediment mass	Božić et al. [42]
Literature sources, Chinese Life Cycle Database (CLCD), European Reference Life Cycle Database (ELCD), and Ecoinvent	SimaPro v. 9.1.5	Available with specific LCI datasets declared	Fill material: 47,5%, 47,5%, 90%; Partition blocks: 16%, 16%, 58%, 85%; Paving Docks: 14%, 14%, 15%, 15%; Mass percentage	Hossain et al. [18]
Ecoinvent v. 3.2, Cut-off	SimaPro	Available in study with specific LCI datasets declared	50%	Monteiro et al. [43]
GEMIS v. 4.95	GEMIS v. 4.95	Available in study without specific LCI datasets declared	ND (partial substitution of cement)	Sadok et al. [44]
Ecoinvent	SimaPro v. 8.5.2.0	Available in study without specific LCI datasets declared	Cement substitution (mass): 0%, 5%, 15% and 25 %; Mortar substitution: 0%, 5, 15 and 25%.	Sadok et al. [45]
Ecoinvent v. 3.5	openLCA v. 1.11.0	ND	10-50% volume sand substitution	Soleimani et al. [46]
Ecoinvent, v. 3.6, allocation at the point of substitution applied	SimaPro v. 9.1.0	Available in appendix with specific LCI datasets declared	100 % treatment and remediation	Svensson et al. [47]
Ecoinvent v. 3.5	SimaPro v. 9.0	Available in study and specific LCI datasets declared in appendix	100 %	Zhou et al. [48]
ND - not declared				

Table 4 Review of LCIA methods and impact categories

The reason for selecting the LCIA method or impact category	LCIA method	No. of Midp. Cat.	Midpoint impact categories	Normalisation	Endpoint	Reference
CML-IA is widely used globally. ReCiPe 2016 – for contribution of each impact category with respect to the total impacts. EN 15804 +A2 LCIA method was also used for comparison with the French CEM I EPD.	CML-IA and ReCiPe endpoint (H/A) 2016; EN 15804 +A2 LCIA; French CEM I EPD	11 + 8	CML-IA: ADPEL., ADPFOS, AP, EP, FTOXP, GWP, HTP, MTOXP, ODP; POP, TEP. EN 15804 +A2: GWP, IR, POP, AP, PMF, MEP, TEP, ADPFOS.	ReCiPe endpoint (H/A)	ReCiPe: HH, ES, RE	Almokdad and Zentar [40]
The ReCiPe 2008 method covers a multitude of environmental aspects and it has a good inventory data coverage as it provides characterization factors (which are particularized for the sea compartment) for more pollutant species than the other considered methods.	ReCiPe 2008, midpoint	18	GWP, ODP, TA, FEP, MEP, HTP, POP, PMF, TTOXP, FTOXP, MTOXP, IR, ALO, ULO, NLT, WD, MD, ADPFOS.	ReCiPe 2008 midpoint (European set) applied on 18 midpoint impact categories results	ND	Barjoveanu et al. [17]
The analysis uses three categories of indicators. The first	IMPACT 2002 +	2	ADPEL, GWP	ND	ND	Bhairappanavar et al. [41]

The reason for selecting the LCIA method or impact category	LCIA method	No. of Midp. Cat.	Midpoint impact categories	Normalisation	Endpoint	Reference
category specifies the impact of emissions on the atmosphere or the water or the land. The second category indicates a specific impact such as Ozone depletion, respiratory effect, and human toxicity. The third category focuses on damage assessment or broader outcome.						
CML 2001 being one of the most commonly used impact assessment methods when evaluating life cycle of bricks	CML 2001 v. Aug. 2016	10	ADPEL, ADPFOS, AP, FEP, GWP, HTP, MTOXP, ODP, POP, TTOXP	ND	ND	Božić et al. [42]
ND	IMPACT 2002 +	3	AP, GWP, ADPFOS	ND	ND	Hossain et al. [18]
Indicators compatible with EN 15804 +A1 standard.	CML-IA baseline method	7	AP, ODP, FEP, POP, GWP, ADPFOS, ADPEL	ND	ND	Monteiro et al. [43]
ND	ND	4	GWP, AP, The tropospheric ozone precursor potential (TOPP eq), and the cumulative energy and exergy demand (MJ)	ND	ND	Sadok et al. [44]
ND	IMPACT 2002+ v. 2.14	15	human toxicity (carcinogenic) (kg C_2H_3Cl eq), human toxicity (non-carcinogenic) (kg C_2H_3Cl eq), respiratory inorganic (kg PM2.5 eq), IR, ODP, respiratory organic (kg C_2H_4 eq), FTOXP, TTOXP, acidification/eutrophication terrestrial (kg SO_2 eq), land use (m^2org.arable), AP, FEP, GWP, ADPEL, and mineral extraction (MJ surplus).	IMPACT 2002+ version 2.14	CC, ES, HH, RE	Sadok et al. [45]
State-of-the-art and harmonized life cycle impact assessment method at the midpoint and endpoint level.	ReCiPe 2016 midpoint (H)	18[1)]	GWP, ODP, TA, FEP, MEP, HTP, POP, PMF, TTOXP, FTOXP, MTOXP, IR, ALO, ULO, NLT, WD, MD, ADPFOS.[1)]	Impacts of the control concrete were applied for the normalization to convert the impact indicator values with varied units into a unitless score by dividing the impact values to the corresponding of control concrete.	SS after normalisation of midpoint results	Soleimani et al. [46]
ND	CML + Additional environmental impacts	1	GWP	ND	Additional environmental impacts (short and long-term environmental impacts on marine organisms, land use, air quality (GHG emissions excluded), terrestrial biota/health, and other potential risks) [2)]	Svensson et al. [47]
CML-IA baseline 3.06 was selected as one of the most common LCIA midpoint methods.	CML-IA baseline v. 3.06	9	ADPEL, AP, FEP, FTOXP, GWP, HTP, ODP, POP, TTOXP	The environmental burden index method: selecting one substance as the standard in each environmental	ND	Zhou et al. [48]

The reason for selecting the LCIA method or impact category	LCIA method	No. of Midp. Cat.	Midpoint impact categories	Normalisation	Endpoint	Reference
				category and normalizing the equivalent value of the standard substance to 1.		

ND - not declared; 1) Results for all 18 ReCiPe impact categories are available in appendix of [46], while results for 8 impact categories are selected for graphical interpretation in paper; 2) Although additional environmental impacts are not declared as endpoint impact categories they have the properties of endpoint impact categories because they are without units and their results can be summed up; Midpoint impact categories: ADPEL - Abiotic Depletion Potential for non-fossil resources (kg Sb eq.), ADPFOS - Abiotic Depletion Potential for Fossil Resources or resource use fossils or fossil depletion or non-renewable energy consumption (MJ or kg oil-eq.), ALO - Agricultural Land Occupation (m^2a), AP - Acidification (terrestrial) Potential (kg SO_2 eq. or mol H+ eq.), CE - Carcinogen Emissions (kg B(a)P-eq.), FEP - Freshwater Eutrophication Potential or Eutrophication Potential (kg PO_4^{3-} eq. or kg P eq.), FTOXP - Freshwater ecoTOXicity Potential (kg 1,4-DB eq. or kg Triethylene glycol into water), GWP - Global Warming Potential or climate change of greenhouse gas emissions (kg CO_2 eq.), HTP - Human Toxicity Potential (kg dichlorobenzene, kg 1,4-DB eq. or kg DCB eq.), HME – Heavy Metal Emissions (kg Pb-eq.), IR - Ionising radiation (kBq U235 eq. or kg U235-Eq or Bq C-14 eq.), MEP - Marine Eutrophication Potential (kg N eq.), MTOXP - Marine ecoTOXicity Potential (kg 1,4-DB eq. of kg. DCB eq.), MD - Metal depletion (kg Fe eq.), NLT - Natural land transformation (m^2 or m^2yr), ODP - Ozone Depletion Potential (kg CFC-11 eq. or kg R11 eq.), PMF - Particulate Matter Formation (kg PM10 eq.), POP - Photochemical Oxidation Potential or photochemical ozone creation potential or smog (kg NMVOC or kg C_2H_4 eq. or kg Ethylene eq.), TA - Terrestrial Acidification (kg SO_2 eq.), TEP - Terrestrial Eutrophication Potential (mol N eq.), TTOXP - Terrestrial Ecotoxicity Potential (kg 1,4-DB eq. or kg DCB eq. or kg Triethylene glycol into soil), ULO - Urban land occupation (m^2a), WD - Water depletion (m^3); Endpoint impact categories: CC - Climate Change (Points), ES – EcoSystem (Points), HH - Human Health (Points), RE - Resources (Points), SS – Single score or total environmental impact (normalisation, grouping and weighting on midpoint impact category results are applied), SS = ES + HH + RE (Points).

Table 5 Review of interpretation

Hotspot analysis	Contribution analysis	Number of scenarios	Scenarios	Sensitivity and uncertainty analysis	Reference
Yes	Yes	10	Four scenarios of cement with dried ground sediments substitution, five scenarios of flash calcined sediments substitution, and one scenario representing ordinary Portland cement.	Sensitivity analysis of sediment transport distance (road + water transport). Uncertainty analysis is ND.	Almokdad and Zentar [40]
Yes	Yes	8	8 mixes.	Monte Carlo simulations (10000 runs)	Barjoveanu et al. [17]
Yes	Yes	5	Five brick alternatives.	ND	Bhairappanavar et al. [41]
Yes	Yes	2	Traditional brick-making material and river sediment	ND	Božić et al. [42]
Yes	Yes	11	Eleven scenarios with different content of sediment or ash in product.	ND	Hossain et al. [18]
Yes	Yes	4	Four scenarios: Ordinary Portland Cement, Geopolymer-based sediment mortar, mortar mixture with 10% metakaolin and mortar mixture with 10% ground granulated blast furnace.	Two sensitivity factors: transport distances for cement and activators and adding a benefit for the recovery of sediment - three scenarios and 1000 Monte Carlo simulations	Monteiro et al. [43]
Yes	Yes	2	Two industrial scenarios.	Sensitivity analysis: variation of dredged sediments moisture content ranging from 0% to 90%. Uncertainty analysis is ND.	Sadok et al. [44]
Yes	Yes (Sankey Flow Charts for GWP)	4	Four types of cement, with partial substitution by calcined sediments.	ND	Sadok et al. [45]
Yes	Yes	9	Nine scenarios of concrete products with different sediment percentage as substitution of sand.	Monte Carlo simulations were run (1000 runs) for uncertainty analysis and parametric life cycle inventories for sensitivity analysis.	Soleimani et al. [46]
Yes	Yes	9	Nine management scenarios.	ND	Svensson et al. [47]
Yes	Yes (Sankey chart for Freshwater aquatic ecotoxicity and human toxicity)	4	Four scenarios: land use, composting and land use, brick, clay.	Monte Carlo analysis (10000 runs).	Zhou et al. [48]

ND - not declared

4 DISCUSSION

Fig. 3 shows that the S/S treatment had two types of outputs: products with sediment and safely disposed sediment. Safely disposed sediment refers to S/S techniques for treating sediments as waste material with no economic value with the aim of environmentally sound disposal. On the other hand, products containing sediment were economically valuable products (building materials such as bricks, concrete, mortar, filling material). In the majority of studies, products with sediments (8 out of 11 studies) were reported as a result of S/S treatment.

It should be noted that the research objective in the reviewed studies was not always limited to LCA, but also included laboratory tests of the physical and chemical properties of sediments and their products [17, 41, 42], as well as other analyses and investigations that were not included in the LCA system boundaries. All studies stated the aim of scientific research (Tab. 1), but some [41, 43,45, 46, 48] did not explicitly state the goal of LCA. The lack of an explicitly stated LCA goal in some of the studies reviewed suggests that the authors assumed that readers would identify the research objective with the LCA goal.

All but one of the studies reported a functional unit (Tab. 1). On the other hand, none of the studies used a declared unit, which can be applied to construction products and is recommended when the use phase of the analysed product is unknown and outside the system boundaries [49]. The "functional unit" is a term defined in the international standard ISO 14040 published in 1997, while the term "declared unit" is more recent (ILCD Handbook in 2010 [4], first version of EN 15804 in 2012 [50]. The main drawback of the LCA by Božić et al [42] is that it does not include information on the functional or declared unit, which makes it difficult for the reader to grasp the magnitude of the sediment treated. In addition, although Božić et al. [42] stated the consistent system modelling in goal and scope, they used the Ecoinvent LCI database with cut-off modelling.

In all studies, the system boundaries are "cradle to gate", and most used flow diagrams to represent the system boundaries. Almokdad and Zentar [40] used the EN 15804 +A2 definition of system boundaries, which provides a more detailed subdivision of life cycle stages into modules. Fig. 3 provides a more detailed overview of the system boundaries and the life cycle phases taken into account. For the system boundaries, all studies have considered the upstream phases of raw material production and transportation of materials and S/S as a core process. On the other hand, not all studies included the dredging/pumping/excavation of sediments in the upstream processes. None of the studies examined the use phase. Only three studies considered landfilling, with Barjovenau et al [17] looking at sediment landfilling, while Božić et al. [42] and Hossain et al. [18] looked at the avoided environmental impact of sediment landfilling.

In the majority of studies, the extracted sediments were contaminated with various pollutants such as heavy metals, polychlorinated biphenyls, organic substances from lubricants, polycyclic aromatic hydrocarbons and others. The studies by Soleimani et al. [46] and Monteiro et al. [43] were the only studies in which the sediment was without the treatment of contaminants. Assumptions and limitations are very rarely explicitly stated. In most studies, the assumptions are scattered in the process description or in the goal and scope.

In none of the studies examined were cut-off rules or the temporal coverage (when the LCA data is collected) specified (Tab. 2). Allocation rules were only mentioned in 3 of the 11 studies examined. All studies provided geographic coverage in the form of the location of the case study, while further information can be found in the geography of the LCI datasets used. Attribution and consequential modelling of systems is also only mentioned in a minority of the studies (4 out of 11). From other information in the reviewed studies, it can be concluded that attributional modelling is used in the majority, while the consequential approach is only stated in the study by Božić et al. [42].

Nine of the eleven studies examined used the Ecoinvent database for background process modelling (Tab. 3). Considering that Ecoinvent is the most comprehensive LCI database providing data for different industrial processes and that several LCI databases have been developed and rely on Ecoinvent data (e.g. Circularity Package, Environmental footprint, PLEX, UVEK, EuGeos' 15804+A2_IA, LC-inventories, SOCA [49]), this is the logical choice for the majority of LCA practitioners. The LCA tool SimaPro is used in 6 of the 11 studies considered, the software openLCA, GaBi and GEMIS were used in 3 studies. In the studies by Barjoveanu et al. [17] and Bhairappanavar et al. [41], however, the LCA tool used was not specified. All but two studies presented an LCI, while 6 of 11 studies presented specific LCI datasets. The detailed inventory and datasets used are important for readers who wish to replicate the LCA study and use the inventory for their own research. The percentage of sediment mass in the product varied from 5% for cement and mortar products [45] to 90% for fill materials [18], while the options for remediation and treatment of sediments considered 100% of the total sediment [47,48].

The reason for selecting the LCIA method or effect category (Tab. 4) in most cases was the use of widely used LCIA methods, the selection of indicators which can be compared with previous study results, or the need for endpoint-effect category results. 5 studies used the CML LCIA method [40, 42, 43, 47, 48], 3 studies [17, 40, 46] used ReCiPe, and 3 studies used the IMPACT 2002+ LCIA method [18, 41, 44]. This confirms the already known fact that ReCiPe and CML are generally recognised as the most commonly used LCIA methods. CML and ReCiPe have similar impact categories with slight differences in the units of the impact categories depending on the version of the LCIA method. For example, acidification potential (AP) can be expressed in kg SO_2 eq. or mol H+ eq. and freshwater eutrophication potential (FEP) in kg PO_4^{3-} eq. or kg P eq. In addition to using known optional LCIA elements such as CML normalisation and ReCiPe endpoint impact categories, some studies used specific methods for normalisation [46, 48].

All reviewed studies included hotspot and contribution analyses in the LCA interpretation phase (Tab. 5). All reviewed studies included a scenario analysis where the differences between the environmental impacts of a conventional product and a product with different sediment content or end-of-life options were investigated. Considering that material and sediment transportation can have significant environmental impacts, two studies [40, 43] investigated different transportation options in a sensitivity analysis. Monte Carlo simulation was used in four of the eleven studies examined for uncertainty analysis with 1000 [43, 46] or 10000 [17, 48] runs. In general, a larger number of runs in the Monte Carlo simulation provides more reliable uncertainty results.

5 CONCLUSIONS

It is well known that the results of different LCA studies are very difficult to compare and, in most cases, not comparable due to differences in product function, system boundaries, sources of LCI data, LCIA methods and other peculiarities related to LCA. Given the challenging comparability of LCA studies, the standardised LCA phases were used as the starting point for this review: Goal and Scope, LCI, LCIA and Interpretation. Considering that limited number of review papers analysed previous studies in terms of LCA elements, especially in field of LCA of sediment stabilisation/solidification treatment, the value of this paper is in the systematically provided information about the LCA phases and provided similarities and differences in LCA modelling.

In this review, eleven LCA studies on the process of sediment S/S management were analysed to find out how the authors overcame the challenge of presenting the LCA. The majority of the analysed studies showed that the studies may deviate from the ISO 14040 standard in terms of simplification and declared information in the LCA phases. The objective of the LCA was not explicitly stated in all studies, while in some cases the system boundaries ranged from cradle to gate. The LCA tools and LCI databases facilitate LCA, and almost all of the LCA studies examined were supported by them. The selection of impact categories depended on the required results, while optional elements, normalisation, grouping and weighting, were used to support the interpretation of the LCA results. In the final LCA phase, interpretation, hotspot, contribution and scenario analyses were performed in all LCA studies examined, while six of the eleven studies also performed sensitivity and uncertainty analyses.

The results of the review will enable future research to identify the life cycle phases that were not analysed in most of the studies, such as the use and end-of-life phases. Besides bricks, blocks, cement, mortar, concrete and filling material, the use of sediments in other products has not yet been studied with LCA and can be a topic for future research.

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