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CONCEPTUAL FRAMEWORK FOR THE INTEGRATED SUSTAINABLE MANAGEMENT OF SOILS AND BOTTOM SEDIMENTS

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Abstract: This study explores a sustainable framework for bottom sediment management, utilizing both SWOT and PESTEL analyses to assess its strategic viability. Through structured evaluations, the study identifies key strengths, including the circular economy benefits of sediment reuse, job creation potential, and improvements in soil fertility. However, challenges such as contamination, regulatory compliance, and logistical costs are also highlighted as factors that need careful management. The PESTEL analysis reveals strong external support in the form of favorable environmental and regulatory conditions, while the SWOT analysis provides a positive strategic potential score, indicating a feasible path forward. Additionally, the study addresses the role of sediment management in post-war recovery, particularly relevant for areas in Ukraine, suggesting its application for landscape restoration and infrastructure reinforcement. By integrating both internal and external factors, this research offers a comprehensive model for sediment repurposing, supporting sustainable development goals in the areas of resource management, environmental protection, and agricultural productivity. The results emphasize the potential of applying sustainable sediment management practices in the agricultural sector to support sustainable development.

Key words: sustainable sediment management, agricultural waste reuse, environmental resource management, circular economy in agriculture, remediation techniques, bioremediation in agriculture, post-war environmental recovery, bottom sediment recycling.

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Introduction

A sustainable approach to managing sedimentary deposits is increasingly important due to the environmental and logistical challenges of their removal and disposal. Sedimentary deposits, formed through natural weathering processes, are transported by water, wind, and gravity, often accumulating far away from their original sources. These particles range from large boulders (>256 mm) to fine colloids (<1 μm) and typically consist of materials such as sand, silt, and clay. Routine dredging is crucial for maintaining the capacity of rivers, lakes, and urban water bodies, protecting against flooding, and ensuring uninterrupted navigation (Helms et al., 2012). In Europe alone, approximately 200 million cubic meters of sediment are extracted annually, primarily from coastal, riverine, and lacustrine environments, as well as from artificial and urban water bodies (Helms et al., 2012).

Sediment accumulation in reservoirs and dams reduces water storage capacity, obstructs flow, and can damage critical infrastructure, such as hydroelectric turbines, necessitating periodic removal (Guy, 1975). Effective sediment management involves assessing factors such as water depth, sediment cohesiveness, organic content, and pollution levels prior to dredging (Puccini et al., 2013; Bates et al., 2015). The extracted sediments are sorted and reused based on their mechanical and chemical properties. For instance, the sediments may be employed in construction, including riverbank reinforcement or beach restoration (De Vincenzo et al., 2019). However, urban sediments often contain anthropogenic contaminants, complicating their direct use in agriculture or construction without treatment (Stojiljkovic et al., 2019).

As natural “accumulators”, sedimentary deposits capture persistent and potentially hazardous compounds from various pollution sources (Perelo, 2010). Contaminants such as heavy metals and organic pollutants often necessitate specialized treatment or even classification as hazardous waste (Vervaeke et al., 2003). The European Union Regulation 850/2004 governs permissible sediment reuse, setting contamination thresholds and imposing stricter restrictions on industrial sites where hazardous substances may be concentrated (Frohne et al., 2015).

Interest in the sustainable reuse of sediments is growing, particularly in agriculture, as researchers explore their potential as soil nutrient sources. Matej-Łukowicz et al. (2021) analyzed urban water body sediments and found significant amounts of iron and sulfur, which enhance phosphorus availability for plants, despite the low content of nitrogen and organic carbon. This finding suggests that nitrogen- and carbon-enriched sediments could serve as alternatives to synthetic fertilizers, aligning with circular economy principles and reducing dependence on non-renewable phosphorus fertilizers (Sandor and Homburg, 2017; Christel et al., 2014).

Sediment reuse has proven to be promising in practice. For example, a project by Studds and Miller (2010) under British Waterways applied sediments for canal bank reinforcement. After confirming the absence of hazardous substances, the project reduced disposal costs and highlighted the potential of sediment reuse in construction, promoting environmental and economic sustainability (Council Directive 67/548/EEC, 1967; Council Regulation (EC) No. 850/2004, 2004).

The diversity of sediment sources, compositions, and contamination levels necessitates a flexible yet regulated approach to sustainable management. While sediment reuse offers significant potential, particularly in agriculture and construction, proper treatment and thorough planning are essential to maximize benefits and ensure compliance with environmental standards.

This paper has three objectives. First, it explores a conceptual framework for the sustainable management of soils and bottom sediments, focusing on environmental safety and economic viability, while addressing their reuse potential in agriculture and construction. Second, the study identifies the critical processes, challenges, and opportunities associated with sediment remediation, utilizing methods such as SADT and IDEF0 modeling to develop an integrated management framework. Third, it evaluates the strategic potential of sediment reuse in post-conflict recovery, particularly within Ukraine, and its implications for broader sustainable development goals.

The study involved a comprehensive methodological approach designed to address the complex challenges of sediment management. Specifically, (i) the SADT and IDEF0 models were used to structure and optimize the sediment management processes, ensuring a clear hierarchy of operations from analysis to reuse; (ii) SWOT and PESTEL analyses were applied to identify the strengths, weaknesses, opportunities, and threats of sediment reuse, as well as to examine external factors influencing its feasibility; (iii) bioremediation techniques, including biostimulation and bioaugmentation, were analyzed to determine their suitability for purifying contaminated sediments; and (iv) economic, environmental, and legal factors were systematically evaluated to ensure alignment with international standards for sediment reuse. These methodologies collectively contribute to a robust framework for advancing sustainable resource management and supporting post-war recovery efforts.

Material and Methods

A comprehensive approach was utilized to design a sustainable management framework for sedimentary deposits, incorporating established SADT (Structured Analysis and Design Technique) (Ross, 1985) and IDEF0 (Integration Definition for Function Modeling) (Presley and Liles, 1995) modeling techniques to address the unique challenges of environmental sediment management. This methodology facilitated the development of a structured management framework aimed at achieving both environmental safety and economic feasibility in the reuse of sediment materials. The final graphic flowchart representing this framework was created using MyMap.ai [https://www.mymap.ai], which helped to visually organize and clarify the sequential operations within the model.

Approaches and Methods

1. Core models (SADT and IDEF0)

- SADT and IDEF0 structured sediment management and remediation processes. SADT provided a hierarchical framework for defining key stages, including initial analysis, cleaning, processing, and reuse options. IDEF0 detailed functional blocks and interconnections between sediment cleaning, processing, and reuse tasks.
- These methodologies facilitated the identification of critical operations and ensured a systematic approach to the preparation and treatment of sedimentary deposits.

2. Adaptation of the sustainable management framework

- The framework builds on Renella's recommendations (Renella, 2021) for sediment reuse in agriculture and construction. It incorporates sequential steps for environmentally safe sediment treatment, ensuring compliance with agricultural quality standards.
- A multi-level cleaning approach, including physical fraction separation, bioremediation, and other methods, enhances material processing efficiency and reduces environmental impact.

3. System of analysis and evaluation

- Sediment management begins with analyzing physicochemical properties to classify materials for further processing or reuse. Verification against European pollution standards ensures regulatory compliance.
- SWOT and PESTEL analyses evaluate the feasibility and strategic implications of sustainable sediment management.
- PESTEL systematically scores political, economic, social, technological, environmental, and legal factors (Kucher et al., 2019) to align the recommendations with the regulatory and economic contexts.
- SWOT highlights internal strengths and weaknesses, as well as external opportunities and threats, offering a balanced perspective on strategic potential (Dankevych, 2018).

To assess strategic feasibility quantitatively, scores were assigned to each factor in the SWOT and PESTEL analyses. The scoring methodology, with impact levels categorized by score ranges, is presented in Table 1.

For the SWOT analysis, we applied a structured approach inspired by Dankevych (2018), which quantifies strategic potential as follows:

$$SP=(S+O)-(W+T), \text{ where:}$$

SP – strategic potential;

S – strengths;

O – opportunities;
W – weaknesses;
T – threats.

This formula, adapted from Dankevych (2018), provides an overall strategic viability score by balancing positive (S + O) and negative (W + T) factors. A positive result suggests that the strengths and opportunities outweigh the weaknesses and threats, indicating a favorable strategic environment. Conversely, a negative or low score signals a challenging scenario, requiring mitigation strategies.

Unlike SWOT, the PESTEL factors were analyzed independently, rather than summed into a single numerical score. Each category—political, economic, social, technological, environmental, and legal—was evaluated separately to ensure a contextual assessment of external influences on sustainable sediment management.

This approach allows for a structured, quantitative analysis while maintaining analytical depth and clarity in assessing strategic feasibility.

Table 1. Criteria for assigning relative importance levels in PESTEL and SWOT analyses.

Score range	Relative importance level	Description
8–10	High	Factors scoring within this range are highly influential and critical to the success or feasibility of sediment management. These factors require primary consideration.
5–7	Medium	Factors in this range have a moderate impact and provide valuable support to the strategy. They are important, but secondary to the high-impact factors.
1–4	Low	Factors scoring in this range have minimal influence and are less likely to affect the overall outcomes significantly. These factors can be deprioritized in strategic focus.

Source: authors' research, refined from previous studies (Dankevych, 2018).

Results and Discussion

Sedimentary deposits accumulating in natural water bodies play a crucial role in maintaining ecological balance and forming fertile soils. However, they may also contain significant concentrations of organic and inorganic contaminants.

Figure 1 illustrates the sustainable sediment management framework developed in this study, detailing the sequence of operations and the connections between stages of sediment analysis, treatment, and reusing/recycling. This framework provides a systematic approach to sediment management, ensuring that each phase – from initial evaluation to final application – meets environmental and regulatory standards while optimizing both ecological and economic outcomes.

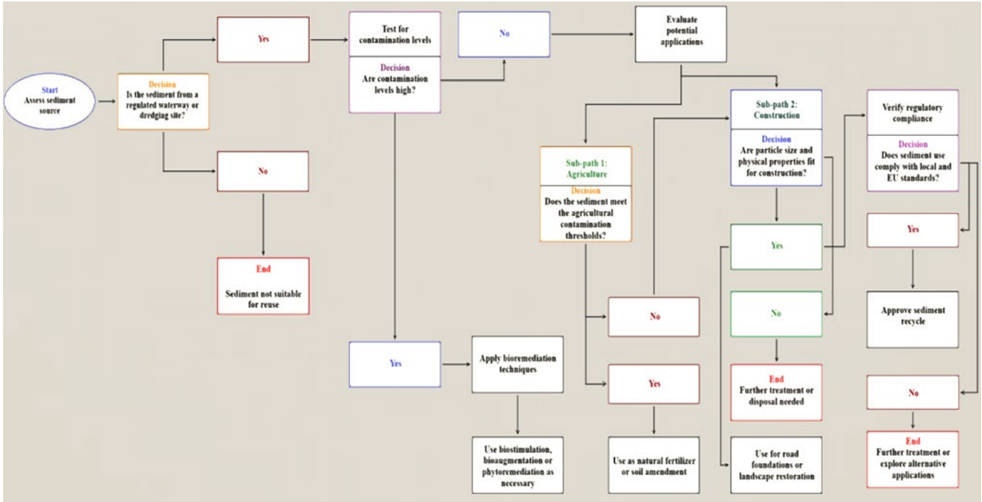

Figure 1. Decision-making flowchart for sustainable sediment recycling.
Source: Authors' adaptation, based on existing research (Renella, 2021).

The structured approach of the framework emphasizes the essential stages of sediment analysis and classification, identifying contaminants and selecting appropriate treatment methods according to sediment type and contamination levels. This approach supports a closed-loop system, enhancing resource efficiency and advancing sustainable development goals by promoting the circular use of sedimentary deposits.

For the safe and sustainable management of sedimentary deposits, it is crucial to adhere to environmental safety principles, employing both modern remediation techniques and regulatory restrictions that ensure the environmentally acceptable use of such materials.

The primary step in sustainable sediment management involves a comprehensive analysis of their physical and chemical properties. Particle size, organic matter content, and pollutant concentrations are critical factors influencing subsequent decisions regarding the use of these deposits. In the Czech Republic (Ministerstvo zemědělství & Ministerstvo životního prostředí, 2009), regulatory frameworks permit the application of sedimentary deposits to agricultural soils, provided that contaminant levels do not exceed established limits. Specifically, the concentrations of pollutants such as heavy metals must fall below the permissible thresholds set for soil conditioners and fertilizers.

If the analytical results indicate that the contaminant levels in the sediments are within acceptable ranges, these materials can be used for a variety of environmentally significant purposes. Experience shows that sedimentary deposits can be employed effectively for riverbank reinforcement, where they help stabilize soils and prevent erosion. Additionally, these materials contribute to landscape restoration and can be used for beach reconstruction, especially in areas where the natural coastal topography requires rehabilitation.

In the context of quarry and abandoned mine reclamation, sedimentary deposits hold considerable potential. They not only aid in stabilizing reclaimed sites but also enhance the physicochemical properties of soils, improving their suitability for ecosystem restoration. In Ukraine's post-war landscape restoration efforts, sedimentary deposits could serve as a valuable resource, potentially useful for filling craters left by military activities.

The processing of sedimentary deposits begins with particle-size-based separation (UNI EN 13242, 2002). This approach divides the sediments into coarse and fine fractions, which is essential for targeted reuse. The primary aim of this step is to isolate materials with different physicochemical properties, each requiring specific treatment and processing methods.

The coarse fraction, containing larger particles, has broad applications in engineering and construction. For example, sand, gravel, and small stones from this fraction are well-suited for road construction, foundation strengthening, and other infrastructure projects. Additionally, the coarse fraction can be used to create artificial embankments or as an aggregate for concrete, reducing the reliance on natural resources such as sand and gravel, thus lowering extraction and transportation costs (Kucher et al., 2024), which may be especially valuable in the context of Ukraine's post-war landscape reconstruction.

By facilitating the sustainable management and the targeted reuse of sedimentary deposits, these practices support both environmental goals and economic efficiency, offering a pathway to reduce environmental impact and conserve natural resources.

The fine fraction of sedimentary deposits, mainly composed of sand, silt, and clay particles, requires further purification after separation from the coarser components. Chemical and biological processes are considered some of the most effective cleaning methods, with bioremediation being recognized as the most environmentally sustainable option. Bioremediation minimizes chemical use and promotes natural pollutant degradation without harming the environment (Mattei et al., 2017). For this reason, bioremediation was chosen in our framework as the optimal method for purifying the fine fraction of sedimentary deposits. Table 2 presents a summary of the main bioremediation techniques and their characteristics.

Once purification is complete, the fine fraction can be reused as a substrate for growing ornamental plants or as a natural fertilizer. This approach is both environmentally sustainable and economically beneficial, reducing reliance on traditional substrates such as peat, a limited resource whose extraction damages ecosystems.

Table 2. Summary of bioremediation techniques for fine fraction sediment purification.

Technique	Key Characteristics	Advantages
Biostimulation	Adjusts conditions (nutrients, moisture, temperature) to promote natural microbial activity.	Facilitates organic contaminant degradation naturally.
Bioaugmentation	Introduces pollutant-degrading microorganisms.	Speeds up contaminant breakdown effectively.
Phytoremediation	Uses plants to extract/stabilize heavy metals and other pollutants.	Lowers contaminant levels while enhancing ecosystem sustainability.

Source: Authors' research.

The purified fine fraction of the sediments serves as an effective substitute for peat-based substrates traditionally used in ornamental horticulture. Peat is a non-renewable resource, and its extraction degrades peatlands—critical ecosystems for biodiversity conservation and carbon sequestration. Coconut substrates, another alternative, have a high environmental footprint due to the long-distance transportation from tropical regions.

Using treated sedimentary deposits offers an eco-friendly and resource-efficient alternative, supporting sustainable horticulture while reducing the environmental impact of traditional substrate materials. These purified sediments are agronomically effective, containing essential macro- and micronutrients necessary for plant growth. Additionally, the fine fraction of purified sediments can function as a natural fertilizer due to its high nutrient content, including nitrogen, phosphorus, potassium, and calcium, which enhance soil fertility (Baran et al., 2019). Replacing synthetic fertilizers with natural materials reduces the chemical burden on soils and water resources, thus contributing to sustainable agroecosystem management.

Integrating sedimentary deposits into agricultural soil promotes environmental sustainability and productivity. Studies show sediments improve soil structure and nutrient content, reduce reliance on synthetic fertilizers, and enhance ecological safety. Leonard et al. (2002) found that sediment application in deteriorated marsh soils improved elevation and plant biomass without disrupting ecological balances. Controlled sediment placement in agriculture could yield similar benefits, enhancing soil stability, supporting root development, and increasing water retention—especially in erosion-prone areas. These sediments supply essential nutrients such as nitrogen and phosphorus, enabling robust plant growth without chemical fertilizers, reversing degradation over time (Leonard et al., 2002).

Expanding on these findings, Spearman and Benson (2023) highlighted sediment recycling for habitat restoration, especially in coastal regions. They identified sediment as a valuable resource to offset environmental degradation by promoting soil health and preventing erosion. When applied to agricultural land, sediments enrich the nutrient-rich topsoil, fostering sustainable crop growth. Additionally, sediment recycling reduces pressure on natural fertilizer resources, allowing local agriculture to rely less on imported or synthetic inputs. This practice aligns with broader conservation efforts by reducing waste directed to offshore disposal, supporting biodiversity, and mitigating pollution risks in water bodies through beneficial land use (Spearman and Benson, 2023).

Research by Szara-Bąk et al. (2023) further emphasizes the nutrient-rich composition of sediments and their agricultural potential, particularly when combined with organic waste. Sediment-based growing media enriched with biomass ash or coffee hulls improve soil quality and reduce potential metal contamination. These substrates exhibit beneficial properties, such as pH balancing, low toxicity, and enhanced soil sorption, critical for long-term agricultural productivity. When blended with organic amendments, sediment mixtures mitigate acidity, improve soil structure, and enhance nutrient density, supporting a circular approach to resource use. This integrated approach minimizes waste, reinforces the resilience of agricultural soils, and ensures high productivity over time (Szara-Bąk et al., 2023).

In summary, the use of sedimentary deposits in agriculture promotes environmental resilience, reduces waste, and supports soil fertility through organic nutrient recycling. These findings suggest that sediment application not only serves as a sustainable alternative to traditional fertilizers, but also bolsters ecosystem health and agricultural productivity, providing a viable solution to some of the pressing challenges in sustainable soil management.

In cases where sediment contaminants exceed the permissible levels, purification procedures are essential before reuse or further processing. To ensure environmental safety, bioremediation is typically the preferred approach, due to its environmental benefits and efficiency, as we have discussed previously. Following the purification process, the sediments must undergo additional analysis to confirm that the pollutant concentrations meet the established standards. If bioremediation successfully reduces the contaminant levels to acceptable thresholds, the sediments will then be redirected for reuse or recycling. Depending on the intended application – such as for riverbank stabilization, landscape restoration, or use as substrates or fertilizers in agriculture – the cleaned sediments are employed in ways that align with both environmental safety and the specific requirements of each project.

For instance, the thresholds for beach restoration may be more flexible than for substrates in ornamental horticulture or agricultural fertilizers. In all cases, regulatory compliance is essential to ensure safe and effective use. If processing is selected after purification, additional bioremediation may not be necessary. Thus, processed materials are also suitable for safe use in agriculture or engineering projects, supporting environmental and economic sustainability goals.

Table 3. SWOT analysis of sustainable sediment management strategies.

Indicators	Helpful to achieve the objective		Harmful to achieve the objective	
	Strengths	Score (1–10)	Weaknesses	Score (1–10)
Structural factors (inherent to sediment management practices)	Environmental sustainability: Sustainable sediment management supports a circular economy, repurposes sediments, reduces waste, and minimizes reliance on non-renewable resources	9	Contamination challenges: High levels of contaminants (heavy metals, organic pollutants) in sediments can complicate and increase the cost of treatment, making some sediments unsuitable for immediate reuse	9
	Economic benefits: Sediment management can create jobs, lower fertilizer costs, and promote the use of local materials, leading to economic advantages for regional communities	8	Regulatory compliance: Ensuring sediment meets regulatory standards for reuse, especially in agriculture, can be challenging and may require extensive testing and purification efforts	8
	Resource efficiency: Treated sediments can substitute for traditional substrates and fertilizers, conserving resources such as peat and reducing reliance on synthetic fertilizers	8	Technical complexity: Advanced purification methods, such as biostimulation, bioaugmentation, and phytoremediation, require specialized knowledge, infrastructure, and financial investment	7
	Improved soil fertility: Nutrient-rich sediments enhance soil structure, water retention, and fertility, which benefits agricultural productivity and reduces erosion risks	9	Logistical requirements: Collecting, transporting, and processing large volumes of sediments can be challenging, especially in regions with limited infrastructure	8
	Opportunities		Threats	
Contextual factors (influences from the broader environment)	Growing demand for sustainable agriculture: Increasing awareness of sustainable practices opens up opportunities for using treated sediments as natural fertilizers in place of synthetic alternatives	9	Environmental and health risks: Improperly managed sediments or inadequate treatment can lead to environmental contamination and health risks, especially if pollutants are not effectively removed	9
	Construction applications: Sediments have promising uses in construction (e.g., road foundations, landscape restoration, riverbank stabilization), presenting new markets for treated sediments	8	Market acceptance and awareness: Public perception and market readiness may be barriers, as stakeholders might view sediment-derived products with scepticism due to potential contamination concerns	7
	Climate change mitigation: Using sediments for natural fertilization and peat replacement helps reduce greenhouse gas emissions associated with synthetic fertilizers and peat extraction	8	Regulatory hurdles: Regulatory standards and permissible limits for contaminants may tighten, restricting the reuse options for sediments and increasing treatment requirements	8
	Post-war reconstruction: In post-conflict areas, such as Ukraine, sediment reuse offers cost-effective materials for landscape restoration, filling craters, and rebuilding infrastructure	7	Economic and infrastructural challenges: High costs of transporting and processing sediments, especially in regions with limited infrastructure, may reduce the economic viability of sediment management practices	8

Source: Authors' research.

Table 4. Scored PESTEL analysis for sustainable bottom sediment management.

Category	Factor	Score (1–10)	Description
Political	Regulatory standards	10	Strict EU and local regulations on allowable contaminant levels in reused sediments are critical. Compliance directly impacts the feasibility of using sediments, particularly in agriculture, where contamination thresholds are stringent
	Government support for sustainability	8	Political support for sustainable practices can facilitate funding and policy incentives, making sediment management more economically viable
	Post-conflict recovery policies	7	In regions such as Ukraine, government prioritization of post-war recovery may boost support for sediment use in landscape restoration, especially in areas with limited resources
Economic	Cost savings in agriculture	9	The substitution of treated sediments for synthetic fertilizers represents a significant cost-saving opportunity for farmers, enhancing agricultural profitability and sustainability
	Job creation	8	Employment opportunities created through sediment management contribute positively to local economies, fostering social acceptance and economic resilience
	Logistics and transportation costs	9	High transportation and handling costs are a major factor in the economic feasibility of sediment management projects, particularly in remote or rural regions
	Local resource utilization	8	By using locally sourced sediments, dependency on imported materials, such as peat, is reduced, lowering costs and supporting local industries
Social	Public perception and acceptance	7	Public support is essential, particularly for agricultural applications. Perceptions around safety and contamination must be managed through transparency and education
	Community engagement and employment	6	Local job creation through sediment management can enhance community support, creating positive social impacts and fostering regional development
	Health and safety	8	Ensuring that reused sediments are free from harmful contaminants is crucial for public health, especially in agriculture where there is direct exposure to treated soils
Technological	Bioremediation techniques	7	Advanced bioremediation methods are essential for meeting safety standards in sediment treatment. Innovation in these techniques can improve purification efficiency and reduce treatment costs
	Particle separation technologies	6	Technologies that categorize sediments into fractions for agriculture or construction increase flexibility and scalability in sediment reuse.
	Monitoring and testing	7	Rapid, accurate testing for contaminants ensures compliance and safety. Advances in monitoring technology can streamline treatment processes and support regulatory adherence
Environmental	Reduction of waste	9	Recycling sediments reduces waste that would otherwise accumulate in landfills or waterways, contributing to the circular economy and environmental sustainability
	Climate impact reduction	8	Using sediments as a substitute for synthetic fertilizers and peat substrates reduces greenhouse gas emissions, supporting climate action goals
	Soil and waterway health	10	Sustainable sediment management promotes waterway health by preventing sediment build up and enhancing soil structure and stability, which is crucial for long-term environmental health
	Contamination risks	9	Effective treatment is necessary to mitigate contamination risks, ensuring sediments do not introduce harmful substances into ecosystems
Legal	Compliance with environmental regulations	10	Legal compliance with EU environmental standards directly impacts the scope of sediment reuse. Strict regulations can limit applications, while flexibility could broaden reuse options
	Waste classification	8	Legal classifications of sediments as hazardous or non-hazardous dictate handling, treatment, and disposal requirements, affecting project feasibility
	Land use and agricultural policies	9	Regulations on land use and soil additives influence sediment reuse in agriculture. Compliance with these policies is essential for project approval and sustainability

Source: Authors' research.

The results of the SWOT analysis, which identifies key strengths, weaknesses, opportunities, and threats associated with sustainable sediment management, are summarized in Table 3. This analysis provides insights into the internal and external factors that influence the feasibility and effectiveness of sediment reuse strategies.

The PESTEL analysis, presented in Table 4, evaluates the external political, economic, social, technological, environmental, and legal factors influencing sustainable sediment management. Rather than aggregating these factors into a single total, each category is examined individually to ensure a precise assessment of external influences without diluting their impact.

Following the PESTEL assessment, the SWOT analysis was conducted to determine the strategic feasibility of sediment management. Using the quantitative approach described in the Methods section, the strategic potential score was calculated as follows:

SWOT analysis calculations

1. Sum of positive factors (strengths + opportunities)

Strengths: 9 + 8 + 8 + 9 = 34

Opportunities: 9 + 8 + 8 + 7 = 32

Total positive factors: 34 + 32 = 66

2. Sum of negative factors (weaknesses + threats)

Weaknesses: 9 + 8 + 7 + 8 = 32

Threats: 9 + 7 + 8 + 8 = 32

Total negative factors: 32 + 32 = 64

3. Strategic potential calculation

SP = (S + O) - (W + T)

SP = 66 - 64 = 2

A strategic potential score of 2 suggests that the strengths and opportunities slightly outweigh the weaknesses and threats (Dankevych, 2018). While this reflects a moderately favorable outlook, the narrow margin indicates that addressing risks and leveraging opportunities is crucial to ensure long-term viability.

Qualitative insights from the PESTEL analysis

Since the PESTEL factors are not summed into a single total, their individual impact is analyzed based on previous research by Dankevych (2018) and Renella (2021):

- Political (regulatory influence = moderate): Environmental policies and sediment reuse regulations provide clear guidelines, but bureaucratic delays can slow implementation.
- Economic (investment and cost feasibility = significant): Market-driven incentives encourage sediment reuse, but funding gaps and financial constraints remain obstacles.

- Social (community engagement = low-moderate): Public awareness is relatively low, indicating a need for greater advocacy and educational outreach.
- Technological (infrastructure and innovation = moderate): Advancements in sediment processing and reuse technologies present growth potential, though implementation challenges exist.
- Environmental (sustainability and risk mitigation = high): Regulatory pressures on contamination control and ecosystem health make environmental considerations a dominant factor.
- Legal (compliance and policy stability = strong): A well-defined regulatory framework supports sediment reuse, yet inconsistent enforcement may introduce uncertainty.

Strategic implications

The SWOT and PESTEL analyses suggest that sustainable sediment management exists in a moderately supportive yet complex environment. While the internal strengths and opportunities outweigh the risks, the external landscape requires proactive strategies to strengthen feasibility.

- To enhance strategic viability, future initiatives should focus on the following:

Regulatory adaptation – streamlining compliance to reduce bureaucratic delays.

- Financial incentives – expanding investment and funding opportunities.
- Technological innovation – improving infrastructure to enhance adoption.
- Community engagement – increasing awareness to drive public and industry support.

By addressing these key areas, sustainable sediment management can fully capitalize on its strategic potential while mitigating existing challenges.

Conclusion

To enhance strategic viability, future sediment management initiatives should prioritize several key areas. Regulatory adaptation is necessary to streamline compliance procedures and reduce bureaucratic delays that may hinder the implementation of sustainable sediment reuse. Expanding financial incentives and investment opportunities will be essential to support the economic feasibility of sediment processing and transportation, particularly in regions where infrastructure limitations increase costs.

Technological innovation must be further encouraged to improve sediment purification methods, particularly in the areas of bioremediation and contaminant monitoring, ensuring that treated sediments meet regulatory and environmental standards. Community engagement and public awareness campaigns should be strengthened to address safety and contamination concerns while increasing the acceptance of sediment-based products in agriculture and construction.

By addressing these challenges and capitalizing on the identified opportunities, sustainable sediment management can become a viable strategy for environmental conservation, economic efficiency, and post-war recovery initiatives. In particular, the potential for sediment reuse in Ukraine's reconstruction efforts highlights its role in restoring landscapes, stabilizing damaged infrastructure, and reducing the need for imported raw materials. A structured approach that integrates strategic planning, regulatory compliance, and technological advancement will be crucial in realizing the full benefits of sediment reuse.

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KONCEPTUALNI OKVIR ZA INTEGRISANO ODRŽIVO UPRAVLJANJE ZEMLJIŠTEM I DONJIM SEDIMENTIMA

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R e z i m e

Ova studija istražuje održivi okvir za upravljanje donjim sedimentima, koristeći *SWOT* i *PESTEL* analize za procenu njegove strateške izvodljivosti. Kroz strukturirane evaluacije, studija identifikuje ključne prednosti, uključujući koristi cirkularne ekonomije kroz ponovnu upotrebu sedimenata, potencijal za otvaranje novih radnih mesta i poboljšanje plodnosti zemljišta. Međutim, istaknuti su takođe i izazovi, poput kontaminacije, usklađenosti sa regulativama i logističkih troškova kao faktori koji zahtevaju pažljivo upravljanje. *PESTEL* analiza otkriva snažnu eksternu podršku u vidu povoljnih ekoloških i regulatornih uslova, dok *SWOT* analiza pokazuje pozitivan strateški potencijal, ukazujući na izvodljiv put napred. Pored toga, studija se bavi ulogom upravljanja sedimentima u posleratnom oporavku, što je posebno relevantno za područja u Ukrajini, sugerišući njegovu primenu u obnovi pejzaža i jačanju infrastrukture. Integracijom internih i eksternih faktora, ovo istraživanje nudi sveobuhvatan model za prenamenu sedimenata, podržavajući ciljeve održivog razvoja u oblastima upravljanja resursima, zaštite životne sredine i poljoprivredne produktivnosti. Rezultati naglašavaju potencijal primene održivih praksi upravljanja sedimentima u poljoprivrednom sektoru kako bi se podržao održivi razvoj.

Ključne reči: održivo upravljanje sedimentima, ponovna upotreba poljoprivrednog otpada, upravljanje ekološkim resursima, cirkularna ekonomija u poljoprivredi, tehnike remedijacije, bioremedijacija u poljoprivredi, posleratni ekološki oporavak, reciklaža donjih sedimenata.

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