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Research article

A systems-based approach to circular sludge management: Data-driven foresight, sustainability assessment, and strategic evaluation

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ABSTRACT

Sustainable sludge management in wastewater treatment plants is a critical challenge that demands strategic planning and holistic evaluation tools. This study presents a novel data-driven framework for sustainable, multifunctional circular sludge management. Unlike conventional models, the framework integrates circular planning, scenario-based foresight, a data-driven approach, and sustainability assessment to identify optimal sludge reuse pathways and treatment alternatives. A dynamic 3D SWOT methodology is employed to prioritise circular actions. We also introduce a modified decision support system incorporating 15 new criteria across 39 parameters, supported by uncertainty analysis. To demonstrate the framework, we applied it to a wastewater treatment plant in Iran. Seven circular reuse strategies were assessed: sanitised landfill, compost for agriculture, incineration for bricks, road pavement, concrete paving blocks, incineration for ceramics, and clay-based pipelines. These were evaluated across 24,000 potential future scenarios. The model was run over 500 times to perform a comprehensive sensitivity analysis on strategic and assessment outcomes. Results identified composting use as the most optimal strategy. The most sustainable treatment configuration included dissolved air flotation, anaerobic digestion, and pressurised strip filters. Sensitivity analysis revealed key external and internal drivers, highlighted the importance of temporal attributes, and showed the influence of expert judgment. The framework delivers resilient, adaptive, and context-sensitive solutions for sustainable sludge management. It serves as a robust decision-making tool for infrastructure planners, policymakers, and environmental engineers. However, the approach has limitations, including dependence on data availability, equal probability for all scenarios, and assumptions in scenario modelling, which should be considered in broader applications.

1. Introduction

Wastewater treatment plants (WWTPs) play a critical role in protecting the environment by treating urban wastewater and preventing pollution from natural water bodies (Maryam and Büyükgüngör, 2019). These facilities help in safeguarding public health and maintaining ecological balance by removing contaminants and pathogens from wastewater (Sathya et al., 2023). However, despite their benefits, WWTPs are not devoid of hazards. A significant challenge created by these plants is the production of by-products, particularly sludge, which can reintroduce pollutants into the environment if not managed properly (Kehrein et al., 2020). Besides, Wastewater sludge poses significant environmental and health risks if not properly treated or disposed of (Rout et al., 2021). It may contain pathogens that can spread infectious diseases, heavy metals and toxic compounds that contaminate soil and water resources, and organic matter that leads to the emission of greenhouse gases such as methane and nitrous oxide during anaerobic decomposition (Balkrishna et al., 2025; Uddin et al., 2025). Leachate from untreated sludge can infiltrate groundwater, posing long-term risks to drinking water supplies, while surface runoff may carry contaminants into nearby ecosystems, disrupting biodiversity and food chains (Gao et al., 2025).

It is estimated that wastewater treatment plants worldwide currently generate approximately 53 million dry tons of sludge annually - comparable to the total amount of municipal solid waste generated each year by the entire United States (Li et al., 2025) - with projections suggesting this could increase to around 160 million tons per year (Feng et al., 2023). This exponential growth is driven by rapid urbanisation,

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population growth, and expanding wastewater treatment infrastructure, particularly in developing countries. For example, China alone is expected to produce over 80 million tons of sludge (wet weight) annually by 2030, while the European Union currently manages more than 10 million tons of dry sludge each year (Huang et al., 2023; Maraveas and Hahladakis, 2025). This highlights the necessity for effective and sustainable sludge management.

Sludge management can be examined from two principal perspectives of sludge disposal and sludge treatment processes (Zhang et al., 2017). Conventionally, disposal methods such as land application, sanitised landfilling, incineration, and ocean dumping were widely adopted to mitigate the environmental hazards of sludge, regardless of its inherent resource potential (Nanda and Berruti, 2021). For example, approximately 60 % of wastewater sludge in the United States is land-applied for use on farms, forests, and in landscaping (EPA, 2023). Landfilling is the second most common disposal method, accounting for around 24 %, while incineration represents approximately 14 % of sludge management. The remaining ~2 % is managed through alternative methods, such as long-term lagoon storage, surface disposal at dedicated sites, or experimental applications. Similarly, in the European Union, land application is the dominant route, representing approximately 40–50 % of total sludge uses as of the late 2010s (Domini et al., 2022; Feng et al., 2023). Incineration is the second primary pathway, accounting for 20–30 % of sludge treatment, often coupled with energy recovery. In contrast, landfilling has declined substantially, comprising well under 20 %, largely due to EU directives that discourage the disposal of organic waste in landfills. Additional practices in the EU include composting, land reclamation (e.g., mine site rehabilitation), and phosphorus recovery research from sludge or incineration ash.

On the other hand, a series of established alternatives, primarily to reduce sludge volume and minimise associated risks, without accounting for its value beyond waste management. These alternatives mainly include thickening, stabilisation, and dewatering (Qrenawi and Rabah, 2021). Combining these processes with circular actions, i.e. actions that align with circular economy principles, focusing on resource recovery, waste minimisation, and closing material loops, can present a transformative approach by reframing sludge not as hazardous waste, but as a valuable resource. These circular applications not only divert sludge from landfills and prevent environmental contamination but also support broader sustainability goals. For example, when adequately treated, sludge's rich organic content, essential nutrients like nitrogen and phosphorus, and trace minerals can be harnessed for beneficial applications (Balkrishna et al., 2025). In the construction industry, treated sludge can be repurposed into value-added materials such as bricks, paving blocks, and road aggregates, contributing to resource efficiency and reducing the environmental footprint of raw material extraction (Muter et al., 2022). Therefore, sludge treatment technologies should be re-envisioned as multifunctional systems designed to meet the quality standards required for specific circular pathways, effectively converting a public health and environmental threat into a platform for resource recovery and circular economy advancement.

Approaches toward sustainable management of WWTP sludge have frequently been undertaken, with assessments of circular actions and treatment alternatives conducted separately. Circular action scope has assessed the sustainability of these actions, such as landfilling, composting, resource utilisation, and incineration by employing multi-criteria decision-making (MCDM) tools, e.g. fuzzy AHP and TOPSIS to determine the optimal reuse of treated sludge (An et al., 2018; Maw et al., 2024). They mainly have identified the available circular actions, particularly emphasising the use of sludge in agriculture, and have subsequently assessed the associated human, ecological, and ecotoxicological risks by monitoring contaminants such as microplastics, pharmaceuticals, pesticides, and heavy metals (Mejías et al., 2021; Fernández-Fernández et al., 2023). However, these studies primarily focus on contaminant detection and hazard identification under current conditions, with limited integration of scenario-based or forward-looking risk frameworks. Therefore, they offer minimal insight into how emerging pollutants or evolving regulatory thresholds might influence long-term sludge application strategies. In addition, suitability assessment of treated sludge has been tested to classify its potential for use as fertiliser or compost by tracking key parameters including pH, electrical conductivity, heavy metal concentrations, and nutrient content (Gusiatin et al., 2018; Jaoude et al., 2025). Although these studies provide valuable insight into the agronomic quality of sludge, they largely rely on static threshold values and localised conditions. This limits its applicability for strategic decision-making across diverse regulatory contexts and future environmental scenarios.

On the other hand, the second group of studies focuses primarily on sludge treatment alternatives, i.e. technical processes or configurations used to convert raw sludge into a form suitable for reuse, often employing indicator-based sustainability assessments and life cycle assessment (LCA) methods. These studies have selected a specific circular action, e.g. agriculture and compare various sludge treatment processes, such as biological, chemical, thermal and thermochemical methods (Teoh and Li, 2020; Hosseinian et al., 2024). They applied LCA to evaluate each alternative based on parameters such as emissions, nutrient recovery, energy savings, sludge volume and weight reduction, toxicity, fossil depletion, and freshwater eutrophication to identify the most optimal process (Mayer et al., 2021; Ding et al., 2021). However, these reviews tend to generalise findings across diverse regional contexts without accounting for variability in environmental conditions, infrastructure, or regulatory frameworks, which can significantly influence the sustainability of treatment options. In the border assessment, other studies have taken a similar approach by considering multiple sustainability dimensions, including economic, social, environmental, and technical aspects, by establishing a set of indicators to assess the treatment options (Tarpani and Azapagic, 2023a,b). However, they tend to rely on static datasets, limiting their responsiveness to evolving system dynamics or future policy shifts. Furthermore, some studies have used MCDM modelling to compare alternatives not only from a sustainability perspective but also in terms of energy and electricity production, aiming to determine the best option for future projects or for replacing existing processes (Flores-Alsina et al., 2021; Ronda et al., 2023). However, they tend to emphasise current operational efficiency without sufficiently accounting for the long-term viability and adaptability of the chosen alternatives - limitations this study seeks to overcome by integrating a data-driven and scenario-resilient evaluation framework.

Furthermore, while expert judgment remains fundamental to assess strategic planning and MCDM models (Liu et al., 2020), an over-reliance on expert input can significantly constrain the analytical process to a narrow set of scenarios, predominantly shaped by the experts' prior experiences and personal or disciplinary biases (Jaoude et al., 2025). This can lead to a problematic form of tunnel vision, where alternative futures, especially those that fall outside the conventional or expected, are insufficiently explored or entirely overlooked (Neri et al., 2024). Such limitations pose serious risks in long-term strategic planning, particularly in complex and dynamic environments where uncertainties are high and change is non-linear (Đurđević et al., 2022). Experts, while highly knowledgeable, may inadvertently underestimate or exclude low-probability but high-impact events, emerging trends, or disruptive technologies that do not align with their established mental models (Liu and Ren, 2022). In effect, the adverse impact of relying too heavily on expert judgment is a reduction in strategic foresight and a missed opportunity to build resilient and adaptable systems. Without expanding the scenario space through computational modelling, participatory approaches, and data-driven foresight tools, planning efforts remain vulnerable to failure in the face of unexpected change or stressors (Sabet et al., 2025). Such oversights can ultimately compromise both the effectiveness and credibility of decision-making frameworks in the long run.

To address these challenges, this study aims to present a new data-driven sustainable framework for multi-function circular sludge management from WWTPs and beyond conventional expert-based MCDM frameworks by adopting data-driven MCDM techniques. By taking this approach, the study aims to answer the following key research questions: (1): What are the essential components of a comprehensive framework for circular sludge management in wastewater treatment plants, and how should these components be integrated to support sustainability and multifunctionality?; (2) Which methods and criteria can be effectively used to identify and prioritise optimal circular actions and corresponding sludge treatment alternatives in a systematic, data-driven manner? (3) Under what conditions and boundaries do the identified optimal circular actions and treatment alternatives remain valid, and how can their resilience be assessed in the face of uncertain future scenarios or changing external factors?

To address the research questions, this study sets out the following objectives: (1) Developing a comprehensive and integrated framework for sludge management in wastewater treatment plants that balances strategic decision-making with adaptability to internal dynamics and external regulatory or environmental factors, (2) Designing and implementing a custom data-driven MCDM method for prioritising circular actions and mapping them to the most suitable sludge treatment alternatives; (3) Evaluating the robustness and long-term validity of selected circular actions and treatment alternatives through sensitivity analyses under diverse future scenarios and shifting operational conditions.

By addressing these objectives, this study not only fills a critical gap in the integration of circular action planning and treatment alternatives but also introduces a resilient, forward-looking methodology that enhances strategic foresight in sustainable sludge management. The proposed framework is designed to support decision-makers in navigating uncertainty, improving sustainability outcomes, and unlocking the full circular potential of wastewater treatment plant sludge. The following sections detail the methodological structure and application of this framework. To demonstrate the advantages of the proposed method, we applied it to a real-world case study of the South Tehran Wastewater Treatment Plant (STWWTP) - the largest WWTP in Iran, processing an average of 450,000 cubic meters of wastewater per day and serving approximately 2.1 million people.

2. Methodology

This study employs a structured three-phase framework to address the complex challenges of sludge treatment management and to identify suitable multi-function alternatives, defined as integrated treatment approaches that simultaneously meet multiple reuse criteria, allowing a single sludge stream to support various circular pathways. Phase 1 involves the development of a strategic plan to identify and prioritise circular actions suitable for wastewater sludge management. This begins with the identification of feasible circular actions through the review of academic and industrial literature sources. The prioritisation is carried out using an enhanced integrated model combining SWOT, PESTEL, and McKinsey 7S frameworks. Internal and external drivers are dynamically categorised and evaluated using expert-informed attribute values, collected through structured methods such as Delphi panels and focus group discussions. These attribute values are used to conduct a multidimensional analysis of circular actions. The phase concludes with the application of a decision tree model to filter and select viable combinations of sludge treatment processes - namely thickening, stabilisation, and dewatering - that form the basis of multi-function alternatives.

Phase 2 focuses on assessing the sustainability of the shortlisted alternatives using a data-driven MCDM model. This phase incorporates a modified AHP integrated with a relative benchmarking method. The assessment is performed across four main sustainability criteria - economic, technical, social, and environmental - subdivided into 39 detailed indices. MATLAB 2024a is used in this phase to execute large-scale scenario simulations. Criterion weights are dynamically adjusted within expert-defined boundaries to assess the average performance and reliability (presence score) of each alternative across diverse future conditions.

Phase 3 conducts a multi-aspect sensitivity analysis to evaluate the robustness and adaptability of the framework. This includes scenario-based sensitivity checks on the prioritisation model (e.g., removal of key drivers or temporal attributes), as well as variations in index weights and expert influence in the MCDM structure. MATLAB is used to facilitate computational modelling and analysis in this phase, providing feedback on how changes in assumptions impact the overall decision outcomes. The framework is also benchmarked against traditional expert-based methods, including expert-driven, process-driven, condition-driven, and quantification-driven approaches.

The methodology is developed to be universally applicable across diverse WWTP contexts, including municipal, industrial, agricultural, and commercial sectors. While acknowledging that local constraints and operational parameters may vary by case, the framework sets out a flexible baseline of minimum requirements. These can be tailored or expanded to ensure their adaptability and effectiveness in a wide range of implementation scenarios. The specific processes involved in each phase are elaborated in the following sections.

2.1. Phase 1: strategic planning framework

Phase 1 establishes a strategic planning framework for managing wastewater sludge through circular actions. The process begins with the identification of applicable circular actions by reviewing academic and industrial sources, excluding unsustainable options like dumping or landfilling. An enhanced integrated prioritisation model is applied, building on SWOT, PESTEL, and McKinsey 7S frameworks, where internal and external drivers are dynamically classified and weighted using expert-informed attribute values to reflect short-, medium-, or long-term impacts. Relevant internal and external driving forces are extracted from official documents, grey literature, and expert input, and refined through clustering to ensure unique and clearly defined statements. Finally, multiple future scenarios are developed to assess the robustness of each circular action, and reuse alternatives - combinations of sludge treatment processes - are generated and filtered using a decision tree that considers practical constraints (e.g., economic viability, regulations, equipment availability) and operational preferences (e.g., simplicity, maintenance needs, adaptability), narrowing down to the most feasible and sustainable solutions.

2.1.1. Step 1: circular action determination

This phase aims to define one of the key functions of alternatives, which is determining the best circular actions for managing urban wastewater sludge. It emphasises that other functions, i.e., the processes involved in sludge management, should align with this strategy. Since this aspect requires strategic and long-term planning, it necessitates the application of multiple strategic planning tools. Depending on the specific conditions of the case study, applicable circular actions are identified from various sources, including industrial or pilot-scale practices documented in academic literature, start-up or early-stage technical reports, industrial practices, or white papers. These strategies must prioritise sustainability and longevity; therefore, unsustainable practices such as dumping and sanitised landfilling are excluded (Masalegooyan et al., 2022).

2.1.2. Step 2: integrated prioritising framework

To determine the applicability of each nominated circular action for the case study, a prioritisation process is required. For this purpose, the model proposed by Naghedi et al. (2020) has been selected and significantly enhanced. While the original method introduced a novel integration of SWOT analysis coupled with PESTEL and McKinsey's 7S to define multi-function alternatives, certain barriers limit its reliability and suitability for strategic planning. One key limitation of the original model is its fixed classification of internal and external driving forces, which does not account for their dynamic nature across different circular actions. For instance, the global economic context may present an opportunity for one circular action, a threat for another, and be neutral or not applicable for a third. To address this, the enhanced model replaces the single-label 2D SWOT matrix with a multi-label 3D SWOT framework. Instead of predefining internal forces as strengths or weaknesses and external forces as opportunities or threats for all circular actions, the enhanced approach first classifies driving forces broadly into internal and external categories and their specific roles are then dynamically allocated, allowing for multi-dimensional characterisation of each force as can be compared between Fig. 1a and b.

Furthermore, in the enhanced model, the nature of the identified statements, categorised as policy, economic, social, technical, environmental, and legal for external driving forces (based on the PESTEL framework) and as strategy, structure, systems, shared values, skills, style, or staff for internal driving forces (based on the McKinsey 7S framework), is used to determine the priority strategy through a sensitivity analysis. This is achieved by allocating circular actions to the nature of these statements as well (See Fig. 1b). This additional step enables a deeper understanding of the relationships between circular actions and their driving factors.

Additionally, in the original model, each statement was assigned equal value, and the superiority of the circular action was determined solely through frequency analysis. However, the actual weight and significance of each statement are influenced by its temporal context and the degree of its establishment over time. For instance, trust between sludge managers and a specific market may take decades to develop, creating a robust and enduring connection. This differs significantly from the value of a new technology that has a booming market but is uncertain for long-term sustainability, despite being ideal for short-term applications. To address this, an attribute value (AV) is introduced for each identified statement in each circular action. The AV represents the temporal significance of a statement, categorised as short-term, medium-term, or long-term, inspired by Shirato et al. (2023). For each circular action, the cumulative AV is calculated using Eq. (1) (see Fig. 1b for clarification). The AVs for statements are determined through expert input, using focus group discussions and the Delphi method to ensure a comprehensive and balanced assessment. This approach allows the model to account for both the immediate and sustained impacts of each statement, enhancing the robustness and reliability of reuse target prioritisation.

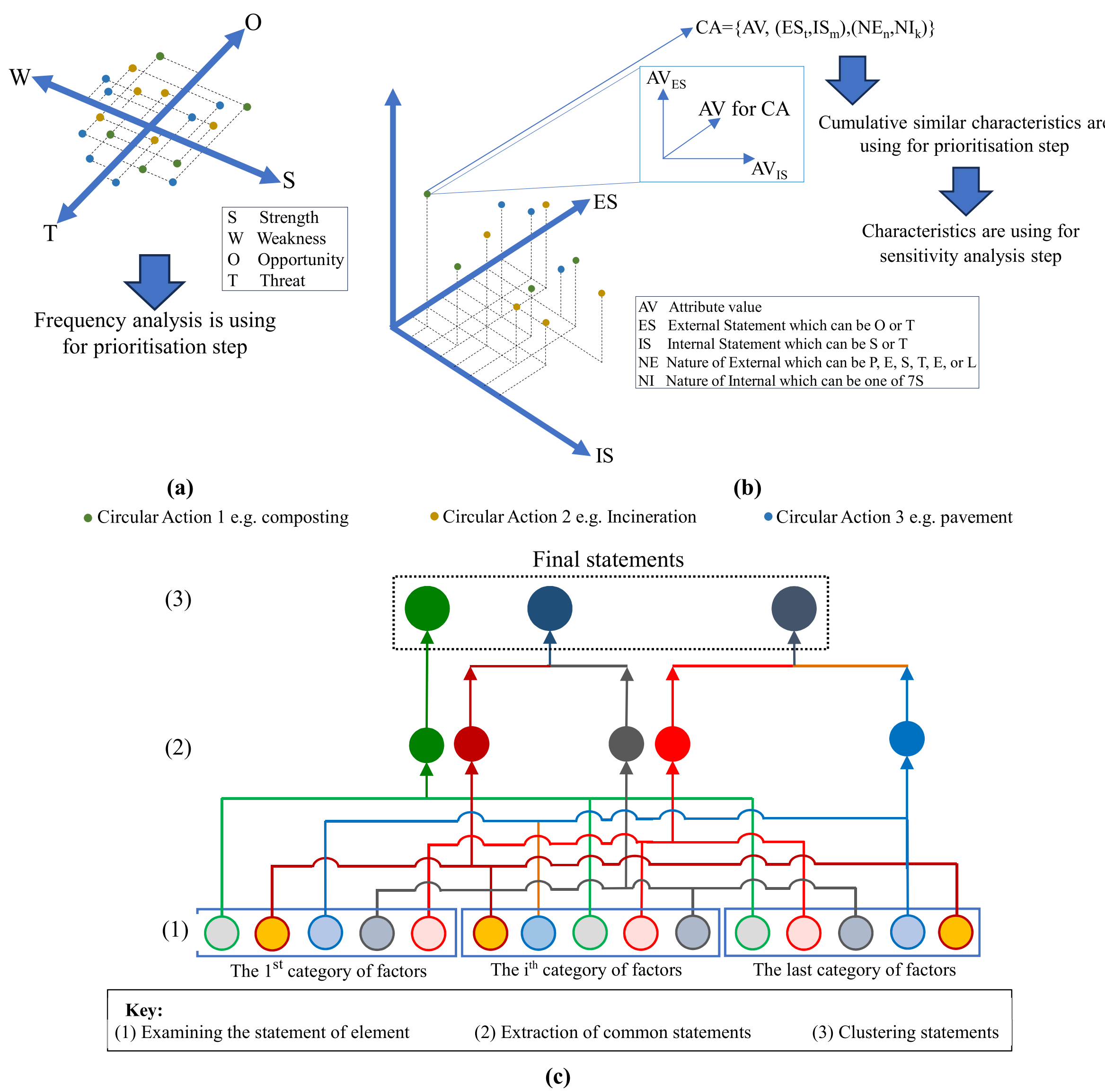


Fig. 1. Schematic illustration of integrated prioritising framework: (a) traditional SWOT, (b) proposed enhanced model built upon; (c) Schematic diagram of clustering factors to provide unique-characteristic statements.

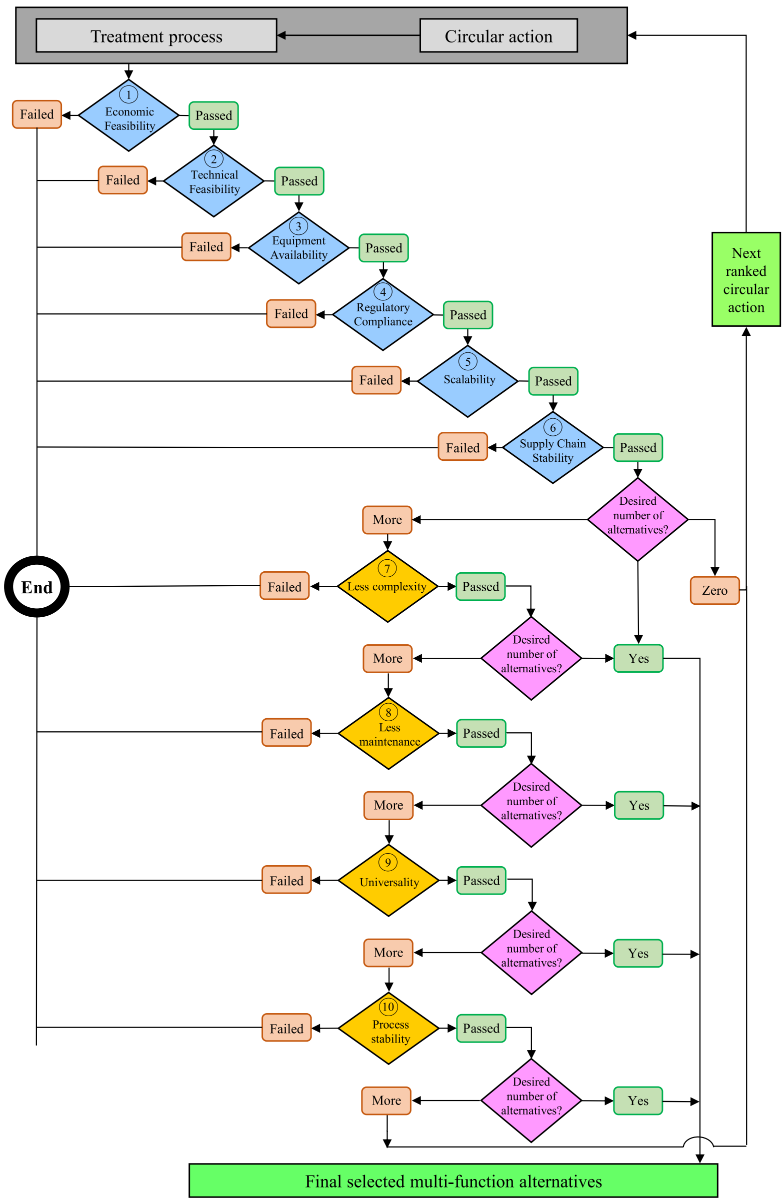
$$AV_{RT_i} = \sqrt{{AV_{ESj}}^2 + {AV_{ISk}}^2} \quad \text{Equation (1)}$$

where AV_{RT_i} is the attribute value of ith reuse target, ESj is the jth external statement, and ISk is the kth internal statement

2.1.3. *Step 3: driving force extraction and clustering*

Statements related to external and internal factors can be identified from three key sources of (1) official documents such as technical, social, and environmental impact assessments, procurements, feasibility studies, (2) unofficial documents such as news articles and health and safety reports following the methods suggested by Masalegooyan et al. (2022), and (3) expert opinions as recommended by Piadeh et al. (2022) or field visits as proposed by Naghedi et al. (2020).

As discussed, each identified statement exhibits multi-label characteristics, i.e. it may belong to multiple categories or be derived from various sources. For instance, a potential market may be identified through either social reports or economic analyses. To address this



Key:
(1) Is it economically viable in both the short and long term?
(2) Is there local knowledge of this method in the country?
(3) Is it possible to obtain the required equipment, considering political or logistical challenges?
(4) Does it align with local, national, and international environmental and safety regulations?
(5) Can it be scaled up or down depending on the size of the plant?
(6) Are there risks of disruptions for critical materials or chemicals?
(7) Preference for less complexity to ensure ease of operation and minimise training requirements
(8) Less maintenance required to avoid frequent downtime and resource strain
(9) Possibility of using the treatment method across all treatment plants, regardless of size or location
(10) Is the method reliable under fluctuating input conditions, such as changes in sludge composition or weather variations?

Fig. 2. Applied decision tree to decrease the number of alternatives - The key parameters were derived from a literature review conducted using the Scopus search engine, with the keywords "sludge," "sustainability," and "circular economy" applied to the title, keywords, and abstract fields. Relevant papers were reviewed, and key parameters were extracted and grouped into thematic clusters. The current decision tree is informed by, but not limited to, studies such as Castelazo et al. (2014), An et al. (2018), Da Silva et al. (2020), and Mohapatra et al. (2025).

complexity, a clustering method is proposed to critically refine and group the characteristics of each statement. This method systematically reduces redundancy and combines similar statements. As shown in Fig. 1c, this iterative process continues until all statements are unique and non-overlapping, ensuring clarity and precision in their classification and analysis. This approach strengthens the reliability of the model by eliminating ambiguities and fostering a more structured framework.

2.1.4. Step 4: scenario development and alternative creation

To account for the inherent uncertainties in future trends and developments, this study employs multiple scenarios to capture a wide range of potential future conditions. These include five scenarios of difficult, poor, current, satisfaction, and ideal (their descriptions are listed in Table A1), while the weighting score methodology follows Piadeh et al. (2018). Furthermore, as mentioned, reuse target prioritisation is enhanced by the incorporation of the dynamic nature and attribute values of each circular action, as formulated in Eq. (2), moving beyond the conventional frequency-based analysis typically used.

$$\text{Score } i = \sum_{j=1}^{n}\sum_{k=1}^{4}\text{weight}_k\sum_{l=1}^{m}\text{AV}_l \qquad \text{Equation (2)}$$

where i is the ith reuse target, j is the scenario, n number of total scenarios which here suggested for at least 5 but can be extended more, k is nature allocated i.e., SO, ST, WO, WT, Weight is the value assigned to kth surface which is −1 for WT, 1 for SO and variable for OT and SW depend on defined scenario, m is the total found RT_i in surface k, AV is the attribute value assigned to lth identified RT_i

Once the optimal circular action is prioritised, the corresponding nominated alternatives can be specified. Regardless of the circular action, each alternative comprises multiple processes identified from the previously mentioned resources. For example, the thickening process may involve gravity thickening or flotation thickening; the stabilisation process may include anaerobic digestion, lime stabilisation, or thermal treatment; and the dewatering process may utilise filter pressing, centrifugation, or natural drying (Radetic, 2024). The combination of these processes creates a multi-function alternative, each capable of converting raw sludge into outputs aligned with the identified usage strategies. However, evaluating all possible alternatives to identify the most sustainable option is both challenging and resource-intensive.

To address this, a decision tree framework, as illustrated in Fig. 2, is proposed to streamline the number of alternatives into a manageable set. The screening process integrates various concerns and preferences derived from sustainability principles. Alternatives are passed through the decision tree, systematically eliminating those that fail to meet specified concerns or address identified preferences. If the number of viable alternatives for a specific usage strategy is insufficient, the decision tree accommodates the consideration of next-ranked circular actions from the previous step. While it is understood that the number of concerns or preferences may vary depending on the specific case, the decision-making process is structured around a minimum of six core concerns - economic feasibility, technical feasibility, equipment feasibility, regulatory compliance, scalability, and supply chain stability - and four key preferences: low complexity, minimal maintenance requirements, universality, and process stability. These elements are embedded within the decision tree to ensure a consistent, structured, and sustainability-oriented screening of alternatives. However, a prospective validation should be conducted by engaging domain experts to review the screening logic and provide feedback through structured interviews or Delphi-style rounds. However, as this process is highly case-specific, it is recommended that such validation be undertaken by practitioners or researchers applying the model to their context.

2.2. Phase 2: data-driven MCDM model for sustainability assessment

Phase 2 establishes a comprehensive sustainability assessment framework to evaluate sludge treatment alternatives. In Step 1, a data-driven MCDM structure is developed, integrating a modified analytic hierarchy process with relative benchmarking to assess alternatives across four main criteria, further broken down into sub-criteria and 39 detailed indices that reflect both standard and context-specific factors. In Step 2, MATLAB 2024a is used to generate a wide range of future scenarios by dynamically adjusting criterion weights within expert-defined boundaries, reducing bias and reliance on static assumptions. Alternatives are scored based on both their average performance and consistency (presence score) across scenarios to evaluate the robustness and sustainability of each option under various future conditions.

2.2.1. Step 1: assessment structure

This step focuses on establishing the foundational structure for assessing the identified sludge treatment alternatives. The proposed assessment framework tackles the challenge of aggregating diverse indices, each with unique weights, units, and levels of importance, by employing a data-driven MCDM model. This model is based on a modified analytic hierarchy process proposed by Piadeh et al. (2018), integrated with a relative benchmarking method inspired by Taheri et al. (2025). At the top level of this hierarchical structure, the framework outlines four general sustainability criteria: economic, technical, social, and environmental. These criteria, which are listed in Table 1, capture the multidimensional nature of sustainability in sludge management. To enable a deeper evaluation, the framework further decomposes each sustainability criterion into sub-criteria. Specifically, the economic dimension is subdivided into cost and income; the technical dimension is further characterised by resistance and maturity; the social dimension encompasses external stakeholders and internal stakeholders; and the environmental dimension is defined by natural resources and sustainability concerns.

As shown in Table A1, 39 indices are listed as minimum vital aspects to comprehensively assess the alternatives of which 15 are proposed based on experts' focus group and reviewing other sustainability frameworks proposed in another field of knowledge, such as energy (Ahmadi et al., 2024, 2025), water management (Asghari et al., 2023; Namavar et al., 2023; Ferdowsi et al., 2024), waste management (Khan and Kabir, 2020; Offie et al., 2023). These proposed indices have been integrated into the assessment structure of this study to account for both hidden and apparent factors that can assist policy and decision-makers in selecting the optimal sludge treatment alternative. As an example, "uncertainties in future ongoing costs" ensure financial resilience by accounting for fluctuating operational expenses, while global economic threats highlight risks from economic instability and trade restrictions. Compensation mechanisms, such as subsidies or grants, can offset high costs and improve feasibility. Transparency and corruption considerations prevent mismanagement and ensure accountability in sludge treatment policies. Cybersecurity is crucial for protecting digital monitoring systems from potential cyberattacks that could disrupt plant operations. Site selection affects logistics, environmental impact, and community relations, while local intervention assesses potential resistance from nearby stakeholders that could delay or prevent implementation. In contrast, strong governmental and institutional support can facilitate policy adoption and funding. Local market impact evaluates whether sludge-derived products have economic value in the region, enhancing their financial viability. Environmental risks are also critical; eutrophication risk ensures alternatives prevent excess nutrient discharge into water bodies, heavy metals risk assesses contamination threats to soil and water, and pathogen risk ensures public health is protected from untreated sludge. Finally, emerging pollutants such as microplastics and pharmaceuticals are considered, as conventional treatment methods may not effectively remove them, posing long-term environmental hazards.

2.2.2. Step 2: data-driven scenario development

This framework leverages the computational capabilities of MATLAB

Table 1
The weighted score of alternatives in each criterion and index[a].

Criterion/Index	Alternatives			
	A1	A2	A3	A4
Economic	0.580	0.615	0.555	0.554
Cost	0.271	0.293	0.257	0.248
Capex	0.073	0.065	0.076	0.076
Opex	0.067	0.067	0.062	0.070
Uncertainties in future ongoing cost	0.069	0.073	0.061	0.056
Global economy threats	0.062	0.088	0.058	0.046
Compensation	0.043	0.045	0.047	0.045
Income	0.309	0.321	0.298	0.306
Net present value	0.071	0.069	0.053	0.071
Return period	0.088	0.099	0.088	0.088
Break-even point	0.089	0.085	0.100	0.092
Transparency/Corruption	0.061	0.069	0.057	0.054
Technical	0.527	0.539	0.575	0.523
Resistance	0.253	0.243	0.236	0.268
Natural disaster	0.054	0.054	0.039	0.052
Quality shock	0.044	0.048	0.038	0.040
Quantity shock	0.070	0.061	0.055	0.058
Operational failure	0.054	0.049	0.069	0.071
Cyber security	0.032	0.032	0.035	0.048
Maturity	0.274	0.296	0.339	0.255
Scalability	0.047	0.043	0.040	0.038
Complexity	0.056	0.058	0.076	0.048
Site selection	0.057	0.059	0.042	0.053
Upgradability	0.049	0.058	0.068	0.049
Technical staff	0.064	0.077	0.114	0.067
Social	0.574	0.563	0.604	0.546
External stakeholders	0.287	0.295	0.292	0.281
Participation	0.035	0.070	0.035	0.035
Local intervention	0.052	0.048	0.050	0.050
Supports	0.043	0.041	0.046	0.043
Task satisfaction	0.050	0.040	0.048	0.048
Local market impact	0.056	0.052	0.061	0.056
Neighbours impact	0.051	0.046	0.053	0.049
Internal stakeholders	0.287	0.268	0.312	0.266
Safety at the construction phase	0.068	0.058	0.063	0.053
Safety at the operation phase	0.079	0.053	0.053	0.079
Risk of pollutants exposure	0.072	0.086	0.107	0.072
Required monitoring	0.068	0.071	0.089	0.061
Environmental aspect	0.655	0.655	0.690	0.651
Natural resources	0.287	0.287	0.287	0.287
Land area	0.078	0.091	0.087	0.108
Water consumption	0.049	0.121	0.068	0.049
Habitats threats	0.070	0.073	0.077	0.077
Raw material consumption	0.101	0.083	0.101	0.097
Sustainability concerns	0.357	0.287	0.356	0.319
Global warming potential	0.043	0.049	0.057	0.029
Eutrophication risk	0.049	0.063	0.047	0.047
Heavy metals risk	0.066	0.043	0.072	0.084
Pathogens	0.077	0.038	0.077	0.081
Emerging pollutants	0.064	0.045	0.051	0.051
Sound pollution	0.058	0.048	0.053	0.028

[a] The value of indices is independent on criteria (scenarios) and is determined by the average of the quantified score of each alternative in each index times the weight of each index. The value of each sub criteria is also independent on scenarios and is determined by the average of all indices in each sub criterion. The value of criteria is only determined for illustration and is determined by summation of sub criterion in each criterion for each alternative.

2024a to iteratively generate a broad spectrum of plausible future scenarios. This approach engages experts primarily in establishing the boundaries of plausibility and evaluating the feasibility of the resulting scenarios in comparison to giving them the task of assigning fixed weights or defining precise future conditions. Although the reliance on expert thoughts is significantly reduced here, the selection of experts still remains critical.

Given the reliance on expert opinion and focus groups, ethical considerations should be carefully addressed. All participants should be provided with clear information about the study's aims, procedures, and intended use of the data. Informed consent was obtained from all contributors before their involvement, either in written or recorded verbal form, depending on the mode of engagement. Although the study may not involve sensitive personal data or vulnerable groups that would require formal ethical approval from an institutional review board, ethical standards related to voluntary participation, confidentiality, and data handling should be strictly observed.

To minimise bias, experts should be selected from a range of relevant professional backgrounds to ensure diverse and balanced input. Experts should be identified based on expertise requirements and diversity in terms of geographic location, demographic background, and professional experience, thereby minimising bias, as recommended by Piadeh et al. (2022). Their qualifications should be verified through peer review and professional endorsements, and a saturation analysis, such as snowball techniques, should be conducted to ensure that the expert panel is sufficiently robust, in line with the guidance of Rhakho et al. (2024).

Once the scenario boundaries are defined, the system dynamically adjusts criterion weights to generate a diverse set of unique, non-redundant scenarios. This process enhances the data-driven scenario analysis approach proposed by Sabet et al. (2025). For each generated scenario, the model computes a total score for each alternative, incorporating the interdependencies among indices, criteria, and alternatives. Two key performance metrics are employed: the average score of each alternative across all scenarios, which highlights the most promising overall option, and the presence score, which indicates the frequency with which an alternative outperforms others, serving as a measure of its reliability. These metrics are stored in a centralised data repository for final analysis to identify the most sustainable and resilient alternatives based on both average performance and consistency.

The resulting scenarios are classified into two main clusters. The first cluster comprises extreme scenarios, where one dimension, such as economic or environmental, receives a weight equivalent to the sum of all other dimensions, simulating futures where decision-making is dominated by a single aspect. The second cluster includes core scenarios, where one dimension holds a relatively higher, but not dominant, weight. These provide a more balanced perspective and are useful for evaluating the performance of alternatives under varying but realistic priority settings.

Finally, it should be acknowledged that although the framework evaluates a large number of scenarios, it is important to clarify that the simulations are deterministic, based on predefined weight combinations rather than stochastic inputs. As such, traditional statistical measures such as confidence intervals or p-values are not directly applicable in this context. However, the robustness of the results is reflected through several metrics, including the stability of rankings across diverse weighting conditions, the presence ratio (i.e., the proportion of scenarios in which each alternative outperforms others), and the consistency of normalised scores.

2.3. Phase 3: multi-aspect sensitivity analysis

The proposed framework for prioritising circular actions is inherently conditional, relying on specific assumptions and constraints. Consequently, it is crucial to acknowledge that changes in these conditions, driven by various influencing factors, may alter the identified optimal solution. To enhance the framework's robustness and adaptability, this study incorporates a sensitivity analysis to identify the key factors and conditions to which the optimal solution is most responsive. This analysis provides valuable insights into the stability of the decision-making process across different scenarios, enabling a proactive approach to anticipating and managing potential future changes.

2.3.1. Step 1: uncertainties in strategic planning

Four sensitivity analyses are proposed here to assess the robustness of the framework: (1) Driving force elimination to evaluate the impact of removing individual statements identified during the prioritisation process by re-evaluating scores to determine whether the best circular action changes. This approach helps assess the dependence of the optimal solution on specific statements and ensures resilience to incomplete data, (2) Nature elimination to examine the broader categories of statements by removing all statements associated with a particular category. It assesses how the absence of these factors influences the optimal solution, identifying the most influential categories of driving forces. This macro-level perspective helps prioritise areas requiring the most attention in data collection and analysis, (3) Temporal attribute elimination to explore the consequences of completely removing each category of temporal attributes to understand how the optimal solution adapts to such exclusions. This ensures that the framework remains stable even when temporal data is incomplete or uncertain, and (4) Attribute reclassification to assess the effects of reclassifying attribute values across temporal categories. For example, statements initially classified as short-term may be reassigned to long-term, and vice versa. This evaluates how shifts in perceived temporal priorities impact the optimal solution, ensuring the framework's flexibility to adapt to evolving conditions and future uncertainties.

The study also examines the complex combo interactions between sensitivity aspects by evaluating the interdependencies between internal and external driving forces. This comprehensive approach enhances the framework's adaptability and resilience in dynamic decision-making environments.

2.3.2. Step 2: uncertainty in sustainability evaluation

Two sensitivity analyses are proposed for the MCDM framework: (1) Index weight variation that examines how fluctuations in the assigned weights of different indices influence results. Since weighting reflects the significance of each index, this analysis is key to understanding how variations impact decision outcomes; (2) Stakeholder influence, which investigates how expert opinions and knowledge affect decision-making. It involves adjusting expert weights based on factors such as service time, education, and role within the process.

2.3.3. Step 3: comparison with well-established methods

To highlight the distinctions between the proposed framework and conventional approaches, the identified criteria were reapplied to the case study using well-known expert-based scenario analysis techniques. These methods were selected through a structured search in the Scopus database, utilising keywords such as "sustainability assessment", "MCDM", and "sludge". The retrieved studies were examined to determine the most appropriate methods for expert-driven scenario analysis. Four key methods were chosen: (1) Expert-driven: This method establishes a single scenario in which weights are assigned to criteria according to expert judgment, reflecting a singular perspective (Eliyan et al., 2023). It relies on domain-specific expertise to prioritise decision factors, incorporating subjective insights (Agarwal and Singh, 2022); (2) Process-driven: This method generates multiple scenarios based on alternative process flows. Each scenario is customised to align with the shared conditions affecting all alternatives, emphasising functional and operational aspects (Zhou et al., 2024). It is particularly useful for analysing variations in process design, system performance, and expected outcomes under different conditions, making it effective for comparing technological pathways (Yang et al., 2015); (3) Condition-driven: This method focuses on a predefined set of factors, such as economic, environmental, or technical conditions (Naghedi et al., 2020). By operating within strict parameters, it assesses how alternatives perform under specific constraints. This is especially relevant for decision-makers interested in evaluating options under realistic, real-world limitations (Piadeh et al., 2018b); (4) Quantification-driven: This approach establishes a scenario by statistically or mathematically determining the weight of each criterion. It provides an objective and data-driven assessment of factor importance, ensuring a systematic and analytical foundation for decision-making (Twagirayezu et al., 2024).

3. Result

This section presents the quantitative findings derived from the implementation of the proposed framework for sustainable sludge management. It includes outputs from strategic scenario development, sustainability assessment, and sensitivity analysis.

3.1. Case study description

The South Tehran wastewater treatment plant (STWWTP) is a critical wastewater infrastructure located south of Tehran, the capital city of Iran (see Fig. 3). Occupying an area of 110 ha, it handles an average wastewater flow of 450,000 cubic meters per day, serving a population of about 2.1 million, the biggest WWTP in Iran. The facility is planned for expansion to accommodate up to 4.2 million people through the construction of eight treatment modules (Ahmadinezhad et al., 2024). The treatment plant is strategically located among industrial complexes, urban areas, and agricultural land, making it an ideal site for implementing circular economy actions (Fig. 3 – upper right image). The treatment process at STWWTP employs a combination of conventional activated sludge and high-rate trickling filters for nitrification (Fig. 3-lower right pic). This integrated approach includes primary treatment units such as mechanical screens and grit removal, followed by primary sedimentation tanks. Subsequently, wastewater undergoes biological treatment in aeration tanks and trickling filters, culminating in secondary clarification (Akbarzadeh et al., 2023).

Sludge generated from the treatment process at STWWTP undergoes thickening, anaerobic digestion, and mechanical dewatering. The treated sludge is currently utilised as a soil conditioner in agriculture, providing a sustainable disposal method while enhancing soil fertility (Kazemi and Gholikandi, 2023). This treatment plant was chosen for this study due to its proximity to extensive local communities, including agricultural lands, urban areas, and industrial complexes, as indicated in Fig. 3. The plant's location and operational scale pose potential risks; for instance, bypassed wastewater could result in significant environmental, social, and financial consequences. Certain wastewater treatment units, such as aeration and chlorine gas disinfection, also carry health and safety risks due to the potential emission of bioaerosols or toxic gases.

Finally, to establish the case study, input was obtained from 27 experts, whose characteristics are detailed in Table A2 in the Appendix. These experts were selected through purposive sampling, following a screening process inspired by the approach of Balali and Kaltungo (2025), to ensure relevant expertise and diversity in perspectives.

3.2. Strategic planning phase

Seven viable circular actions were identified, each representing a potential path for the treated sludge (See Fig. 3-Lower left pic). These circular actions include: (1) Sanitised landfill (SL) utilising the treated sludge as a resource for safe disposal in landfills, (2) Compost for agriculture (CA) reprocessing the treated sludge into compost for agricultural purposes, (3) Incineration for bricks (IB) using incinerated sludge as a raw material in the production of bricks, (4) Road pavement (RP) employing treated sludge as an aggregate in the construction of roads and pavements, (5) Concrete paving blocks (CP) incorporating treated sludge into the manufacturing of durable concrete paving blocks, (6) Incineration for ceramics (IC) using sludge as a component in the production of ceramics, and (7) Clay-based pipelines (CB) recycling treated sludge for the creation of clay-based pipelines. According to the applied framework, internal and external driving forces are identified, as presented in Tables A3 and A4. Each driving force is then further characterised by its nature and temporal attribute, and its relationship with potential circular actions is systematically analysed.

3.2.1. Statement analysis

Tables A3 and A4 in the Appendix illustrate identified internal and

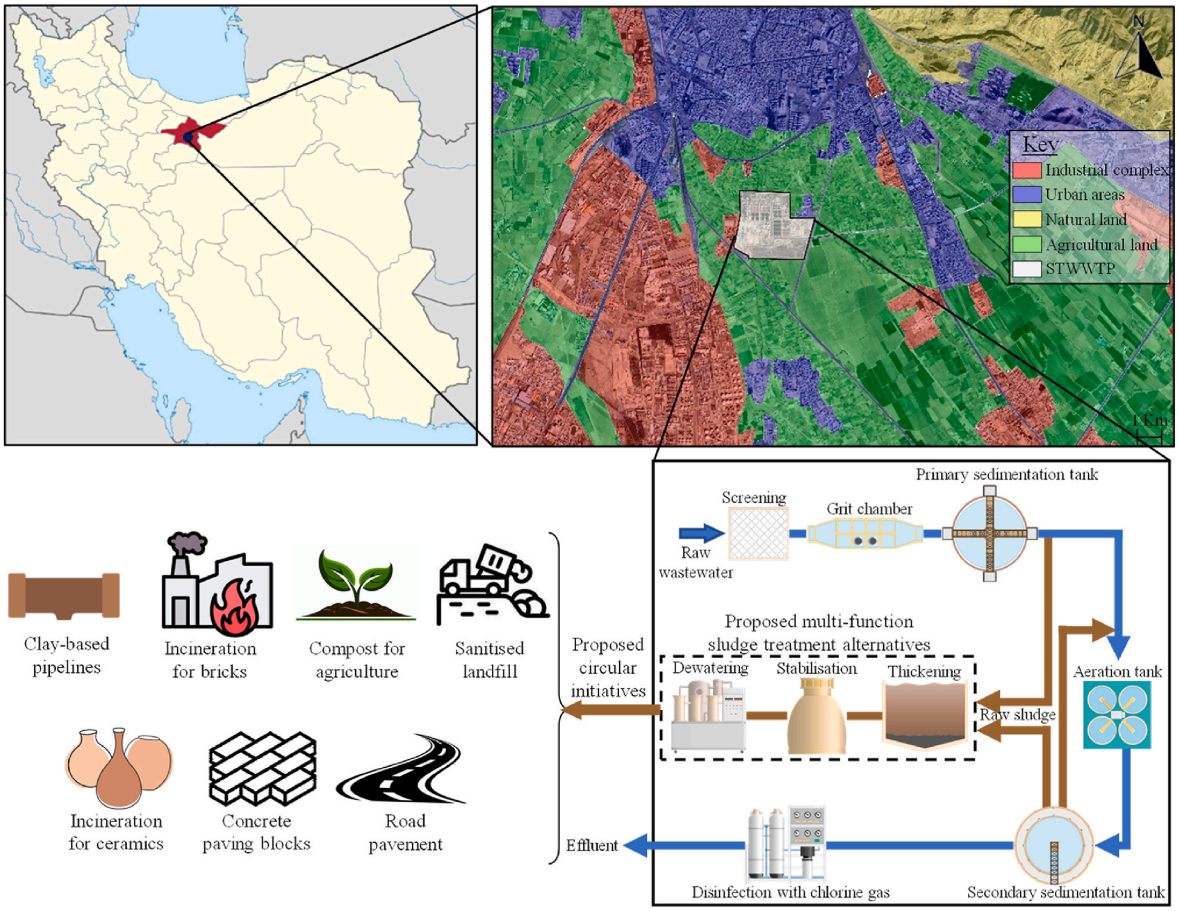


Fig. 3. Case study location and its characteristics used for applying the framework to a real case.

external statements as outputs of steps 1–3 in phase 1. Totally 20 external factors and 17 internal factors are identified. A total of 40 instances were classified as threats across the seven circular actions, while 40 instances were recognised as opportunities. On the other hand, 52 instances were categorised as strengths supporting the circular actions, while an equal number of 45 instances were identified as weaknesses, reflecting internal organisational and operational challenges. These tables clearly show that the factors influencing strategic planning in sludge management and the selection of optimal circular actions are complex and multifaceted, including statements of varying natures.

3.2.2. Strategies analysis and defined alternatives

Fig. 4 illustrates the distribution of scores for each circular action across the four SWOT surfaces and five scenario types, as calculated using Equation (2). Among the evaluated options, composting for agricultural use achieved the highest cumulative score (1779), ranking as the most favourable circular action. This was largely due to its dominant performance on the S-O, S-T, and W-O surfaces. Road pavement, sanitised landfill, and concrete paving blocks followed in descending order, each achieving positive scores indicative of strategic suitability. Conversely, incineration for ceramics, clay-based pipelines, and incineration for bricks returned negative scores, with incineration for bricks registering the lowest total score (−1025) despite scoring highest on the W–T surface.

After identifying the treatment alternatives, four alternatives were obtained. Alternative A1 consists of gravity filtering, anaerobic digestion, and pressurised strip filters; Alternative A2 comprises gravity filtering, aerobic composting, and dryer sludge beds; Alternative A3 includes dissolved air flotation, anaerobic digestion, and pressurised strip filters; and Alternative A4 is based on centrifugation, anaerobic digestion, and pressurised strip filters.

3.3. MCDM analysis and optimal alternative

3.3.1. Index analysis

Fig. 5 presents the relative scores of the four selected alternatives across 39 sustainability indices, as determined in Step 1 of Phase 2. The values are visually coded: quantified values are shown in blue, performance enhancements are highlighted in green, and performance deficiencies are marked in red. The figure indicates a wide variation in scores across alternatives and indices. For instance, in the investment cost index (Fig. 5a), alternative A4 exhibits the lowest value, suggesting cost-efficiency. Meanwhile, in the operational cost index (Fig. 5b), alternative A2 outperforms the others with the most favourable score. No single alternative consistently dominates all indices.

3.3.2. Criteria analysis

Table 1 presents the weighted scores of four alternatives across four main sustainability criteria. In the economic dimension, Alternative A2 scored the highest overall (0.615), showing superior performance particularly in operational cost (0.295), future cost uncertainties (0.065), and compensation mechanisms (0.061). This indicates that A2 not only maintains low expenditures but also benefits from more stable and predictable financial performance. In contrast, A4 obtained the lowest economic score (0.554), primarily due to its high capital expenditure (Capex = 0.285) and weaker performance in income-related metrics such as net present value and break-even point. In the technical dimension, Alternative A3 recorded the highest cumulative score (0.608), demonstrating robust performance across both the resistance (0.269) and maturity (0.339) sub-criteria. Within resistance, A3

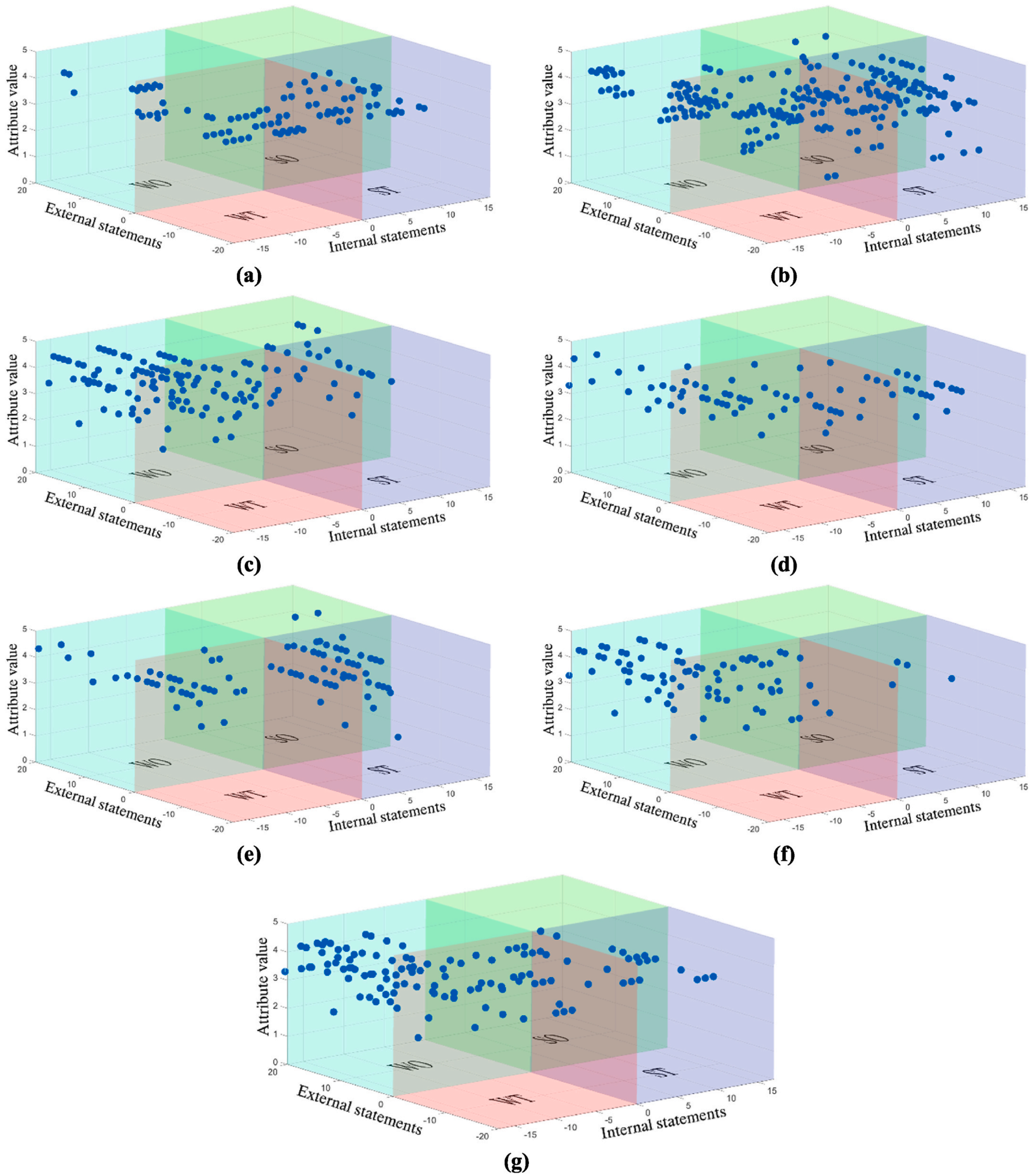


Fig. 4. Distribution of valid statements for each circular action: (a) SL, (b) CA, (c) IB, (d) RP, (e) CP, (f) IC, (g) CB.

showed balanced resilience against shocks in quality and quantity, as well as strong cybersecurity and operational stability. Conversely, A4 scored the lowest (0.527) in this criterion despite having the strongest resistance to operational shocks (e.g., natural disasters = 0.236). Its low scores in scalability (0.043), complexity (0.035), and required technical staff (0.013) indicate technical inefficiencies that significantly diminish its overall performance.

For the social dimension, A3 again emerged as the best-performing alternative (0.604), excelling in internal stakeholder support (0.332), safety metrics, and construction/operational acceptance. This reflects strong organisational capacity and effective engagement strategies. Although A2 led in external stakeholder engagement (0.365), its lower

A1	A2	A3	A4	
0.11	1.09	1.10	0.08	A1
	0.12	1.01	0.07	A2
		0.12	0.07	A3
			0.01	A4

(a)

A1	A2	A3	A4	
0.19	0.45	0.96	1.15	A1
	0.08	2.13	2.55	A2
		0.18	1.20	A3
			0.21	A4

(b)

A1	A2	A3	A4	
15.00	0.89	1.04	1.20	A1
	13.33	1.18	1.35	A2
		15.67	1.15	A3
			18.00	A4

(c)

A1	A2	A3	A4	
0.72	0.98	1.07	1.16	A1
	0.70	1.10	1.19	A2
		0.77	1.09	A3
			0.83	A4

(d)

A1	A2	A3	A4	
39.00	0.90	1.13	1.26	A1
	35.00	1.26	1.40	A2
		44.00	1.11	A3
			49.00	A4

(e)

A1	A2	A3	A4	
9.46	1.16	1.14	0.88	A1
	10.93	0.99	0.76	A2
		10.81	0.77	A3
			8.32	A4

(f)

A1	A2	A3	A4	
3.00	0.67	1.67	2.33	A1
	2.00	2.50	3.50	A2
		5.00	1.40	A3
			7.00	A4

(g)

A1	A2	A3	A4	
0.28	1.18	1.19	0.82	A1
	0.34	1.01	0.70	A2
		0.34	0.69	A3
			0.23	A4

(h)

A1	A2	A3	A4	
7.80	0.95	1.03	1.08	A1
	7.40	1.08	1.14	A2
		8.00	1.05	A3
			8.40	A4

(i)

A1	A2	A3	A4	
13.67	1.20	0.98	0.95	A1
	16.33	0.82	0.80	A2
		13.33	0.98	A3
			13.00	A4

(j)

A1	A2	A3	A4	
13.33	1.08	1.30	1.40	A1
	14.33	1.21	1.30	A2
		17.33	1.08	A3
			18.67	A4

(k)

A1	A2	A3	A4	
13.33	1.38	1.03	1.43	A1
	18.33	0.75	1.04	A2
		13.67	1.39	A3
			19.00	A4

(l)

A1	A2	A3	A4	
15.67	0.96	0.98	0.98	A1
	15.00	1.02	1.02	A2
		15.33	1.00	A3
			15.33	A4

(m)

A1	A2	A3	A4	
6.67	1.10	1.70	2.60	A1
	7.33	1.55	2.36	A2
		11.33	1.53	A3
			17.33	A4

(n)

A1	A2	A3	A4	
16.33	0.98	1.00	1.00	A1
	16.00	1.02	1.02	A2
		16.33	1.00	A3
			16.33	A4

(o)

A1	A2	A3	A4	
14.33	0.95	1.07	1.02	A1
	13.67	1.12	1.07	A2
		15.33	0.96	A3
			14.67	A4

(p)

A1	A2	A3	A4	
15.67	1.06	0.98	0.94	A1
	16.67	0.92	0.88	A2
		15.33	0.96	A3
			14.67	A4

(q)

A1	A2	A3	A4	
12.67	0.97	1.03	1.13	A1
	12.33	1.05	1.16	A2
		13.00	1.10	A3
			14.33	A4

(r)

A1	A2	A3	A4	
5.00	0.80	1.00	1.25	A1
	4.00	1.00	1.25	A2
		4.00	1.25	A3
			5.00	A4

(s)

A1	A2	A3	A4	
0.14	1.05	1.00	0.98	A1
	0.14	0.95	0.93	A2
		0.14	0.98	A3
			0.13	A4

(t)

A1	A2	A3	A4	
0.12	1.41	1.03	1.00	A1
	0.17	0.73	0.71	A2
		0.13	0.97	A3
			0.12	A4

(u)

A1	A2	A3	A4	
0.14	1.09	0.91	0.81	A1
	0.16	0.83	0.74	A2
		0.13	0.90	A3
			0.12	A4

(v)

A1	A2	A3	A4	
14.11	1.13	1.09	1.25	A1
	15.89	0.97	1.11	A2
		15.44	1.14	A3
			17.67	A4

(w)

A1	A2	A3	A4	
94.90	1.00	1.00	1.00	A1
	95.10	1.00	1.00	A2
		95.20	1.00	A3
			95.00	A4

(x)

A1	A2	A3	A4	
95.35	1.00	1.00	1.00	A1
	95.32	1.00	1.00	A2
		95.30	1.00	A3
			95.20	A4

(y)

A1	A2	A3	A4	
39.00	0.85	0.97	0.82	A1
	33.00	1.15	0.97	A2
		38.00	0.84	A3
			32.00	A4

(z)

A1	A2	A3	A4	
35.00	1.14	1.03	1.06	A1
	40.00	0.90	0.93	A2
		36.00	1.03	A3
			37.00	A4

(aa)

A1	A2	A3	A4	
4.78	1.16	0.93	0.81	A1
	5.56	0.80	0.70	A2
		4.44	0.88	A3
			3.89	A4

(ab)

A1	A2	A3	A4	
0.26	0.96	1.06	1.09	A1
	0.25	1.11	1.13	A2
		0.28	1.02	A3
			0.28	A4

(ac)

A1	A2	A3	A4	
0.16	0.88	5.63	0.88	A1
	0.14	6.43	1.00	A2
		0.90	0.16	A3
			0.14	A4

(ad)

A1	A2	A3	A4	
0.10	0.71	0.97	1.00	A1
	0.07	1.37	1.41	A2
		0.10	1.03	A3
			0.10	A4

(ae)

A1	A2	A3	A4	
39.00	1.08	1.03	1.05	A1
	42.00	0.95	0.98	A2
		40.00	1.03	A3
			41.00	A4

(af)

A1	A2	A3	A4	
0.51	1.12	0.76	0.63	A1
	0.57	0.68	0.56	A2
		0.39	0.82	A3
			0.32	A4

(ag)

A1	A2	A3	A4	
1.60	2.22	1.47	2.22	A1
	3.55	0.66	1.00	A2
		2.35	1.51	A3
			3.55	A4

(ah)

A1	A2	A3	A4	
3.90	1.03	1.10	1.05	A1
	4.00	1.08	1.03	A2
		4.30	0.95	A3
			4.10	A4

(ai)

A1	A2	A3	A4	
3.80	1.32	0.97	0.79	A1
	5.00	0.74	0.60	A2
		3.70	0.81	A3
			3.00	A4

(aj)

A1	A2	A3	A4	
3.80	1.24	0.92	0.79	A1
	4.70	0.74	0.64	A2
		3.50	0.86	A3
			3.00	A4

(ak)

A1	A2	A3	A4	
36.00	0.97	1.00	1.06	A1
	35.00	1.03	1.09	A2
		36.00	1.06	A3
			38.00	A4

(al)

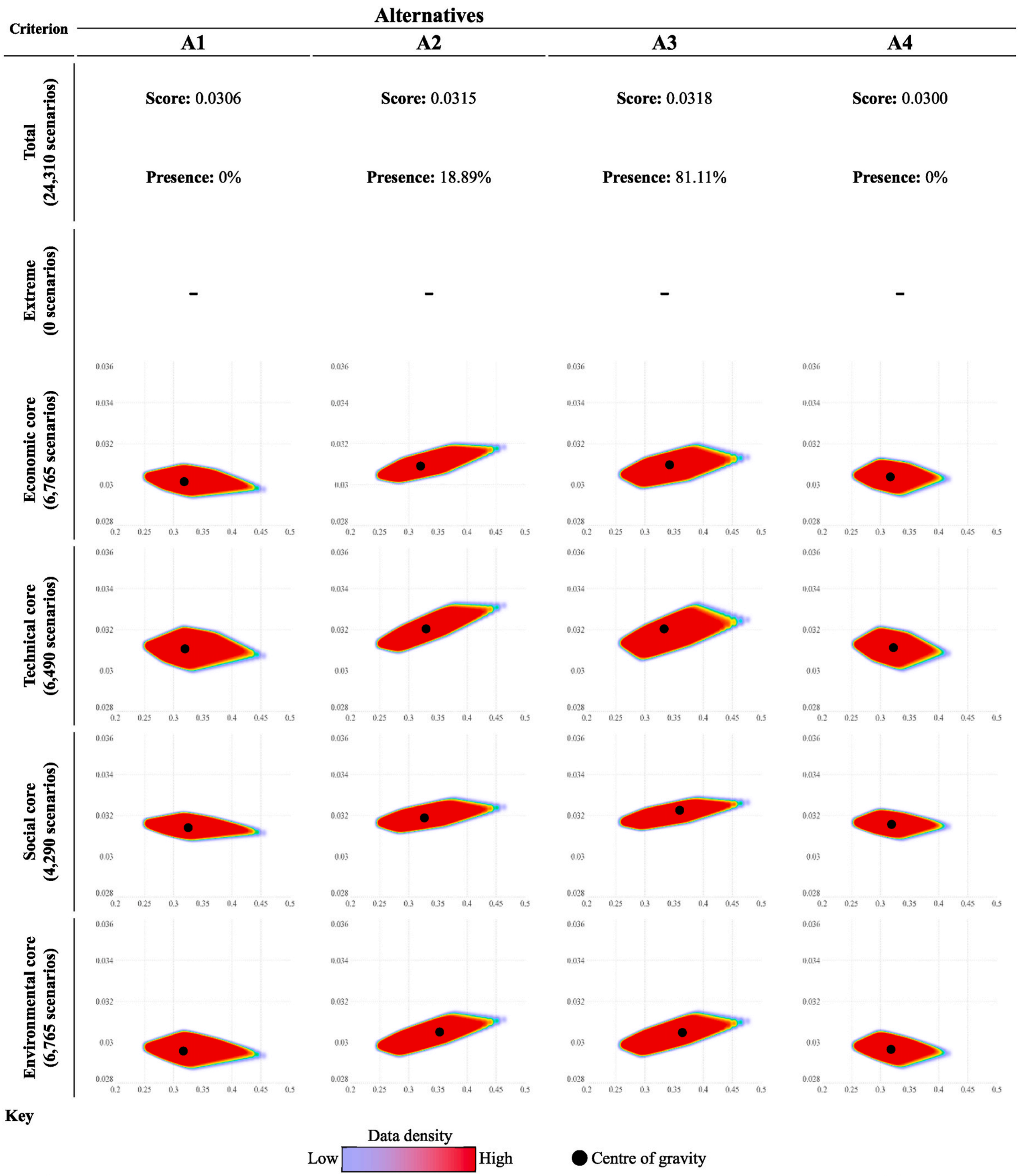
A1	A2	A3	A4	
1.10	0.64	1.09	1.36	A1
	0.70	1.71	2.14	A2
		1.20	1.25	A3
			1.50	A4

(am)

Quantified value | Enhacement | Deficiency | No difference

Fig. 5. Relative scores of each alternative in each index: (a) investment cost, (b) operational cost, (c) future uncertainties, (d) global economy threats, (e) compensations, (f) net present value, (g) return period, (h) operational break-even point, (i) Lack of transparently, (j) natural disasters, (k) shock of wastewater quality, (l) shock of wastewater quantity, (m) operational failure, (n) cyber security, (o) scalability, (p) complexity, (q) site selection, (r) upgradability, (s) required technical staff, (t) participation, (u) local intervention, (v) supports, (w) local market, (x) neighbours, (y) construction safety, (z) operation safety, (aa) task satisfaction, (ab) exposure to pollutants, (ac) monitoring, (ad) land area, (ae) consumed water, (af) habitats, (ag) raw material, (ah) global warming, (ai) eutrophication, (aj) heavy metals, (ak) pathogens, (al) emerging pollutants, (am) sound pollution.

score in internal support (0.208) placed it behind A3. A4, once more, ranked the lowest (0.546), hindered by poor scores in both internal and external engagement and weak performance in risk and safety measures. In the environmental dimension, A3 achieved the highest total score (0.689), with notable strengths in land area conservation (0.097), raw material efficiency (0.072), and pollution reduction across multiple vectors, including microplastics, heavy metals, and eutrophication. In contrast, A4 scored the lowest (0.601), dragged down by high environmental burdens in categories such as consumed water, global warming impact, and risk of emerging pollutants. A2 also



Note: i-core scenarios” refer to those scenarios in which the i-th aspect (e.g., economic, technical, environmental, etc.) is assigned the highest weight among all aspects.
Extreme scenarios are defined as scenarios where a single aspect holds a weight equal to or greater than the combined weight of all other aspects, thereby dominating the decision-making criteria.
The total score represents the average score achieved by each alternative across all scenarios.
Presence refers to the proportion of total scenarios in which a given alternative demonstrates superior performance compared to others.
The X-axis in the graph represents the range of weights, while the Y-axis indicates the corresponding scores obtained. The centre of gravity, shown as a black dot, represents the weighted average position of all data points within the coloured density region. It reflects the average outcome across the distribution, accounting for both axes. The surrounding colour gradient—from red (highest density) to blue (lowest density)—illustrates the data density and confidence regions, where red areas denote the most probable values. The centre of gravity is calculated as the mean of the distribution in both the X and Y directions, weighted by the density at each point.

Fig. 6. Results and score density of each alternative for core scenarios.

underperformed in several sustainability concern indices despite its otherwise strong economic profile.

3.3.3. Optimal answer

Fig. 6 displays the outcome of 24,310 model-generated scenarios evaluating the sustainability of sludge treatment alternatives. The results show that Alternative A3 achieved the highest overall selection frequency, being chosen as the optimal alternative in 81.11 % of all scenarios, with a corresponding average score of 0.0318. Alternative A2 followed, selected in 18.89 % of the cases with a slightly lower score of 0.0315. Alternatives A1 and A4 were effectively ruled out across all scenarios, each with a selection frequency of 0 %, highlighting their consistent underperformance. The heatmaps in Fig. 6 illustrate the density of core scenario outcomes across four key sustainability dimensions. For each dimension, the density distribution is visualised, with darker red indicating a higher concentration of favourable outcomes. The black dots represent the centre of gravity for each alternative in the respective scenario clusters. A3 consistently shows higher density concentration and more favourable positioning across all cores, especially in the social and environmental dimensions.

3.4. Sensitivity analysis

As an output of phase 3, two sensitivity analysis cases were conducted: (1) single elimination of statements and (2) mutual elimination of statements. In the single elimination scenario, where individual statements were removed, five statements were found to be critical (see Fig. 7a): ES2 (Local market for products), ES9 (High tendency to use healthier and recycled products), IS1 (Quality of sludge includes carbon, nitrogen, phosphorus, and organic matter), IS2 (Quality of sludge excludes heavy metals and hazardous materials), and IS7 (Supporting management system). The removal of any of these resulted in a change in the optimal circular action. In the mutual elimination scenario, simultaneous removal of certain internal-external pairs led to shifts in optimal outcomes. Specifically, the pairs (ES11, IS3), (ES11, IS4), (ES12, IS5), and (ES19, IS16) were identified as influential. Fig. 7b presents results from the nature-based elimination test. It was found that eliminating external economic factors and internal staff-related forces independently caused a shift in the optimal circular action. A similar shift was observed when policy-driven external forces and strategy-oriented internal forces were simultaneously removed.

Fig. 7c presents the outcome of the temporal attribution elimination. It shows that when short-term external driving forces are removed, the optimal circular action changes. However, eliminating internal driving forces - regardless of whether they are short-term, mid-term, or long-term - does not impact the selected optimal action. The scenario shifts only when short-term external and short-term internal forces are eliminated together. Fig. 7d shows the results of attribute reclassification, demonstrating that altering the temporal classification of driving forces (either internal or external) can change the optimal circular action. This was observed both when attributes were changed individually (e.g. short-to medium-term) and in combination (e.g. medium-term to long-term). Fig. 7e identifies 18 out of 39 indices that, when weighted more heavily, change the selected sludge treatment alternative. These include indices such as I2 - I4, I6 - I7, I9 - I12, I17, I20, I31, and I35. Conversely, the results also show that decreasing the weight of indices like I1, I8, I19, I36, and I37 can lead to a change in the final decision, highlighting both positive and negative influences.

Fig. 7f presents the influence of stakeholder characteristics on decision outcomes. When expert weights were adjusted by job title, alternative A2 was identified as the best option in 80.84 % of the scenarios, followed by A3 (15.59 %) and A1 (3.57 %). Education and service time had comparatively less impact on the decision outcome. However, service time influenced selection slightly more than education. Overall, when all stakeholder attributes were weighted simultaneously, A2 and A3 shared similar dominance, with 47.51 % and 47.56 % presence, respectively. Fig. 7g compares the alternatives identified as optimal by different scenario analysis methods. All three conventional expert-based approaches, i.e., expert-driven, process-driven, and condition-driven, consistently identified A2 as the best alternative. In contrast, the quantification-driven method and the proposed data-driven framework both selected A3 as the optimal configuration.

4. Discussion

This section interprets and contextualises the quantitative findings reported in the results section. It explains the practical implications of the model outputs, explores how they align with global sludge reuse practices, and identifies key drivers behind the prioritised outcomes. The discussion also draws connections to the study's original objectives, highlights strategic insights for stakeholders, and reflects on the model's broader applicability and resilience under varied conditions. The results of section 3.2.1 demonstrate the complex and multifaceted nature of the strategic decision-making environment in sludge management. The balanced distribution of external threats and opportunities suggests that external conditions offer as many challenges as they do prospects for circular action implementation. Similarly, the near-equal number of strengths and weaknesses within internal factors reflects the dual nature of organisational capacity, while certain internal systems and resources are supportive, others may hinder effective sludge reuse initiatives. This balance underscores the importance of employing an adaptable prioritisation framework that can account for both supportive and inhibiting conditions. These insights are crucial to addressing the first research objective of developing a comprehensive framework capable of integrating varied internal and external influences when selecting optimal circular actions for sludge management.

Section 3.2.2 results reinforce composting as the optimal circular action, owing to its alignment with strengths, opportunities, and mitigated weaknesses in the context of the study. Its versatility, regulatory alignment, and environmental benefits contribute to its high ranking, especially in the case study region, where agricultural reuse is both feasible and desirable.

Importantly, the selection of composting as the top-ranked strategy is not only supported by the model's analytical outcomes but is also consistent with global real-world sludge management trends, thereby reinforcing the validity of the proposed framework. For instance, as noted earlier in the introduction, the latest data from the U.S. EPA (EPA, 2023) indicate that approximately 60 % of wastewater sludge in the United States is applied on land - often in the form of composted biosolids - for agricultural, forestry, and landscaping purposes. Similarly, in the European Union, land application remains the dominant pathway for sludge reuse, accounting for 40–50 % of total sludge utilisation in recent years (Domini et al., 2022; Feng et al., 2023). Many EU member states actively promote composting and agricultural recycling due to their alignment with circular economy goals and soil enhancement benefits. This consistency between model output and international sludge reuse practices serves as a form of indirect validation for the prioritised circular action in this study. It suggests that the framework demonstrates potential for generalisability and practical alignment with industry preferences and policy directions in other regions. Future work may extend this validation by directly incorporating stakeholder feedback or comparing outcomes with retrospective case data to further strengthen the empirical grounding of the model.

The strong performance of road pavement and concrete block alternatives reflects their relative technical and economic viability, particularly under moderate and satisfactory scenario conditions. In contrast, the underperformance of incineration-based options, especially for bricks and ceramics, can be attributed to several factors. These options often involve high energy demands, stricter emissions controls, limited local acceptance, and weaker alignment with sustainability indicators. Clay-based pipelines also scored poorly, potentially due to technical and regulatory complexities, as well as logistical limitations in

Internal driving force (columns) × **External driving force** (rows)

	IS1	IS2	IS3	IS4	IS5	IS6	IS7	IS8	IS9	IS10	IS11	IS12	IS13	IS14	IS15	IS16	IS17	
ES1																		
ES2																		RC
ES3																		
ES4																		
ES5																		
ES6																		
ES7																		
ES8																		
ES9																		RP
ES10																		
ES11			RP	RC														
ES12					RP													
ES13																		
ES14																		
ES15																		
ES16																		
ES17																		
ES18																		
ES19																SL		
ES20																		
	RC	RP					RC											

(a)

Internal driving force (columns) × **External driving force** (rows)

	Strategy	Structure	System	Shared value	Skill	Style	Staff	
Policy	CP							
Economic								RP
Social								
Technical								
Envirnment								
Legal								
							RC	

(b)

Internal driving force (columns) × **External driving force** (rows)

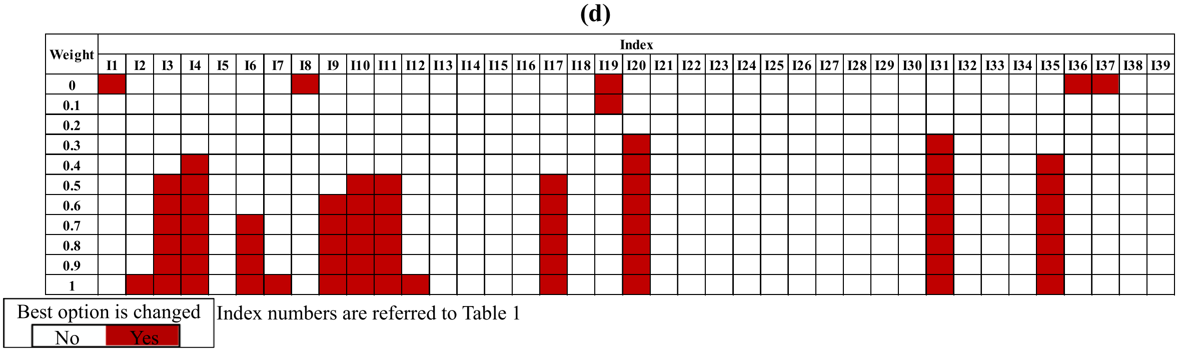
	Short-term	Mid-term	Long-term	
Short-term	IC			RC
Mid-term				
Long-term				

(c)

Internal driving force (columns) × **External driving force** (rows)

	S to M	S to L	M to L	L to S	L to M	M to S	
S to M	RP	RP					RP
S to L							IB
M to L							
L to S				CP			
L to M						RC	RC
M to S						RC	RC
	RP	RP				RC	

(d)



(e)

Weighting part		Alternative A1	A2	A3	A4
Education	Score	0.0303	0.0308	0.0316	0.299
	Presence (%)	0	21.52	78.48	0
Job title	Score	0.0307	0.0309	0.0307	0.0301
	Presence (%)	3.57	80.84	15.59	0
Service time	Score	0.0274	0.0283	0.0287	0.0254
	Presence (%)	12.34	19.27	68.39	0
All	Score	0.0239	0.0259	0.0256	0.218
	Presence (%)	4.93	47.51	47.56	0

(f)

Method	Best identified alternative A1	A2	A3	A4
Expert driven		✓		
Process driven		✓		
Condition driven		✓		
Quantification driven			✓	
Data driven - Proposed			✓	

(g)

Fig. 7. Sensitivity analysis on the result of: (a) Driving force elimination – based on 370 runs, (b) Nature elimination-based on 54 runs, (c) Temporal attribute elimination-based on 15 runs, (d) Attribute reclassification – based on 48 runs, (e) indices weights in changing the best option - based on 390 runs, (f) the weight of experts on the best answer, (g) comparison between scenario analysis of proposed method and conventional expert-based scenario analysis.

production and deployment. These insights support the framework's ability to filter out less viable options and justify its focus on multi-functional, scalable, and context-sensitive alternatives, fulfilling the second research objective related to identifying and mapping suitable sludge treatment actions.

According to section 3.3.1, the comparison across multiple indices reveals that each alternative demonstrates both strengths and weaknesses depending on the evaluation dimension. This supports the notion that sustainability in sludge treatment is inherently multi-dimensional, requiring a comprehensive approach rather than reliance on any single indicator. The variation in dominance among alternatives (e.g., A4 for investment cost and A2 for operational cost) underscores the need for an integrated decision-making framework - one that accounts for trade-offs and prioritises overall balance across economic, technical, environmental, and social criteria. These findings reinforce the study's second research objective by illustrating the complexity of assessing and selecting optimal treatment alternatives under diverse conditions and metrics.

The findings of section 3.3.2 confirm that A3 is the most robust and balanced alternative in terms of overall sustainability, particularly excelling in technical reliability, stakeholder alignment, and environmental protection. Its strong performance likely stems from the synergy of its treatment processes, which enhance operational stability, resource efficiency, and risk reduction. In contrast, A4 consistently underperforms across all criteria except for resistance in the technical dimension. This suggests that while A4 may be resilient to shocks, its greater complexity, maintenance burden, and stakeholder challenges reduce its overall desirability. Alternative A2 emerges as the most financially efficient option due to its low capital and operational costs and higher revenue-generating potential. However, it shows limitations in resistance. In the social domain, A2 leads in external stakeholder engagement, but A3 surpasses it overall due to better internal management and institutional support. Environmentally, A4 performs particularly poorly due to elevated impacts related to pollutants and resource consumption, solidifying its classification as the least sustainable option. These results support the framework's ability to capture multi-criteria trade-offs and justify the prioritisation of alternatives like A3 that provide strong cross-dimensional performance-aligning with the study's second and third research objectives.

According to section 3.3.3, the clear dominance of A3 across the majority of scenarios confirms its status as the most sustainable and resilient sludge treatment alternative within this study's decision-making framework. The significant presence rate of 81.11 % not only supports its robustness under a wide array of conditions but also reflects its strong performance across all criteria categories. A3's ability to maintain consistent scores under multiple weighting combinations, without reliance on extreme or isolated factors, further reinforces its strategic viability for composting-based sludge reuse. The marginal competitiveness of A2, particularly in economic and technical core scenarios, suggests that while A2 may offer financial and operational advantages in some contexts, its social and environmental performance does not match that of A3. This aligns with earlier findings where A2 excelled in cost-related indices but fell behind in stakeholder engagement and ecological safety.

The fact that no extreme scenario—where a single aspect was given a weight equal to or greater than the combined weight of all other aspects—resulted in the dominance of any one criterion further validates the model's capacity to maintain a balanced, multi-criteria perspective. This outcome suggests that the framework does not disproportionately favour any individual aspect, even under highly skewed weighting conditions. Instead, it confirms that the alternatives were evaluated through a robust and integrated lens, reinforcing the credibility of the prioritised solutions and the sensitivity-resilient nature of the model. This analysis aligns with and reinforces the third research objective by demonstrating A3's consistent performance and ability to remain optimal even as criterion weightings and contextual assumptions vary.

The sensitivity analysis (section 3.4) demonstrates the significant role of both individual and combined driving forces in shaping circular action prioritisation. The five critical statements identified in the single elimination test highlight the importance of product market availability, public preference for recycled products, and sludge quality in strategic planning. These factors directly relate to the study's first and second research objectives, as they influence both the feasibility and sustainability of specific circular actions. The mutual elimination results suggest that some internal and external factors, though non-critical in isolation, can substantially influence outcomes when interacting. For example, the combination of operational experience (IS3, IS4, IS5) and external contextual enablers (ES11, ES12, ES19) reflects the intertwined nature of infrastructure readiness and local socio-economic context. This underscores the need for holistic frameworks that do not treat factors in isolation. The nature of elimination findings further affirms that economic and workforce-related factors are core to resilient sludge management planning. Economic viability and strategic regulatory alignment are essential not only for short-term adoption but also for long-term success and institutionalisation, aligning with the third research objective regarding future-proofing the selected strategies under varying conditions.

The findings from the temporal attribution analysis indicate that short-term external factors - such as volatile market conditions or regulatory transitions, have a disproportionately high impact on strategic sludge reuse planning. Although internal factors may not shift the decision independently, their short-term nature appears to amplify the volatility introduced by short-term external elements. This suggests that decision-makers must pay close attention to short-lived external influences, especially when internal readiness is also short-term. The attribute reclassification sensitivity underscores the dynamic nature of strategic planning. It confirms that the classification of drivers into short-, mid, or long-term significantly affects the final recommendation. Hence, routine updates to the classification of driving forces are necessary. Strategically, upgrading positive internal statements from medium-to long-term enhances stability, while adjusting negative ones to shorter terms can contain their impact. Similarly, converting external positive drivers to long-term status strengthens their benefit, and downgrading negative ones limits harm. Finally, the index weight sensitivity highlights that decision outcomes are highly dependent on the importance placed on specific indicators, particularly those tied to cost efficiency, operational resilience, and environmental responsibility. This demonstrates the non-linear sensitivity of the model to certain variables and justifies the need for adaptable weight assignments over time. Failure to account for such evolving priorities could lead to suboptimal or outdated sludge treatment decisions, particularly under dynamic environmental, economic, or technological conditions.

The results in Fig. 6f highlight that expert background, particularly job title, substantially affects the selection of the optimal sludge treatment alternative. This suggests that domain-specific roles bring unique perspectives and criteria to the evaluation process. While education and service time contribute less, their combined effects with job title illustrate the value of a diverse and experienced expert panel in minimising bias. It becomes evident that stakeholder weighting is not merely a procedural formality but a crucial element influencing the robustness of the outcome. In Fig. 6g, the comparison between conventional expert-based methods and data-driven techniques reveals an important divergence. The agreement among expert, process-, and condition-driven methods on A2 likely reflects their alignment with traditional decision heuristics and real-world operational familiarity. However, the fact that both the quantification-driven and data-driven models select A3 points to the hidden strengths of data-centric analysis in revealing trade-offs that conventional frameworks may overlook. This reinforces the value of incorporating computational methods for greater objectivity. Nonetheless, without real-world implementation or retrospective validation against historical data, no method's outcome can be considered conclusive. Therefore, future work should explore empirical testing to validate model predictions and enhance stakeholder confidence in data-driven decisions.

These findings reveal that the proposed framework offers more than an academic exercise - it provides a structured, adaptable decision-support tool that can be translated into policy instruments, operational strategies, and planning guidelines. Its phased and modular architecture enables policymakers to embed the methodology within national or regional sludge management plans, sustainability roadmaps, and circular economy strategies. Specifically, the prioritisation logic and multi-criteria sustainability assessment can be codified into policy guidance documents, technical standards (e.g., biosolids reuse protocols), procurement criteria for sludge treatment technologies, or environmental compliance checklists. For urban planners and regulatory bodies, the framework provides a defensible basis for permitting decisions and investment prioritisation, particularly in evaluating sludge reuse options against socio-environmental constraints. Moreover, the framework supports a broad spectrum of stakeholders. Plant managers and process engineers can utilise the detailed alternative evaluation and scenario analyses to guide technology selection, infrastructure upgrades, and risk mitigation planning. For urban authorities and public agencies, the model offers a transparent mechanism for stakeholder engagement and participatory decision-making, as it highlights which criteria (economic, technical, social, or environmental) most influence long-term viability. The adaptability of the framework also makes it suitable for development organisations working in resource-constrained contexts, as its core structure can be modified to reflect local limitations in capacity, regulation, or finance. In this way, the research not only advances sludge treatment science but also delivers a flexible, evidence-based foundation for real-world policy development, operational optimisation, and strategic planning.

5. Conclusions

This paper presented a novel data-driven sustainable framework for multi-function circular sludge management in WWTPs. The method integrates the identification of potential circular actions for sludge reuse, their prioritisation using an enhanced multi-label 3D SWOT approach, the selection of optimal sludge treatment alternatives, and the subsequent sustainability assessment of these alternatives using a data-driven MCDM approach. Also, uncertainty and sensitivity analysis are applied for both strategic and MCDM phases. The methodology is demonstrated through its application to a case study, and key findings from the analysis are as follows.

- Composting for agriculture was identified as the best option (Obtained 65.40 % of the maximum possible score), followed by road pavement (46.36 %), sanitised landfill (20.81 %), and concrete paving blocks (11.62 %). In contrast, incineration for ceramics or bricks and clay-based pipelines scored negatively.
- Eliminating individual driving forces, such as the local market for products or the quality of sludge, can independently change the optimal circular action. Besides, pairing of local experience is available for running methods with quantity of wastewater is high, altering the optimal circular action, highlighting the critical impact of their interactions.
- Nature elimination reveals that removing external economic factors and internal staff-related factors can shift the optimal circular action, and that eliminating policy-driven external and strategy-oriented internal factors together further influences the decision.
- Temporal attribute elimination shows that short-term external factors are critical in altering the optimal action, while internal temporal factors alone have little impact; however, their combined removal does change the strategic outcome.
- Attribute reclassification reveals that the framework is highly sensitive to shifts in driving force attributes. Reclassifying positive internal factors from medium-to long-term enhances stability, while converting negative internal factors from long-to short-term mitigates adverse effects. Similarly, adjusting the temporal attributes of external factors can further optimise the circular action.
- The final data-driven sustainability assessment shows that, across 24,310 scenarios, Alternative A3 (dissolved air flotation, anaerobic digestion, pressurised strip filters) is the best option. Composting emerged as the optimal alternative in 81.11 % of the scenarios, with a normalised score of 0.318. In the remaining 18.89 % of cases, Alternative A2 was preferred, achieving a comparatively close normalised score of 0.300.
- Variations in index weights can significantly shift the optimal alternative, as 18 indices, covering aspects like operational cost (0.076 for both A3 and A4, which is sensitive to changes), are highly influential. Meanwhile, stakeholder influence, particularly expert job title, strongly affects decision outcomes, causing A2 to be the best option in most scenarios (where 0.0315 and 0.0318 for A2 and A3, respectively, were converted to 0.0309 and 0.0307) while education and service time have a smaller impact.
- The proposed framework serves as a practical decision-support tool that can guide policy development, operational planning, and investment decisions in WWTP sludge management. It can be adapted into policy documents, technical standards, and procurement criteria, while supporting diverse stakeholders - including engineers, planners, and regulators - in selecting sustainable circular actions and engaging in transparent, data-informed decision-making.

Despite the strengths of the proposed data-driven framework for sustainable and multifunctional circular sludge management, several limitations must be acknowledged, which also offer pathways for future enhancement. Although statistical tools were used to minimise bias, the framework still relies partially on expert-defined boundaries and judgments, particularly during the identification and classification of driving forces, the weighting of sustainability indices, and the prioritisation of circular actions. This introduces a degree of subjectivity and variability, which can influence outcomes depending on the perspectives of involved stakeholders. Another limitation is the computational intensity associated with evaluating thousands of alternative scenarios. This presents a practical barrier for small or resource-constrained utilities, which may lack the technical infrastructure or expertise required to run such simulations efficiently. To enhance scalability and broader applicability, future research should explore integrating the framework with big data platforms, API-based data pipelines, and remote sensing technologies to support real-time monitoring, automated updates, and adaptive decision-making. On the other hand, the current study lies in the assumption that all scenarios are equally probable and that uncertainty is solely captured through variations in weight distributions across aspects. While this assumption simplifies analysis and ensures an unbiased comparison, it does not account for the fact that, in real-world decision-making, certain scenarios may occur more frequently or be more plausible than others. As a future extension, incorporating scenario-specific probabilities into the decision model could enhance its realism and provide a more refined evaluation of alternative strategies. This probabilistic weighting would allow decision-makers to prioritise solutions not only based on performance under different conditions but also based on the likelihood of those conditions occurring, thereby strengthening the practical applicability of the framework. Finally, while the current framework relies on a deterministic structure based on predefined weight distributions, future research could benefit from the incorporation of probabilistic modelling techniques. Specifically, the use of Monte Carlo simulations or bootstrapping methods would allow for the estimation of confidence intervals and statistical significance of outcomes. This would enhance the interpretability and robustness of the model by quantifying uncertainty and offering confidence-based assessments for decision-makers.

CRediT authorship contribution statement

Arghavan Panahi: Writing – original draft, Formal analysis, Conceptualization. **Vahid Bakhtiari:** Writing – original draft, Methodology, Formal analysis. **Farzad Piadeh:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Kourosh Behzadian:** Writing – review & editing, Validation.

Declaration of competing interest

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

Appendix

Table A1
Definition of Scenarios for Strategic Planning in Circular Sludge Management* (inspired by Piadeh et al., 2018; Naghedi et al., 2020)

Scenario name	Description
Difficult situation	Regulations related to sludge management from Water and Wastewater Company (WWC) and Regional Water Company (RWC) are unclear or inconsistently enforced. Private sector engagement is minimal due to the absence of clear financial incentives. Public and governmental interest in circular sludge management is limited, and the role of non-governmental organisations (NGOs) remains marginal and ineffective.
Poor situation	The WWC, RWC, and private companies focus primarily on cost minimisation and short-term operational goals rather than long-term, sustainable sludge management practices. Although NGOs attempt to advocate for circular strategies, they struggle to raise sufficient awareness or influence policy. Public participation remains low due to inadequate institutional support, despite slightly improved knowledge levels.
Transition situation	WWC and RWC begin allocating more resources and attention to sustainable sludge management, including piloting circular alternatives. NGOs and private firms gain a more active role in influencing policy and proposing innovative treatment solutions. Growing public awareness and moderate government support facilitate initial progress toward circularity in sludge practices.
Satisfied situation	WWC and RWC actively support and invest in circular sludge management strategies. NGOs and private companies contribute to driving innovation, policy shifts, and economic opportunities within the sludge sector. Government initiatives prioritise public awareness, stakeholder engagement, and integrated infrastructure planning.
Ideal situation	The WWC and RWC fully endorse and implement circular sludge management principles. Private sector investments and NGO advocacy are aligned with national environmental goals, significantly increasing public involvement and political will. This alignment accelerates the mainstream adoption of sustainable sludge treatment and reuse strategies across Tehran.

Table A2
Considerations for weight and constitution of different experts (inspired by Piadeh et al., 2018)

Classification	No.	Score
1. Job position		
• Consultant (manager and professional designer)	6	1
• Low-level decision-maker (e.g., Iran's Department of Environment)	2	2
• Mid-level decision-maker (e.g., Iran Water Resources Management Company, National Water and Wastewater Engineering Company of Iran, and Ministry of Energy)	4	2.5
• High-level decision-maker (e.g., Tehran Province Water and Wastewater Company, Tehran Municipality, and Tehran Regional Water Company)	6	3
• University boards		
- Assistant professor	3	2
- Associated professor	3	2.5
- Professor	3	3
2. Educational level		
• Diploma or lower	3	1
• B.Sc.	3	2
• M.Sc.	5	2.5
• Ph.D.	16	3
3. Professional experience		
<10 years	9	1
>10 years	18	2

Table A3
Recommended list of indices for sustainability assessment of multi-function sludge treatment alternatives

Indices	Code	Covered concern and description	Type*	Unit**	Inspired reference
Economic	C1				
Cost	S1.1				
Capex	I1	High lumpsum e.g. initial infrastructure, technology, and operational expenses for establishing alternative in the site impacts on feasibility of the project	N	$\frac{10^3\text{US\$ 2024}}{\text{kg WTS}}$	Turkson et al. (2020)
Opex	I2	Minimising ongoing expenses e.g. ongoing expenses such as energy, labour, maintenance, consumables, and chemicals to operate the project sustainable	N	$\frac{10^3\text{US\$ 2024}}{\text{kg DTS}}$	Twagirayezu et al., 2024

(continued on next page)

Table A3 (*continued*)

Indices	Code	Covered concern and description	Type*	Unit**	Inspired reference
Uncertainties in future ongoing cost	I3	Flexible budgeting and cost evaluations adapt to changing markets. Energy bills or labour strikes vary with unseen inflation or economic crisis	N	Qualitative	Proposed
Global economy threats	I4	Local expertise is essential for independent design and operations. Proposed alternative may face sanctions, resource limitation or politic race	N	US$ 2024 in local economy / US$ 2024 total cost	Proposed
Compensation	I5	Compensation policies can reduce the intensive costs. Includes loans, grants, industrial funds, research funds, or seed funds	N	US$ 2024 / US$ 2024 total cost	Proposed
Income	S1.2				
Net present value	I6	Profitability of investors over a project's lifespan	P	10^3US$ 2024 / kg WTS	Castelazo and Azapagic (2014)
Return period	I7	Time to recover initial investments through revenue or savings	P	Years	Pires et al. (2017)
Break-even point	I8	Minimum required product for economic justification of alternative	N	Ton treated sludge	Da Silva et al. (2020)
Transparency/ Corruption	I9	Market uncertainties stem from supporting/against regulations and public perception	N	Historical hidden costs / kg WTS	Proposed
Technical	C2				
Resistance	S2.1				
Natural disaster	I10	Maintain performance during natural disasters such as flooding, fire, drought, earthquake, and storm	P	Qualitative	Girotto et al. (2024)
Quality shock	I11	Adapt to sudden wastewater quality change	P	Qualitative	Taheri et al. (2025)
Quantity shock	I12	Adapt to sudden hydraulic load shocks raised by unseen discharge/ connections	P	Qualitative	Singh et al. (2020)
Operational failure	I13	Operational failures like blockages or outages	P	Qualitative	Firmansyah et al. (2021)
Cyber security	I14	Level of vulnerability to cyber attacks	P	Qualitative	Proposed
Maturity	S2.2				
Scalability	I15	Level of generalisability across diverse facilities and contexts	P	Qualitative	Ren and Lützen (2017)
Complexity	I16	System complexity necessitates advanced expertise and more monitoring for optimisation	N	Qualitative	Tarpani and Azapagic (2023)
Site selection	I17	Total covered area of treatment processes and location of circular initiative. Minimising results in reduction of environmental and public health risks	P	Km^2	Proposed
Upgradability	I18	Accommodating advanced technologies over time without re-operationalisation	P	Qualitative	Liew et al. (2023)
Technical staff	I19	Low number of skilled technical staff reduce errors and improve management efficiency	P	Annual required staff / kg DTS	Sun et al. (2020)
Social	C3				
External stakeholders	S3.1				
Participation	I20	High participation boosts job creation and public awareness and promotes collaborative and effective management practices.	P	External participant / Total managmeent team	Piadeh et al. (2020)
Local intervention	I21	Harmful interventions and negative forces against the project that can increase costs and enforcement challenges	N	External participant / Total managmeent team	Proposed
Supports	I22	Collaborative local, reginal, national, and international supports	P	Institutional documents / Total managmeent team	Proposed
Local market	I23	Community engagement for economic opportunities and acceptance	P	Qualitative	Proposed
Neighbours impact	I24	Odour/noise control and community well-being near treatment facilities	N	Qualitative	Proposed
Internal stakeholders	S3.2				
Construction safety)	I25	Construction events may impact public opinion negatively	N	%	Martín et al. (2017)
Operation safety	I26	Mitigation of occupational and environmental risks	N	%	Castillo et al. (2017)
Task satisfaction	I27	Improving task performance and motivation based on survey of current projects	P	Satisfied persons / Total managmeent team	Bakhtiari et al. (2024)
Pollutants exposure	I28	Risk of leachate substances during process.		%	Namavar et al. (2023)
Monitoring	I29	Higher value increases the errors and requires more regulatory compliance	N	min / Day	Khan and Kabir et al. (2020)
Environmental aspect	C4				
Natural resources	S4.1				
Land occupation	I30	Preserving natural land and resources	N	10^3m^2	Yoshida et al. (2018)
Water consumption	I31	Water usage in lifecycle of the project	N	10^3m^3 / kg WTS	Laura et al. (2020)
Habitats threats	I32	Impacts on neighboured habitats including terrestrial, aquatic, or urban animals and vegetation	N	Qualitative	Proposed
Raw material consumption	I33	Maintaining usage of virgin natural resources.	N	Ton / kg WTS	Sabet et al. (2025)
Sustainability concerns	S4.2				
Global warming potential	I34	Greenhouse gas emissions including embodied and operation carbon during lifespan of the project	N	kg CO_2 / kg DTS	Ahmadi et al. (2025)
Eutrophication risk	I35	Nutrient leakage during processes and transferring the product	N	kg N&P / kg DTS	Proposed
Heavy metals risk	I36	Heavy metal leakage during processes and transferring the product	N	kg / kg DTS	Proposed
Pathogens	I37	Pathogen leakage during processes and transferring the product	N	CFU / kg DTS	Proposed
Emerging pollutants	I38	Microplastic and Pharmaceutical personal care leakage during processes and transferring the product	N	g / kg DTS	Proposed
Sound pollution	I39	Disruptive impacts on wildlife and staff	N	dB / dB base ambient	Molinos-Senante et al. (2014)

*N: Negative P: Positive.
**DTS:Daily Treated Sludge WTS: Whole life Treated Sludge.

Table A4
Identified external driving forces for circular actions of STWWTP sludge

Identified external driving forces	Code	Potential circular action*							Nature**						Attribute+		
		SL	CA	IB	RC	CP	IC	CB	Po	Ec	So	Te	En	Le	S	M	L
Relation between water company and neighbour stakeholders	ES1		T	T	O	O					*					*	
Local market for products	ES2		O	T	O	T	O	O		*					*		
Loading/discharging soil pollutants	ES3	T	O	O	O		O		*				*	*	*		
Loading/discharging air pollutants	ES4	T	T	T			T	T			*		*		*		
Loading/discharging water pollutants	ES5	T	T								*		*		*		
Biodiversity/habitat	ES6	T	O					O					*		*		
Governmental funds can be allocated for start-up	ES7			O		O	O	O		*				*	*		
Climatic characteristics includes high sun radiation, low rainfall, relatively high wind	ES8	O	O					O					*		*		
High tendency to use healthier and recycled products	ES9		O	T			T	T			*						*
Investors are ready to share the creation experience	ES10		O	O				O			*					*	
Local experience is available for running method	ES11	O	O	T		O	T	T				*			*		
Crowdfunding and operation are available in some methods	ES12	O	O		O					*		*			*		
International market for product	ES13		O		O				*	*							*
Clear regulations and standards	ES14	O	T	O	T	T	T	T	*				*	*			*
Sensitivity on production/transfer by DoE and Health minister	ES15	T	T	T				T	*				*	*			*
Groundwater level is not high and is very sensitive to any potential risks	ES16	O	T		O								*				*
The economic level of the region is not good enough to invest on something new	ES17				T	T	T	T		*							*
Relation between water company and international stakeholders	ES18			T	T				*			*					*
Lack of access to water, fuel, and energy sources in all time	ES19	O	O	T	O	T	T	T		*		*				*	
Availability of good access and road mobilities	ES20	O	O		T					*						*	

++: statement type: O: Opportunity T: Threat.
*Circular action: SL: Landfill CA: Compost IB: Brick RP: Road pavement CP: Concrete IC: Ceramics CB: Pipelines.
**PESTEL aspect: Po: Political Ec: Economic So: Social Te: Technological En: Environmental Le: Legal.
+Attribute type: S: Short-term M: Mid-term L: Long-term.

Table A5
Identified internal driving forces for circular actions of STWWTP sludge

Identified internal driving forces	Code	Potential circular action*							Nature**							Attribute+		
		SL	CA	IB	RC	CP	IC	CB	S1	S2	S3	S4	S5	S6	S7	S	M	L
Quality of sludge includes carbon, nitrogen, phosphorus, and organic matter	IS1		S	S		W	W	W			*					*		
Quality of sludge excludes heavy metals and hazardous materials	IS2	S	S	S		S	S	S			*						*	
Quantity of wastewater is high	IS3	W	S	S	S	S	S	S			*							*
Level of wastewater treatment facilities are conventional but there is chance for upgrading	IS4		S	S	S	S	S	S			*							*
Company knowledge and experiences for internal running and operation	IS5	S	S	W	W	W	W	W					*		*		*	
Ability to obtain special privileges/funds	IS6	S	S		S	S			*	*								*
Supporting management system	IS7		S	W	S	W	W	W	*					*	*			*
Level of negotiation and agreement	IS8		S	S	S							*	*		*			*
Financial resource mobility	IS9		W	W				W	*								*	
System thinking/integral management	IS10		S	W	W	S	W	W		*					*			*
Trust to external stakeholders	IS11	S	W	W	S	S	W		*			*		*				*
Providing physical requirements such as space	IS12	W	W	W	S	S		W			*						*	
Tendency to least responsibility	IS13	W	W	W	S	S	S	W	*			*						*
Rejecting responsibilities beyond the zone of company	IS14	W	W	W	S	S	W	W		*								*
Depending on province company and ministry of power	IS15	S	S	W	S	S	W	S		*								*
Political management system rather than knowledge	IS16	S	S	W	W	W				*				*				*
Short-term achievement is welcome	IS17		S	W	S	W	W	W	*			*				*		

++: statement type: W: Weakness S: Strength.
*Circular action: SL: Landfill CA: Compost IB: Brick RP: Road pavement CP: Concrete IC: Ceramics CB: Pipelines.
**McKinsey 7S aspect: S1: Strategy S2: Structure S3: Systems S4: Shared Values S5: Skills S6: Style S7: Staff.
+Attribute type: S: Short-term M: Mid-term L: Long-term.

Data availability

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

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