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Research Article

Intelligent Sludge Management in Urban Water Treatment Facilities: A Sustainable Decision-Making Framework Informed by Industrial Ecology Principles

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Abstract

Within the context of urban infrastructure, this study presents a sustainable decision-making framework designed for the efficient management of sludge in water treatment facilities. The framework is comprised of various integral components, incorporating statistical computations for precise sludge production assessment and an exhaustive evaluation of water treatment plant (WTP) efficiency, rooted in a historical analysis. A comprehensive database was first established, drawing on pertinent literature that classifies construction materials applicable to WTP sludge, while prioritizing primary criteria from economic and environmental standpoints. Further, a collection of secondary indicators, encompassing factors such as operational ease, durability, product quality, and safety indices, were aggregated from diverse construction products. To streamline the decision-making process, a blend of three multi-criteria decision-making (MCDM) techniques was deployed, including the Analytic Hierarchy Process (AHP), the Order of Preference by Similarity to Ideal Solution (TOPSIS), and Ordered Weighted Averaging (OWA). Additionally, this study integrates a rigorous appraisal based on Porter's Five Forces (PFF) methodology, employing a combination of questionnaires and descriptive statistical analysis to construct a comprehensive conceptual model. The findings underscore the adaptability of the proposed framework, showcasing its efficacy in facilitating intelligent scheduling and adept management of water treatment sludge. Notably, the framework is designed to encompass the principles of industrial ecology and account for eco-environmental considerations, thereby presenting a holistic approach to sustainable sludge management within the realm of urban water treatment.

Keywords: Circular economy; Urban management; Green technology; Multi-criteria decision-making (MCDM); Porter's Five Forces (PFF); Economic Assessment

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INTRODUCTION

Urbanization has led to a significant surge in the global urban population, particularly prominent in developing nations, where an anticipated influx of approximately 2.1 billion people is expected to reside in urban regions by 2030 [1,2]. Consequently, the demand for water and its associated byproducts in treatment plants has surged in direct correlation with population growth and escalating waste levels [3]. The treatment processes yield a residual substance, commonly known as sludge, which typically manifests as a slurry or semi-solid residue necessitating additional processing before proper disposal can be carried out. Depending on the specific local context, this resultant sludge can either undergo direct or indirect reuse [4].

Effluent treatment currently stands as a significant global challenge, demanding meticulous disposal, treatment, and management strategies [5]. Within sludge lie a host of noxious pollutants, comprising pathogens, hazardous metals, and specific organic compounds, capable of inflicting substantial harm upon ecosystems [1]. The presence of heavy metals like Pb, Cr, and Zn, alongside persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs), significantly restricts the viable disposal options for wastewater treatment sludge. Hence, it becomes imperative to exercise precautionary measures, particularly in delineating thresholds for potential contaminants and pollutants that pose threats to both ecological integrity and human well-being [6].

Disposal of excess sludge remains a significant environmental concern in water treatment, often involving the discharge of water into rivers or the deposition of solid waste in landfills [3]. This challenge is compounded by the global issue of dwindling landfill space, particularly in large urban centers. Inappropriate sludge disposal poses a grave environmental risk, leading to substantial alterations in the physical and chemical attributes of adjacent soil, resulting in morphological changes. Vegetation in recipient soils has reportedly suffered from nutritional deficiencies and stunted growth as a result. The high viscosity of sludge often leads to its accumulation within soil pores, forming a persistent layer across the terrain. With a moisture content nearing 98 percent, water treatment sludge possesses excessive dampness, falling short of the preferred moisture content of less than 60% for disposal in landfills and construction applications [7]. Researchers have explored the potential utilization of Water Treatment Sludge (WTS) in the construction sector, considering factors such as moisture content, contamination levels, and socioeconomic considerations [8]. However, the energy-intensive nature of the drying process occasionally diminishes its perceived efficiency.

Embedded within a nation's development blueprint is the strategic incorporation of the circular economy (CE) concept on a global scale. The circular economy, defined as a system that minimizes waste generation while preserving the economic value of goods, materials, and resources through technical cycles and biological separations, underscores the importance of monitoring non-renewable resource reserves [9, 10]. The technical cycle focuses on reclaiming materials that have been previously utilized. In its essence, the circular economy mandates an understanding of the intricate interplay between the environment, the economy, and society, enabling a targeted approach toward maximizing efficiency [11].

The wastewater sector is increasingly embracing the principles of the circular economy to curtail resource loss and extend system longevity [7]. Nonetheless, implementing the CE concept with the WTS remains a challenge, given the potential variation in the chemical and physical properties of sludge across different water treatment plants and even within a single plant over time, necessitating comprehensive large-scale characterization efforts [12]. Nevertheless, to foster a cyclical approach to managing water and sludge resources, the adoption of municipal water reuse has been proposed, addressing diverse water supply needs such as agricultural irrigation and urban landscaping [13].

With the advancement of industrialization and the accelerating pace of urbanization in developed nations, the effective management and recycling of the WTS have emerged as pivotal concerns in water resource management. The sludge treatment phase involves thickening and volume reduction, thereby curtailing ancillary costs associated with its disposal as waste. Notwithstanding the comprehensive steps undertaken at the treatment plant, a profound understanding of water volume remains imperative. Accurate volume prediction holds significant sway over the overall performance of the treatment plant [14]. The residual byproducts find diverse applications within the construction industry, thus underscoring the critical need to estimate and regulate effluent quantities, both for the design of distinct treatment plant units and for subsequent post-treatment utilization. In light of the varying composition of wastewater during the treatment process, quantitatively estimating the volume of WTS poses a considerable challenge, given the inherent uncertainties and temporal dynamics associated with the treatment stages [15].

In essence, the complex challenges arising from rapid urbanization and industrial expansion underline the critical necessity for robust, sustainable management approaches to tackle the complexities associated with water treatment sludge. Emphasizing the intricate interplay between environmental sustainability, technological progress, and economic feasibility, the adoption of circular economy principles emerges as a promising pathway for addressing the multifaceted issues linked with sludge management. This calls for a comprehensive understanding of the nuanced interrelationships among sludge properties, treatment procedures, and potential environmental ramifications. Furthermore, the demand for innovative strategies for sludge handling and reutilization underscores the need for continuous research and development, fostering enhanced interdisciplinary collaboration to steer the trajectory of water treatment systems toward a more resilient and sustainable future. In this regard, the current study endeavours to achieve the following objectives:

- Conduct statistical analyses of sludge production and evaluate the efficiency of water treatment plants (WTP) through a historical analysis of the case study.
- Systematically categorize relevant literature on WTP sludge applications in construction materials for a comprehensive meta-analysis, compiling them as primary data.
- Extract key criteria, including economic, environmental, operational ease, durability, quality, and safety indices from diverse construction products, to inform the decision-making process.
- Analyze the sustainable decision-making framework using methodologies such as the Analytic Hierarchy Process (AHP), the Order of Preference by Similarity to Ideal Solution (TOPSIS), and Ordered Weighted Averaging (OWA).
- Develop a comprehensive conceptual model by integrating Porter's Five Forces (PFF) appraisal, involving questionnaire-based surveys and descriptive statistical analyses within the context of the case study.

In the subsequent sections, this paper undertakes the following tasks: Section 2 entails a comprehensive review of pertinent literature to pinpoint research gaps. Section 3 delineates the materials and methods utilized in this study, while Section 4 presents a detailed analysis and discussion of the results, juxtaposed with relevant findings from other studies. Finally, in Section 5, the conclusion appraises the principal accomplishments, outlines the identified limitations, proposes avenues for future research, and assesses the sustainability implications of the study's outcomes.

LITERATURE REVIEW

The effective management of WTS generated within WTPs constitutes a primary focus for researchers due to its environmental implications. To address the challenges associated with material disposal, there has been a growing emphasis on repurposing both constructional and non-constructional materials, such as bricks, ceramics, and lightweight aggregates. Given the substantial consumption of primary and non-renewable resources in the construction sector, utilizing WTP byproducts for the development of construction materials has emerged as a compelling strategy [16]. Notably, the incorporation of WTP products in cementitious materials, including concrete, mortar, and cement, as well as ceramics like bricks and pottery, has garnered significant research attention [17].

Investigations into the effects of lime sludge on burned clay ceramics and bricks [18] have shed light on the role of silicate and calcium phases in enhancing brick strength. Studies have also explored the potential of aluminium sludge as a substitute for clay in the production of construction materials, highlighting its comparable properties to clay [19]. These endeavours have paved the way for establishing a productive cycle through the integration of sludge reuse into comprehensive treatment management, thereby promoting effective environmental stewardship [20].

The concept of the 'circular economy' stands as a pivotal strategy in mitigating the environmental repercussions of waste disposal [11], playing a crucial role in fostering sustainable development, particularly within developing nations. Rosiek [21] assessed municipal WTS management through the lens of the circular economy, combining the fundamental principles and tools of this approach with the prevailing state of municipal sewage sludge. In response to the escalating water scarcity stemming from rapid urbanization and climate variability, concerted efforts have been made to curtail water consumption, primarily through the adoption of circular economy principles. Smol et al. [10] contributed to this endeavour by devising a comprehensive circular model framework within the wastewater sector, encompassing reduction, reclamation, recovery, recycling, and reconsideration. Additionally, Rusmanis et al. [22] presented a study highlighting the benefits of the circular economy in the context of wastewater management, advocating for water recycling as a sustainable solution to ensure a consistent water supply for agricultural purposes in regions prone to drought. In essence, the amalgamation of resource recovery and circular economy strategies within municipal wastewater management not only yields economic and environmental advantages but also contributes to urban sustainability through the restoration of nutrients and reusable water.

Amin et al. [23] investigated the impact of incorporating silica fume into pozzolanic cement mixtures containing burned clay, suggesting that replacing an appropriate quantity of aluminium-based material with clay in bricks yields comparable performance to reference samples. Additionally, Cremades et al. [24] suggested that the compressive strength of ceramic samples could be enhanced through the utilization of iron-based sludge. Vashistha et al. [25] explored the feasibility of utilizing lime sludge, comprising primarily of calcium carbonate, alumina, and silica, as an alternative method for cement production, conducting a series of experiments to evaluate its potential reuse in cement manufacturing. Lee et al. [26] identified the potential of WTS in the production of low-density mixtures.

In the literature review, lightweight aggregate analysis (LWA), serves as a non-structural material and has been explored for potential production utilizing diverse elements such as thickened clay, reservoir sediment, zeolite tuffs, and sewage sludge [27]. Moreover, the incorporation of sawdust and sewage sludge from water treatment facilities in building construction has been proposed as a measure to mitigate environmental degradation.

Assessing the quality and quantity of the resultant volume in water treatment facilities crucially hinges upon the examination of raw water inflow and the performance of various plant components. Variations in the inflow volume, climatic fluctuations, or the dosage of coagulants and absorbent materials can significantly impact the overall volume [28]. Given the diverse influent types in water treatment plants, the precise estimation of effluent volume assumes paramount significance. Subsequently, the determination of sludge characteristics and volume remains essential for informed decision-making concerning its potential application in construction projects [29]. However, the existing research on WTS management primarily focuses on volume reduction or prediction, necessitating comprehensive computational methodologies for accurate evaluation [30]. Consequently, in addition to environmental considerations, the optimization of precise material dosages introduced into the treatment plant holds significant implications. Despite the critical role of coagulants, minimal research has been dedicated to volume prediction, highlighting the need for a more robust framework [12]. Daily fluctuations in water volumes within treatment facilities can be attributed to several variable factors [31]. Hence, in the context of sludge and effluent management, particularly with regard to diverse applications of residue in the construction industry, the accurate assessment of volume assumes utmost importance, calling for the integration of advanced computational methodologies. Appropriate prediction of effluent quantities leaving the treatment plant is as crucial as estimating the inflow volume for effective treatment management [14].

In the realm of water treatment plant parameter determination and computation, the utilization of soft computing methods remains relatively underutilized, although its benefits have been well-established. While the Artificial Neural Network (ANN) technique proves effective in predicting parameters related to wastewater performance, its efficacy in handling complex equations and computer programs remains limited. Recent applications of metaheuristic algorithms for optimizing water supply chain parameters have shown promise [3]. However, despite the ability of Recurrent Neural Networks (RNNs) to capture diverse plant nonlinearities, the constraint of consistently fixed hidden nodes poses a notable challenge [32]. While studies focusing on the economic and environmental efficacy of these concepts are valuable for decision-makers, limitations persist within the WTS management industry, particularly regarding social standards and adaptability to technological shifts within treatment [33]. As of recent, data-driven approaches and Multi-Criteria Decision-Making (MCDM) have emerged as efficient methodologies for modelling water treatment issues.

Categorized as a subfield of operational research, MCDM serves as the most effective approach, taking into account all available options, along with economic, environmental, and social factors. Given the multifaceted factors influencing WTS management, the implementation of the MCDM strategy proves highly effective in facilitating informed decision-making. Furthermore, the widespread use of MCDM in treatment plant evaluations has been well-documented, with studies emphasizing the selection of the most relevant indicators for water treatment. In a similar vein, Ali et al. [34] employed a fuzzy method to assess five different wastewater treatment technologies, showcasing the versatility of the MCDM approach. Anaokar et al. [35] addressed the challenges of evaluating treatment plant performance by employing MCDM, thereby contributing to the advancement of assessment methodologies. Additionally, optimization methods based on mathematical models and SWOT analysis have been devised for evaluating the performance of ceramic filters [36]. Kiyan's research [37] has also demonstrated the effective implementation of MCDM approaches to facilitate operational adjustments and management enhancements, ultimately leading to improved water quality. Notably, the employment of MCDM techniques not only simplifies computations but also enhances their precision in various scenarios.

Contrasting other approaches, MCDM outshines its counterparts in certain contexts, particularly in aiding decision-making within the sustainable environment and waste management domain. For instance, Campos-Guzman et al. [38] leveraged the MCDM approach, instead of Machine Learning (ML) methods, to determine the optimal disposal method for sludge post-treatment. Similarly, Bertanza et al. [39] contributed insights into the decision-making process regarding the utilization of residue after treatment in construction cement or other applications. Notably, most MCDM methods demonstrate environmental compatibility, drawing on classic methodologies such as uncertainty theory, fuzzy methods, and rough theory. AHP and TOPSIS, along with applicable theories, prove instrumental in addressing issues pertaining to parameter selection within sustainable environments. Although MCDM and the TOPSIS process share commonalities in their goal of reaching the best compromise solution from multiple alternatives, the nuanced difference lies in their initial problem hypothesis, wherein TOPSIS emphasizes dominant features, while other methods consider individual regression before maximizing rankings. Notably, S. de C. Gomes et al. [40] utilized MCDM approaches, focusing on the AHP and TOPSIS, to evaluate WTS management, providing validation for the WTS management model through MCDM methodologies. Overall, the application of MCDM approaches facilitates the prioritization of criteria preferences and the optimization of material selection, thereby enhancing the precision of the analysis.

Additionally, the PFF framework serves as an analytical tool for comprehensively assessing the competitive landscape within an industry. By examining the threat of new entrants, bargaining power of suppliers, bargaining power of buyers, threat of substitute products/services, and competitive rivalry, PFF offers insights into industry attractiveness, competitiveness, profitability potential, and strategies for improving a firm's position [41]. Its application spans across various sectors, serving as a strategic planning and competitive analysis mechanism.

The Boston Consulting Group (BCG) matrix, another strategic tool, aids in resource allocation decision-making among products or business units, considering market share and growth rate as primary parameters. Categorizing business units as stars (high growth, high share), cash cows (low growth, high share), dogs (low growth, low share), or question marks (high growth, low share), the BCG matrix guides decisions regarding investment prioritization and potential divestments. Widely utilized by companies for marketing, brand, and product portfolio management, the BCG matrix offers a strategic lens for resource allocation.

Industrial Ecology (IE), operating within a systems-based framework, aims to optimize resource utilization and minimize environmental impacts within industrial systems. With a holistic, lifecycle approach to production, consumption, and waste management, IE emphasizes circular flows, diversity, locality, succession, and resilience, fostering synergistic exchanges of materials, energy, and information across industrial sectors to promote closed-loop processes and waste limitation. IE finds applications in the design of eco-industrial parks, material and energy flow analysis, and sustainable policymaking, spanning sectors including water, wastewater, and sludge management [42]. Its principles foster integrated models for sludge treatment, reuse, and resource recovery, with a focus on circularity, cascading use, and industrial symbiosis, thereby steering wastewater treatment systems toward circular economy models. IE offers a comprehensive systems perspective to optimize the sustainability of sludge management practices, promoting symbiotic exchanges and industrial synergies while accentuating circularity and resilience.

In light of the reviewed literature, the integration of MCDM, CE, PFF, BCG matrix, and IE within the context of scheduling WTP sludge utilization as construction materials not only addresses a crucial research gap but also offers a holistic approach to sustainable and efficient water treatment sludge management. By leveraging the analytical power of MCDM methodologies, decision-makers can navigate complex trade-offs and prioritize criteria based on a comprehensive evaluation of economic, environmental, and social factors. The integration of the CE framework enables the systematic reduction, reclamation, recovery, and recycling of resources, aligning with the principles of sustainable development and waste minimization. Meanwhile, the application of the PFF framework provides invaluable insights into the competitive dynamics of the industry, allowing stakeholders to devise strategic interventions that enhance market positioning and profitability.

Moreover, the incorporation of the BCG matrix facilitates strategic resource allocation, guiding investment decisions and portfolio management to optimize business unit performance and growth trajectory. By employing IE principles, the study adopts a systems-based approach to optimize resource utilization and minimize environmental impacts, fostering circular flows, synergistic exchanges, and closed-loop processes within the industrial ecosystem. The amalgamation of these methodologies not only enriches the current research but also paves the way for a comprehensive and integrated strategy to address the multifaceted challenges of WTP sludge management. By considering the intricate interplay of economic viability, environmental sustainability, and societal well-being, the proposed framework presents a promising pathway toward a more resilient, efficient, and environmentally conscious water treatment sludge management system.

MATERIALS AND METHODS

In this section, we commence by delineating the research roadmap, providing a comprehensive overview of the study's trajectory. Subsequently, we elucidate the intricacies of our MCDM computations and formulations, underscoring the systematic approach employed in the decision-making process. Following this, we present a detailed illustration of the PFF modelling, shedding light on the strategic insights derived from the competitive analysis. Lastly, we provide a comprehensive exposition of our case study, offering key findings and implications.

Research Roadmap

The research roadmap of the current study is illustrated in Figure 1, showcasing the sequential progression of the research methodology. Initially, the analysis entails an assessment of the variation in effective parameters influencing the Sludge Production Amount (SPA) through a comprehensive histogram and descriptive statistical analysis. Subsequently, the second step involves the application of Regression Trees (RT) for the predictive modelling of SPA, considering influential parameters such as Treatment Units (TU), energy consumption, coagulant usage, and influent flow rate. The study further incorporates MCDM methods, emphasizing the integration of sludge application within the circular economy framework. Finally, the eco-environmental aspects of the proposed plan are thoroughly evaluated through the implementation of PFF conceptual models.

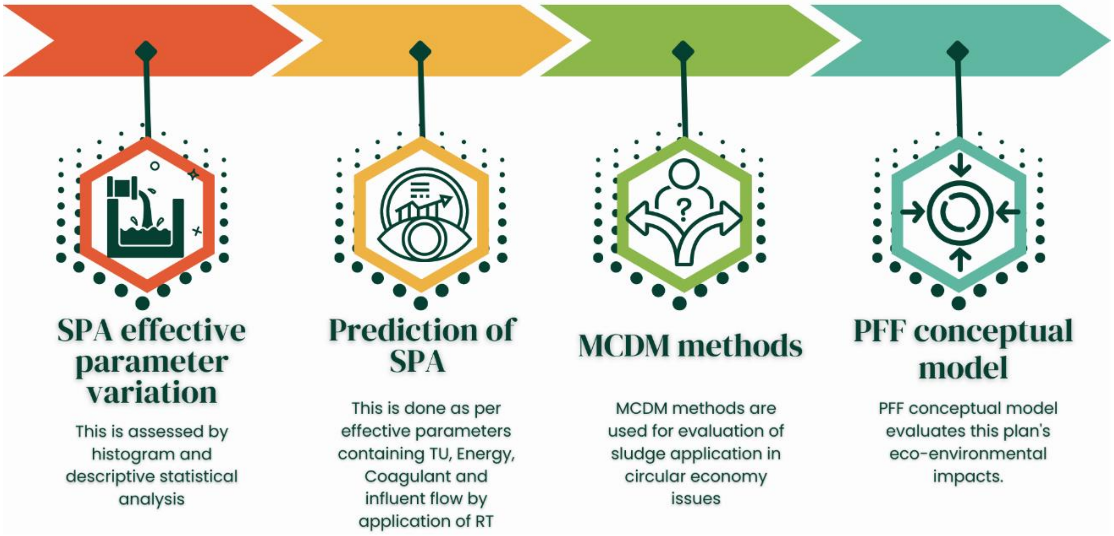


Figure 1. The research roadmap in the present study

MCDM computations

In justifying the adoption of a hybrid methodology involving three MCDM tools, namely OWA, AHP, and TOPSIS, it is essential to illuminate the rationale behind this seemingly ad hoc selection. The complex interplay between water supply and power generation [3], necessitates a nuanced approach that considers various factors influencing decision-making processes. These MCDM algorithms have been strategically chosen due to their versatility in handling multifaceted decision contexts and facilitating well-informed judgments.

AHP, renowned as the most popular and extensively studied MCDM method, empowers decision-makers to assess and prioritize diverse factors systematically. Its reliability and trustworthiness emanate from a robust theoretical foundation. TOPSIS, on the other hand, emerges as a preferred method when confronted with a multitude of variables and outcomes. Its ability to evaluate options against a set of criteria and rank the most favorable ones makes it a valuable tool in decision-making processes. OWA, as a modern MCDM technique, accommodates imperfect or unreliable information by allowing for both optimistic and pessimistic assessments of criteria and choices.

However, the use of these methodologies may introduce challenges, demanding additional assumptions and experience, potentially intensifying the complexity of the analysis. Consequently, the selection of an MCDM approach should transcend subjective inclinations and consider the distinctive features of the decision-making issue along with the available information.

The rationale behind opting for AHP, OWA, and TOPSIS in this study is grounded in their well-established principles, broad applicability, and efficacy in addressing a spectrum of decision-making challenges. Acknowledged for their stability and dependability, these MCDM methods find widespread application in both academic research and professional settings. The subsequent section offers a concise yet comprehensive mathematical elucidation of these selected approaches.

Additionally, the use of MCDM models required distributing three separate questionnaires to twenty-five professionals from the Water and Wastewater Industry in Mashhad City, Iran. Using their provided ratings, all calculations were conducted and final prioritizations were determined.

TOPSIS method

Much research advocated for TOPSIS as a robust MCDM approach based on the concept of proximity to both negative and positive ideal solutions. The positive ideal solution is determined by aggregating the best possible values for each characteristic, while the negative ideal solution comprises the worst possible values. The detailed stages of the technique is explained as follows:

a. Generating and standardising a ranking decision-matrix.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}} \qquad (1)$$

b. Computing the normalised weighted decision-matrix

$$w_j = (w_1, w_2, w_3, \ldots, w_n) \qquad (2)$$

Where w_j is the criteria's weight for all j and $\sum j = 1, w_j = 1$.

Here is V's normalised weight matrix:

$$v_{ij} = w_j \times r_{ij} \tag{3}$$

c. Determining the optimal positive and negative solutions.

$$A^+ = \{(max\, v_{ij} \,|j \in J), (min\, v_{ij} \,|j \in J'), i = 1,2,3,\dots,m\} \tag{4}$$

$$A^- = \{(min\, v_{ij} \,|j \in J), (max\, v_{ij} \,|j \in J'), i = 1,2,3,\dots,m\} \tag{5}$$

d. Compare each choice with the negative and positive ideal solutions by computing the Euclidean distance between them.

$$d^+{}_i = \left[\sum_{j=1}^{n} (v_{ij} - v^+{}_j)^{0.5}\right]^{0.5} , i = 1,2,3,\dots,n \tag{6}$$

$$d^-{}_i = \left[\sum_{j=1}^{n} (v_{ij} - v^-{}_j)^{0.5}\right]^{0.5} , i = 1,2,3,\dots,n \tag{7}$$

e. Determine the relative proximity coefficient of the ith option to the optimal answer.

f. $cl^+{}_i = \frac{d^-{}_i}{d^+{}_i + d^-{}_i}, i = 1,2,3,\dots,n$ (8)

g. Sort the choices depending on the cl_i^+ to discover the best solution.

OWA method

An aggregate operator estimates the degree of pessimism or optimism as part of the OWA approach to decision making. Especially, the function F: $R^n \rightarrow J$ maps to a weighting vector *W* with length *n*.

$$W = \{w_1, w_2, w_3, \dots, w_n\}^T \tag{9}$$

where $w_i \in [0,1]$ and $\sum_{i=1}^{n} w_i = 1$

$$OWA(a_1, a_2, a_3, \dots, a_n) = \sum_{i=1}^{n} w_i b_i \tag{10}$$

where b_i is the i^{th} largest member in the set (a_1, a_2, a_3, …, a_n).

Several methods exist for determining values for the OWA function's weights. Important among all is the fact that it enables us to derive the weights of the linguistic quantifier in a functional manner, as shown below.

$$w_i = Q(\frac{i}{n}) - Q(\frac{i-1}{n}) \tag{11}$$

where the equation holds true when Q is varied: [0,1]→ [0,1] where Q(0)=0 and Q(1)=1, and $Q(x) \geq Q(y)$ for $x > y$.

Depending on the semantics of the Q operator, the weighting vector may be used to provide more or less weight to certain aspects of the aggregate. Quantifiers are used to identify the technique and the construction of the weighted vector.

AHP method

AHP is a popular MCDM technique that helps decision-makers determine the relative importance of significant elements through pair-wise comparison. The method includes four steps: organising the decision hierarchy, creating a comparison matrix, determining the relative relevance of elements, and evaluating the consistency of judgments with the Consistency Ratio (CR) and Consistency Index (CI), as described below.

$$CI = \frac{\lambda_{max}}{n-1} \tag{12}$$

where n is the number of items being compared and λ_{max} is the Eigen value associated with the matrix of pair-wise comparisons.

Additionally, CR is well-defined as

$$CR = \frac{CI}{RCI} \tag{13}$$

RCI stands for "random consistency index."

When CR is less than 10%, the comparison may be safely made; otherwise, more investigation is required to eliminate confusion.

There are many applications for the management of WTP sludge, and in this study, the TOPSIS, OWA, and AHP approaches are utilised for the determination of the best application of sludge management as raw material in the different construction product procedures with consideration to different normal, environmental, economic, energy, and market scenarios. Computations of AHP, TOPSIS, and OWA are done in Expert Choice 11, Excel 2016, and MATLAB 2013b, respectively. Likewise, the stages of MCDM computations are demonstrated in Figure 2. It goes without saying that for the evaluation of different comparisons, input data is extracted from the literature review.

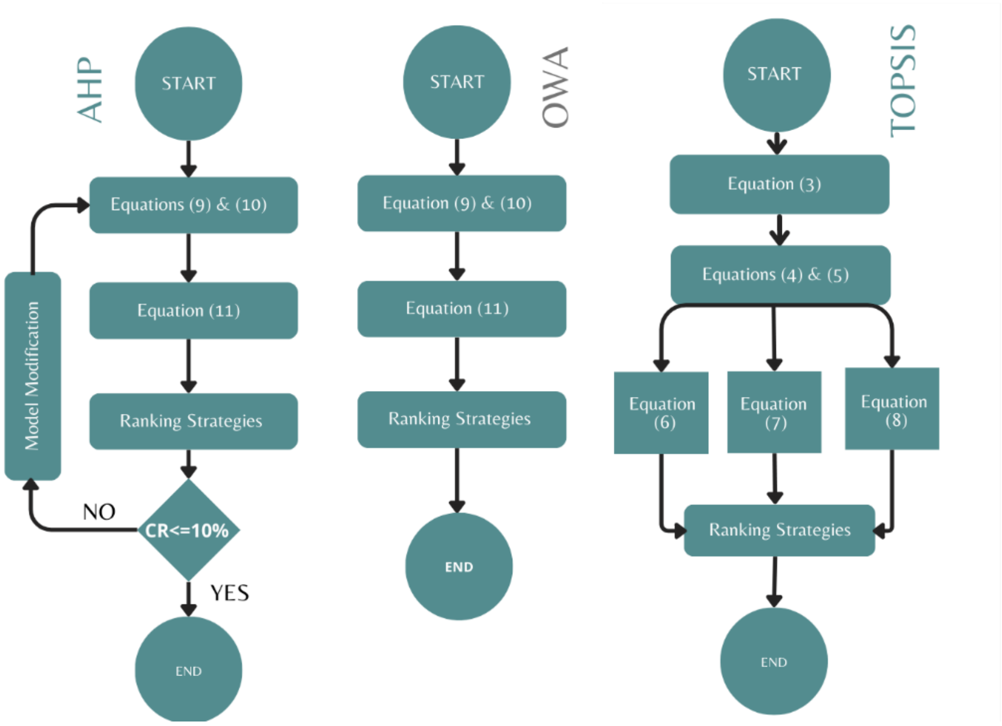


Figure 2. The MCDM computations in present study

PFF conceptual modelling

In this study, the evaluation of eco-environmental considerations employed the PFF conceptual model, as depicted in Fig. 3. As a result of analyzing various materials in PFF assessment, questionnaires were given to twenty-five professionals from the Water and Wastewater Industry in Mashhad City, Iran. The final consensus of their views, following discussion among them, is presented as PFF information.

The PFF Framework is a well-established analytical tool widely utilized in the domain of business strategy. It operates on the premise that the competitive forces within an industry can be characterized by five key factors: the bargaining power of suppliers, the threat of new entrants, the bargaining power of buyers, the threat of substitute products or services, and the intensity of competitive rivalry. This framework serves as a valuable guide for organizations to assess the competitive landscape of their industry and formulate strategies to gain or sustain a competitive edge.

In this particular study, we apply Porter's Five Forces Framework, as depicted in Figure 3, to the context of water treatment plant management. Specifically, we utilize the framework to analyze the market dynamics and competitive forces that significantly impact the management of sludge generated by water treatment plants. Our analysis delves into aspects such as the potential threat of new entrants into the sludge management market, the bargaining power of both sludge suppliers and buyers, the threat posed by substitute products or services, and the overall intensity of competition among existing sludge management entities. By leveraging this framework, we aim to acquire a comprehensive understanding of the factors influencing the management of water treatment plant sludge and to identify potential avenues for innovation and enhancement in this critical domain.

Figure 3. The present-day PFF conceptual model

Our case study

The WTP No. 1 is located in the southwest of Mashhad and was established in June 1992. The nominal capacity of the mentioned WTP is 96,000 m^3/d, which charges from the Kardeh (40 kilometers northeast of Mashhad). The Kardeh dam's water is transferred gravitationally using ductile iron pipes with a 46-kilometer water supply pipeline. As shown in Figure 4, the WTP's process in this complex contains preliminary disinfection (usually using potassium permanganate in 0.25–1 mg/L concentration), aeration for the gas phase pollutant elimination, and activated carbon addition for the adsorption of organic materials. In the following, the coagulation and flocculation processes are utilised by the injection of $FeCl_3$ and a super pulsator. Also, with the application of rapid sand filtration, the extra suspended particles are trapped. In the last section, all remaining microbial loads are disinfected by chlorination.

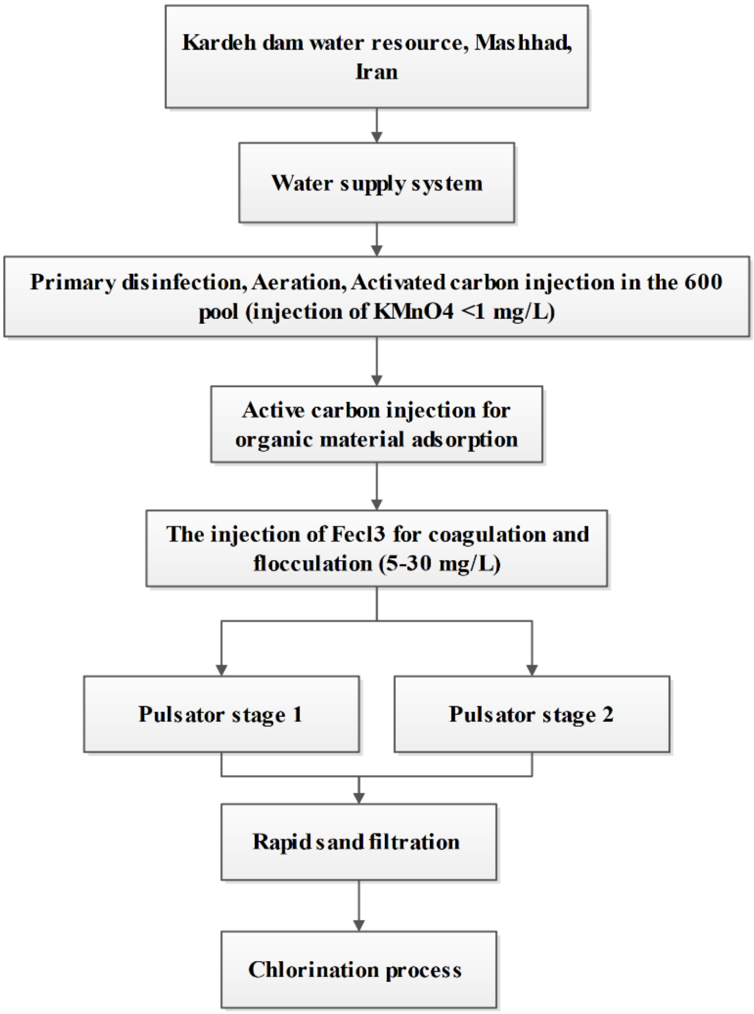


Figure 4. Mashhad, Iran's Water Treatment Plant No. 1's Water Treatment Stages

This diagram displays the amount of surface water that has entered the WTP's, No.1, Mashhad, Iran, during a year with this tolerance (Figure 5). Hence, the amount of refined water output can be calculated from the daily volume. It is worth noting that all the collected data is related to 2019–2020.

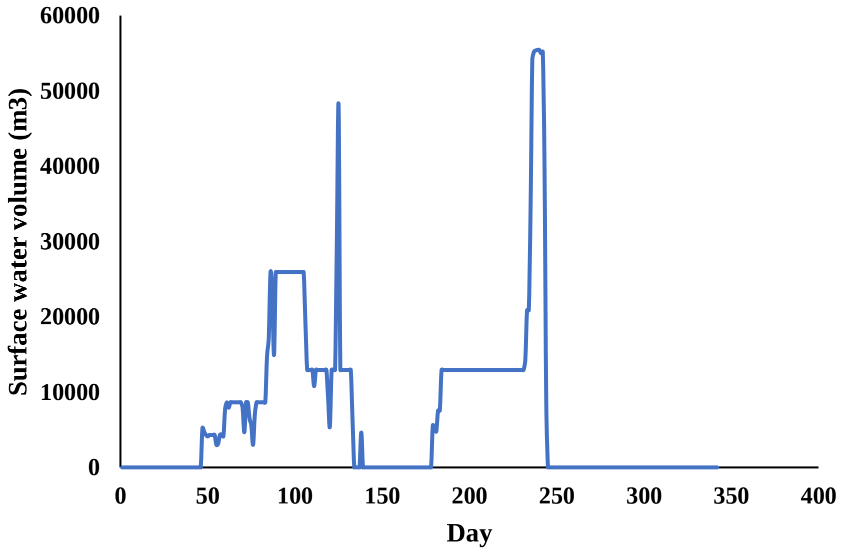


Figure 5. The volume of surface water per day in WTP's No. 1, Mashhad, Iran

The amount of energy consumption of the coagulation and flocculation units as the main sludge production procedures in WTP, No.1 is demonstrated as per Figure 6. The amount of energy consumed in the coagulation and flocculation units is extracted in order to estimate the amount of sludge that is produced in the coagulation and flocculation units. This diagram presents significant information to compute the product. This correlation will be demonstrated in the upcoming parts of the article. There are many fluctuations in the energy consumption of this unit due to the operation of the WTP throughout the year. Therefore, these fluctuations have a direct effect on the amount of sludge leaving the coagulation and flocculation units. The amount of $FeCl_3$ mg L^{-1} consumed as coagulant in the coagulation and flocculation units is illustrated as per Figure 7. Finally, the fluctuation of influent TU is demonstrated in Figure 8. For prediction of SPA and by-product production from it, the quantity value of TU, energy, coagulant, and influent flow should be determined. Because of that, in this section, all input parameters mentioned as effect parameters are appraised.

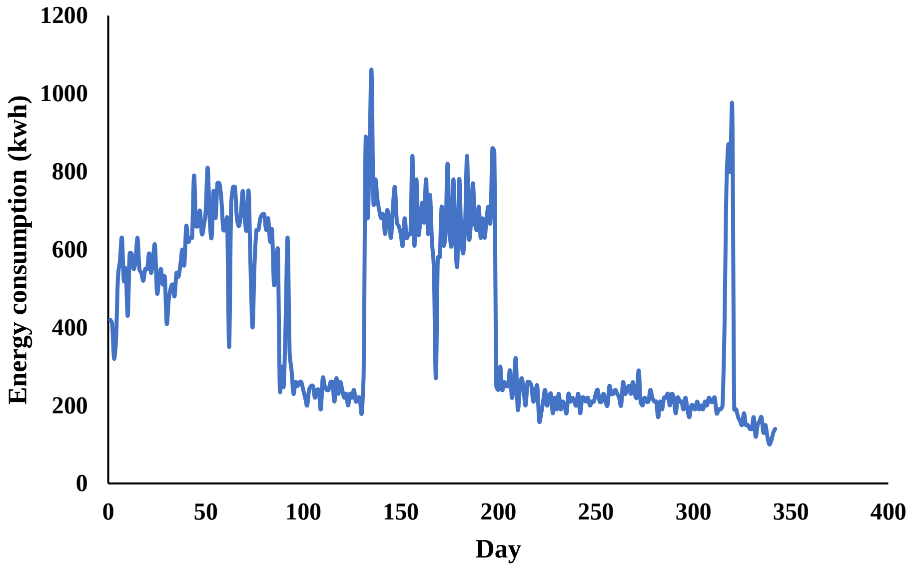


Figure 6. The Energy consumption of coagulation and flocculation unit per day in WTP's No. 1

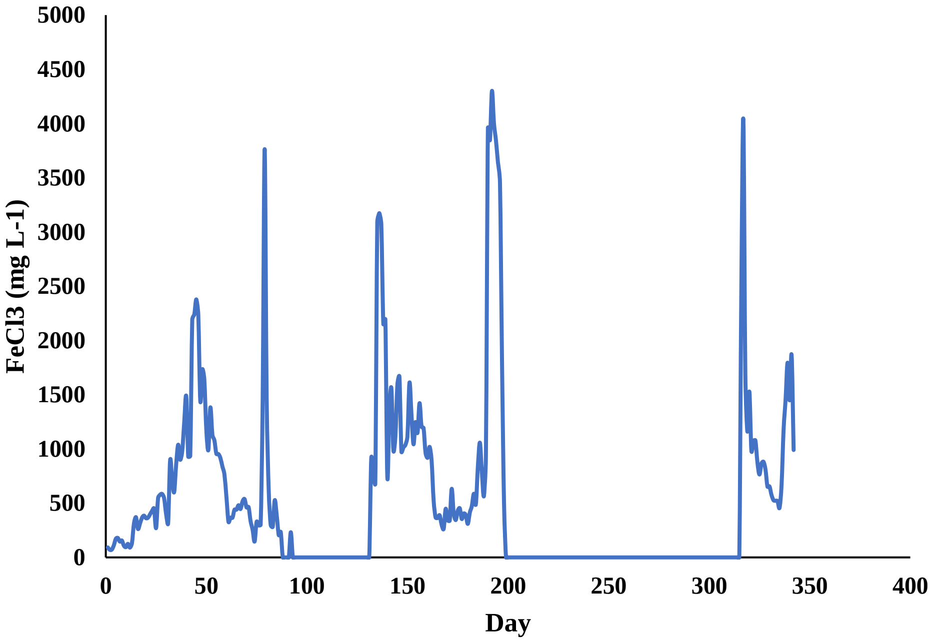


Figure 7. The amount of $FeCl_3$ per day in WTP's No. 1, Mashhad, Iran

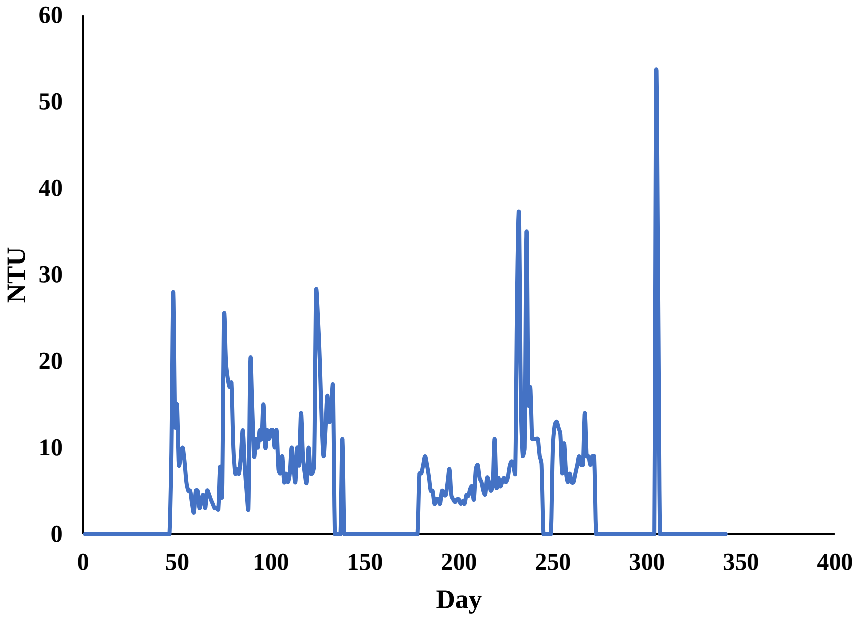


Figure 8. The fluctuation of influent TU per day in WTP's No. 1, Mashhad, Iran

RESULTS AND DISCUSSIONS

In this section, we embark on our comprehensive MCDM analyses, meticulously evaluating the various criteria and decision-making processes essential to the study. Subsequently, we delve into an in-depth analysis using PFF framework, carefully assessing the competitive dynamics and market intricacies that significantly influence the overarching objectives of the research. By employing these robust analytical methodologies, we aim to offer a nuanced and comprehensive understanding of the intricate relationships between the diverse decision-making criteria and the competitive landscape, thereby providing a solid foundation for informed and sustainable decision-making.

MCDM analysis

The comparison of various applications of WTP sludge was conducted across five distinct scenarios, encompassing considerations of energy consumption, market viability, environmental impact, economic feasibility, and standard operational conditions. The survey data were sourced from 20 experts, each possessing over 5 years of professional experience and at least a master's degree qualification. These experts were tasked with assessing and scoring sludge applications based on criteria such as facility costs, environmental implications, operational convenience, technical expenses, workforce requirements, energy usage, and market competitiveness. Subsequently, each scenario underwent meticulous evaluation and weighting, employing a comprehensive methodology to determine the relative importance of each criterion. The comparative analysis was performed across a range of sludge applications, including bricks, ceramic materials, cement, lightweight composite concrete, and structural concrete.

The assessment of sludge applications was carried out using the TOPSIS, OWA, and AHP methodologies. TOPSIS, a decision-making technique, involves identifying the optimal solution from a set of alternatives by assessing their distances from the anti-ideal and ideal solutions. This method is premised on minimizing the gap between the ideal solution and other potential outcomes. The outcomes from the TOPSIS analysis, as depicted in Figure 9, indicate that the application of sludge in ceramic materials scored higher across all scenarios except for the normal condition, with a marginal variance. In contrast, the utilization of sludge in cement scored the lowest across all scenarios.

OWA, another decision-making method, employs a weighted average to amalgamate multiple criteria into a single score. The weights are determined based on the relative importance of each criterion and can be adjusted to accommodate various decision-making scenarios. The results from the OWA analysis, illustrated in Figure 10, suggest that despite the outcomes from TOPSIS, cement demonstrates dominance over other alternatives in moderately optimistic to highly pessimistic situations. Additionally, the results highlight that structural concrete achieves the highest scores in both highly optimistic and moderately optimistic scenarios. Notably, the application of sludge in ceramic materials garnered the lowest scores across all scenarios in this analysis.

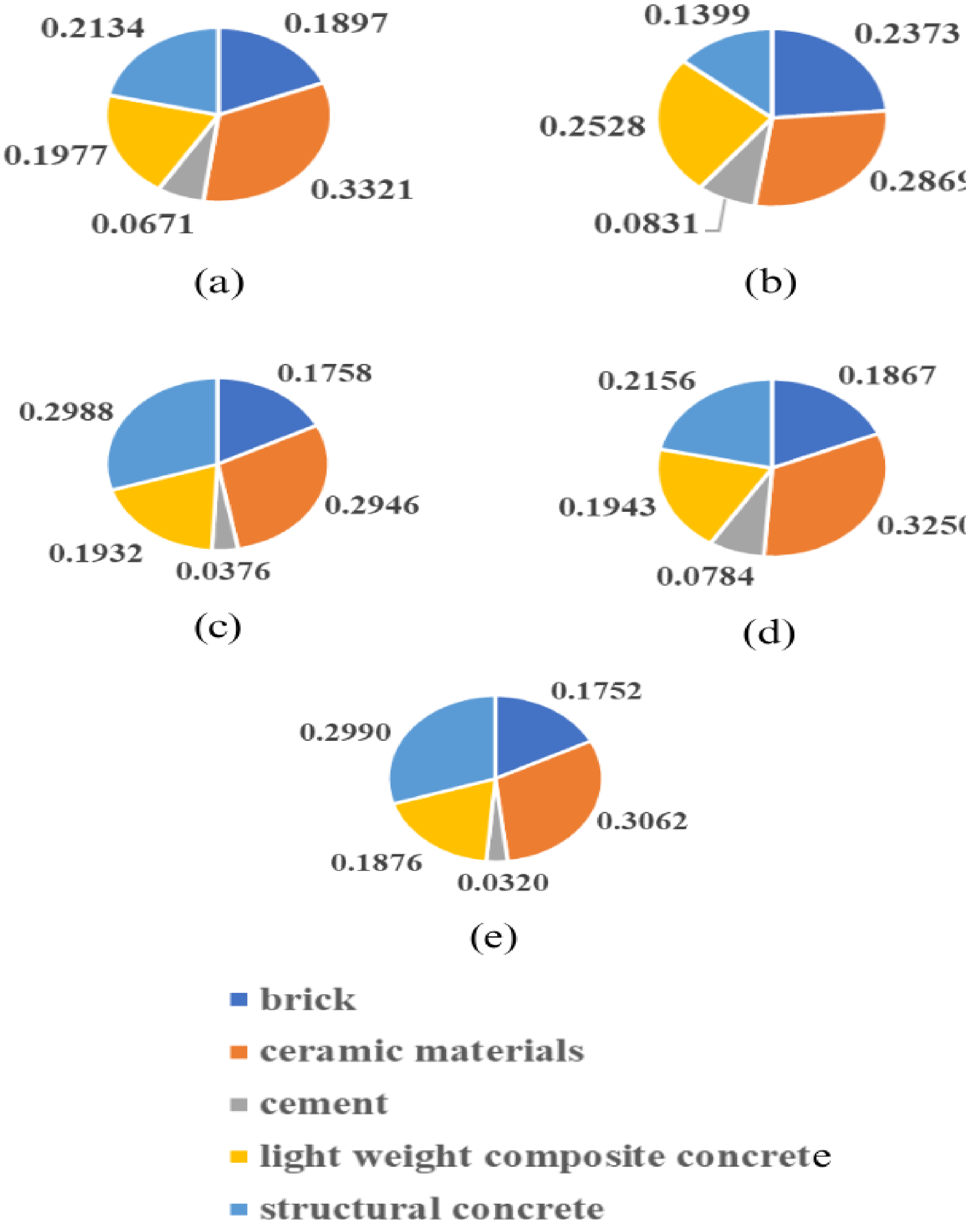


Figure 9. The outcomes of the TOPSIS method on different WTS applications; (a) energy consumption scenario, (b) market scenario, (c) normal scenario, (d) environmental scenario, (e) economic scenario

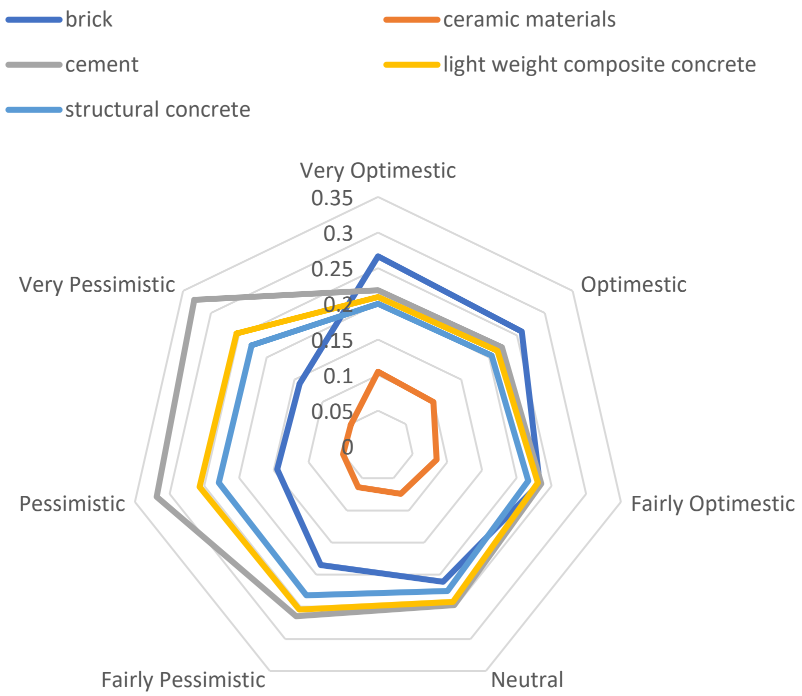


Figure 10. The outcomes of the OWA method on different WTS applications

AHP is a decision-making method that involves breaking down multifaceted problems into smaller, more manageable parts and then making pairwise comparisons between them. The technique organises the criteria and possible solutions in a hierarchical structure and gives different criteria different weights. The results of this approach show the superiority of using WTS for brick production in normal, economic, and energy consumption scenarios. However, the application of WTS as a raw material to produce cement scored higher when applying environmental and market scenarios. Figure 11 illustrates the weights allocated to each WTS application in different scenarios.

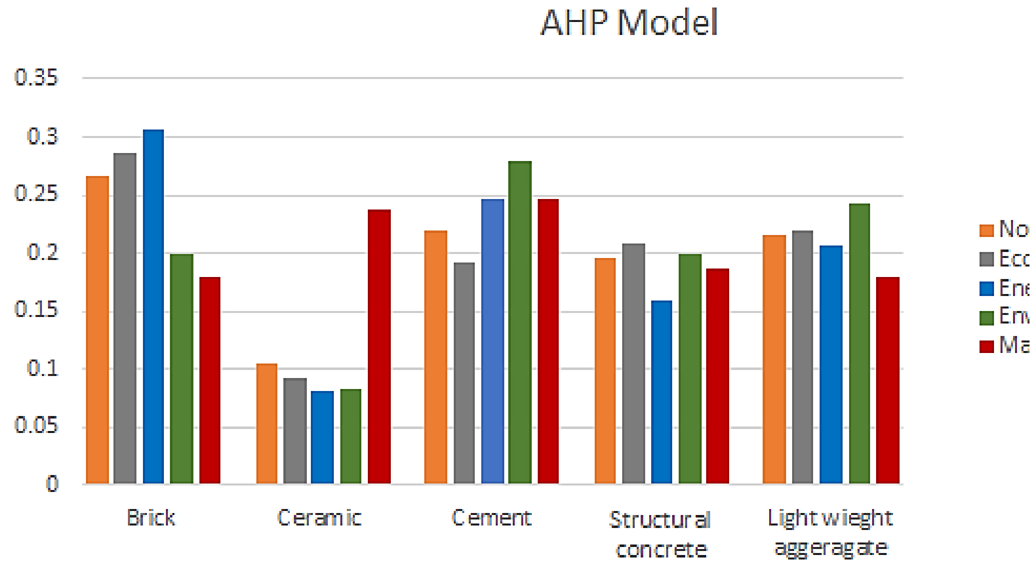


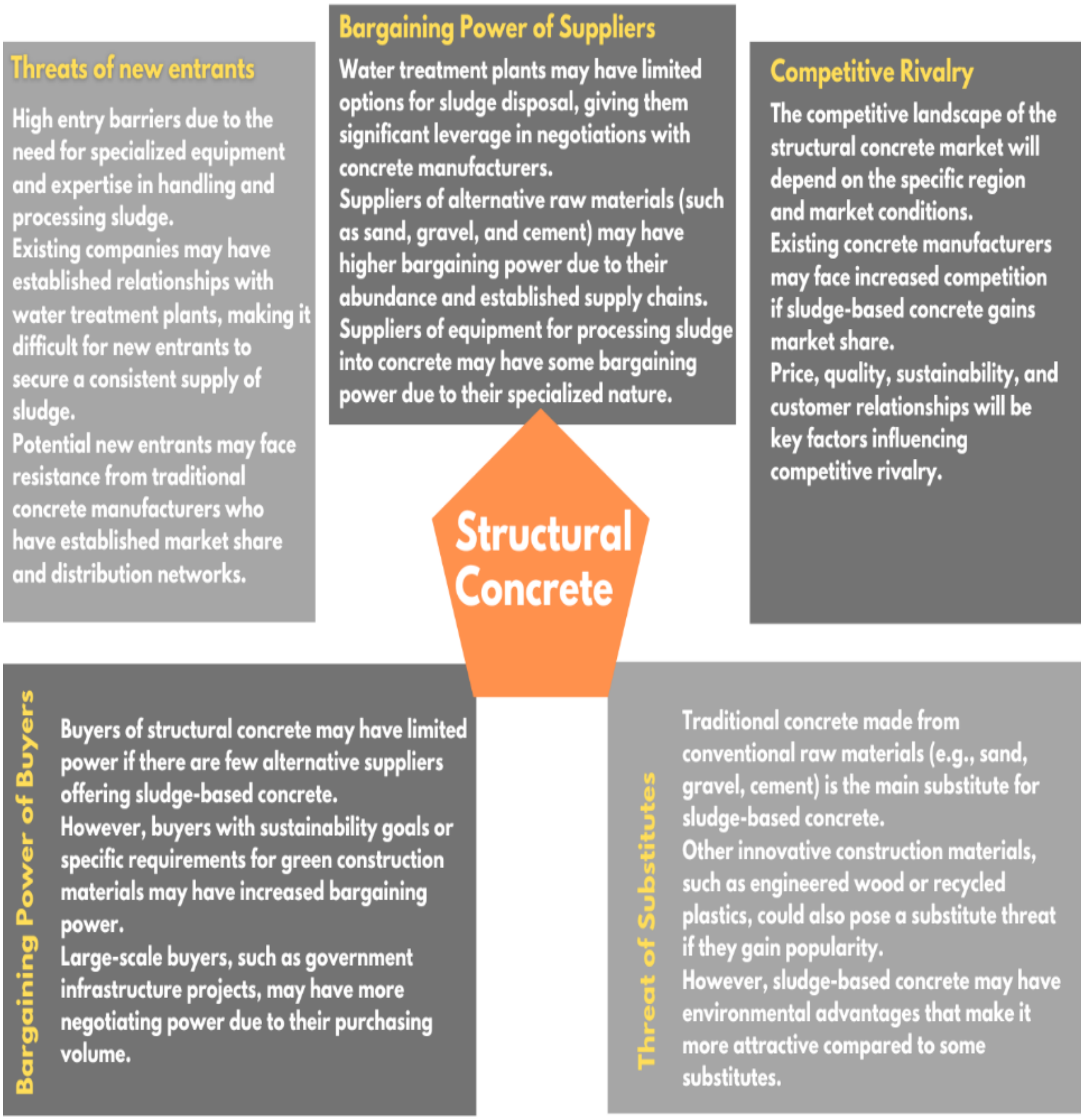
Figure 11. The outcomes of the AHP method on different WTS applications; (a) normal scenario, (b) economic scenario, (c) energy consumption scenario, (d) environmental scenario, (e) market scenario

The differences in results between these methods may rely on a number of variables, such as the nature of the decision problem, the criteria used, and the preferences of the decision-maker. TOPSIS may be more suitable for problems where there is a clear ideal and anti-ideal solution, while AHP may be more appropriate for problems with multiple criteria and complex relationships between them. OWA might be helpful if the requirements are not clear or when different decision-makers have different preferences. Ultimately, the choice of method to solve a particular problem depending on the details of the situation and goals of the decision-making procedure.

A significant number of studies have shown the excessive potential of WTS in construction materials. As clay and WTS are very comparable in chemical composition (mainly oxides of silica and hydroxides, ferric, aluminium), and given the huge potential of replacing clay with solid waste for producing ceramic artifacts, it is extremely beneficial to substitute clay with WTS for building bricks and ceramics [24]. There is much research indicating the application of WTS as a raw material producing cement and brick to mix with commercial clay in different amounts [43]. In another research the authors have shown that an optimum amount of 20% substitution of the clay by WTS has positive results without compromising the compressive strength of the bricks [43]. However, Benlalla et al., [44] found that even by replacing 30% of traditional clay with WTS at a temperature of a thousand degrees Celsius, the mechanical strength of the new brick is still higher than the reference ones. Additionally, reports show that the mechanical properties of WTS bricks may diminish because sludge with a higher lime content absorbs more water [12]. Also, great proportions of WTS have shown a reduction in the tensile strength of bricks. Huang & Wang [27] combined the WTS with dam sediment to produce ceramic and illustrated that the mentioned combination can produce high-quality ceramics under the Chinese Governmental Regulations. Many other investigations have shown the successful application of a high silica content WTS for use in producing strong bricks and ceramics [45]. Cremades et al., [24] investigated the efficiency of using a spray-dried WTS mixed with clay to form ceramic. The results showed that this method has a high potential for replacing clay and is completely environmentally friendly. Teixeira et al., [46] illustrated that iron-based sludge is more advantageous for ceramic fabrication than aluminium-based sludge.

PFF analysis

The application of WTS for five different purposes, including structural concrete, non-structural concrete, cement, and ceramic, has been evaluated in this study, and the Five Porter Forces have been employed for the economic evaluation of the mentioned applications. As illustrated in Figure 12, due to Porter's forces, the economic status of the application of WTS in structural concrete is investigated in five aspects, including threats from new entrants, bargaining power of suppliers, competitive rivalry, bargaining power of buyers, and threats from substitutes. The potential risk as a new entrant in the market is relatively high due to the need for high-tech equipment and expertise. Also, existing companies will do their best to prevent emerging new rivals, and traditional concrete manufacturers will do the same as they have a high share of the market. In addition, to make structural concrete out of WTS, water treatment plants and other raw material and equipment suppliers may have high bargaining power due to the limited amount of WTS at their disposal. On the other hand, the bargaining power of buyers can be enhanced when they are devoted to sustainable development and green construction materials. Also, large-scale buyers such as governments may have much higher bargaining power due to their purchasing volume. The competitive vision of the market for the structural concrete made by WTS depends on the region and economic conditions. If WTS concrete can be a part of the market, the other concrete manufacturers may face increased competition due to price, quality, customer service, and other marketing factors. Moreover, traditional concrete made from gravel and cement is the main substitute for WTS concrete. However, other emerging kinds of concrete, such as wood-based and recycled plastic, may be considered rivals, although WTS concrete is much more environmentally friendly. These conditions are almost the same for the production of WTS non-structural concrete, except for the threat of substitutes. The WTS non-structural concrete can be replaced by traditional non-structural concrete, fiber-reinforced concretes, and recycled plastics. Figure 13 illustrates the PFF model for the production of WTS non-structural concrete.



Threats of new entrants

High entry barriers due to the need for specialized equipment and expertise in handling and processing sludge.
Existing companies may have established relationships with water treatment plants, making it difficult for new entrants to secure a consistent supply of sludge.
Potential new entrants may face resistance from traditional concrete manufacturers who have established market share and distribution networks.

Bargaining Power of Suppliers

Water treatment plants may have limited options for sludge disposal, giving them significant leverage in negotiations with concrete manufacturers.
Suppliers of alternative raw materials (such as sand, gravel, and cement) may have higher bargaining power due to their abundance and established supply chains.
Suppliers of equipment for processing sludge into concrete may have some bargaining power due to their specialized nature.

Competitive Rivalry

The competitive landscape of the structural concrete market will depend on the specific region and market conditions.
Existing concrete manufacturers may face increased competition if sludge-based concrete gains market share.
Price, quality, sustainability, and customer relationships will be key factors influencing competitive rivalry.

Bargaining Power of Buyers

Buyers of structural concrete may have limited power if there are few alternative suppliers offering sludge-based concrete.
However, buyers with sustainability goals or specific requirements for green construction materials may have increased bargaining power.
Large-scale buyers, such as government infrastructure projects, may have more negotiating power due to their purchasing volume.

Threat of Substitutes

Traditional concrete made from conventional raw materials (e.g., sand, gravel, cement) is the main substitute for sludge-based concrete.
Other innovative construction materials, such as engineered wood or recycled plastics, could also pose a substitute threat if they gain popularity.
However, sludge-based concrete may have environmental advantages that make it more attractive compared to some substitutes.

Figure 12. The PFF of the WTS structural concrete

Threats of new entrants

Similar to structural concrete, high entry barriers exist due to specialized knowledge and equipment required for processing sludge into non-structural concrete products.
Existing manufacturers may have established relationships with water treatment plants, making it challenging for new entrants to secure a reliable sludge supply.
New entrants may face competition from traditional non-structural concrete products and need to differentiate their sludge-based offerings.

Bargaining Power of Suppliers

Water treatment plants' limited disposal options give them significant bargaining power when negotiating with non-structural concrete manufacturers. Suppliers of alternative raw materials for non-structural concrete (e.g., aggregates, admixtures) may have higher bargaining power due to their abundance and established supply chains.
Suppliers of specialized equipment for sludge processing and concrete production may also exert some bargaining power.

Competitive Rivalry

The level of competitive rivalry in the non-structural concrete market will depend on the specific region and market conditions.
Existing manufacturers may face increased competition if sludge-based non-structural concrete gains market share.
Differentiation factors, such as price, quality, sustainability, and product performance, will influence competitive dynamics.

Bargaining Power of Buyers

Buyers of non-structural concrete may have limited power if there are few alternative suppliers offering sludge-based concrete products.
Buyers focused on sustainability or specific project requirements may have increased bargaining power.
Large-scale buyers, such as contractors or commercial developers, may have more negotiating power due to their purchasing volume.

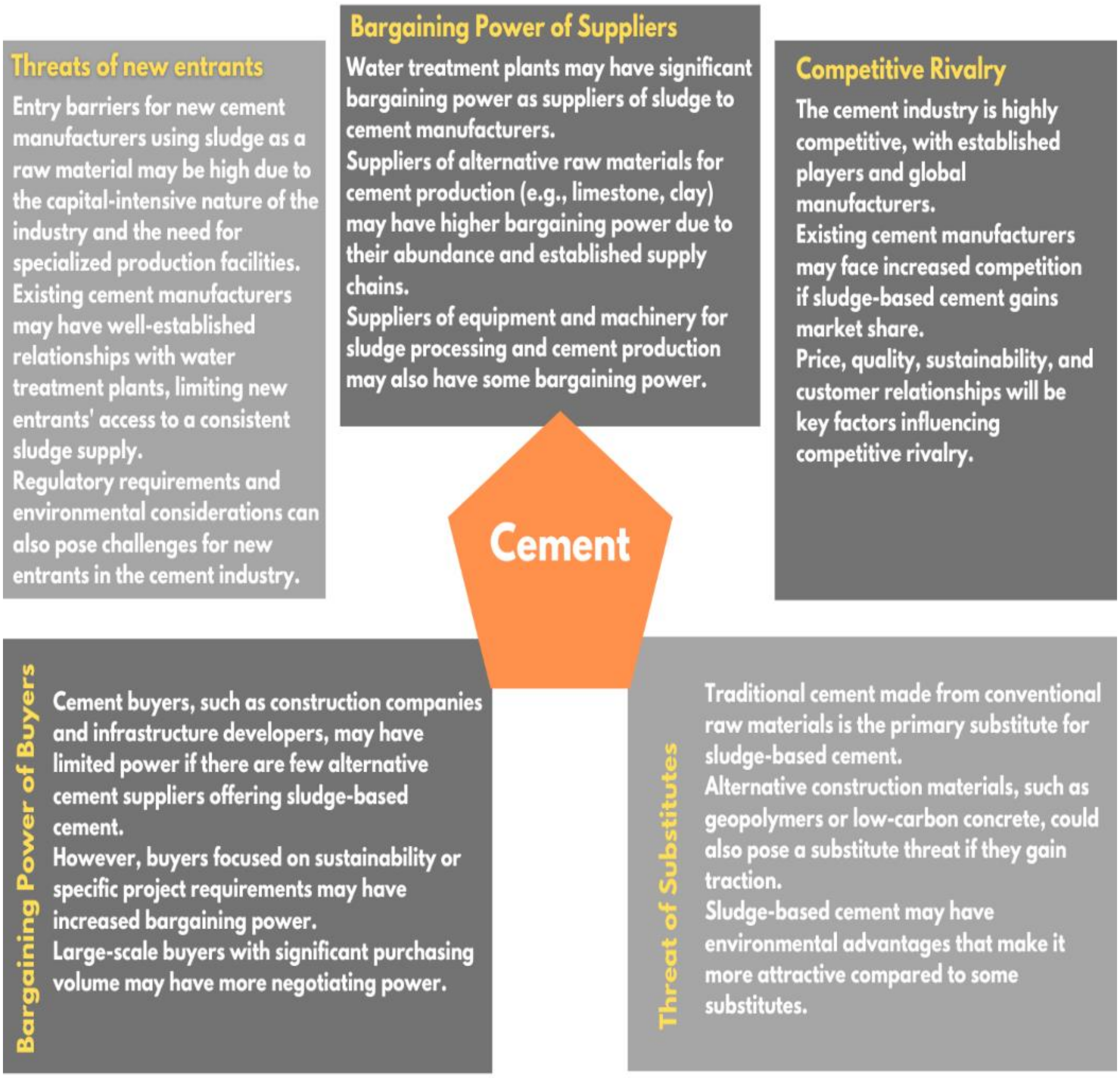
Threat of Substitutes

Traditional non-structural concrete made from conventional raw materials is the primary substitute for sludge-based non-structural concrete.
Other alternative materials for non-structural applications, such as fiber-reinforced composites or recycled plastics, could pose a substitute threat.
Sludge-based concrete may have environmental advantages that make it a more attractive substitute compared to some alternatives.

Figure 13. The PFF of the WTS non-structural concrete

Figure 14 illustrates the five forces of Porter for the application of WTS in cement production. New companies in this industry may face many challenges as it is a capital-intensive industry and special facilities are needed. Existing WTS cement production companies may have deep relationships with WTPs and may restrict access to resources. Also, as it is a highly delicate industry, regulatory settings and environmental considerations may create challenges for new entrants. WTPs have a high bargaining power as they are the only suppliers of the WTS, and other suppliers of raw materials for cement production also have a high bargaining power as they have established connections and abundant supplies. Additionally, cement machinery manufacturers may have bargaining power that needs special attention. On the other hand, cement buyers may have limited bargaining power if there are only a few manufacturers offering WTS cement. Also, buyers who are more concerned with sustainable development goals or specific project requirements may have higher bargaining power.

The cement industry is highly competitive, with strong rivals. Existing traditional cement producers will face increased competition, which will influence price, quality, and other production standards to be more competitive. Moreover, the WTS cement is highly susceptible to being replaced mainly by traditional cement. Also, new materials such as geopolymers and low-carbon concrete are likely to be substituted by WTS cement if they gain traction.



Entry barriers for new cement manufacturers using sludge as a raw material may be high due to the capital-intensive nature of the industry and the need for specialized production facilities.
Existing cement manufacturers may have well-established relationships with water treatment plants, limiting new entrants' access to a consistent sludge supply.
Regulatory requirements and environmental considerations can also pose challenges for new entrants in the cement industry.

Water treatment plants may have significant bargaining power as suppliers of sludge to cement manufacturers.
Suppliers of alternative raw materials for cement production (e.g., limestone, clay) may have higher bargaining power due to their abundance and established supply chains.
Suppliers of equipment and machinery for sludge processing and cement production may also have some bargaining power.

The cement industry is highly competitive, with established players and global manufacturers.
Existing cement manufacturers may face increased competition if sludge-based cement gains market share.
Price, quality, sustainability, and customer relationships will be key factors influencing competitive rivalry.

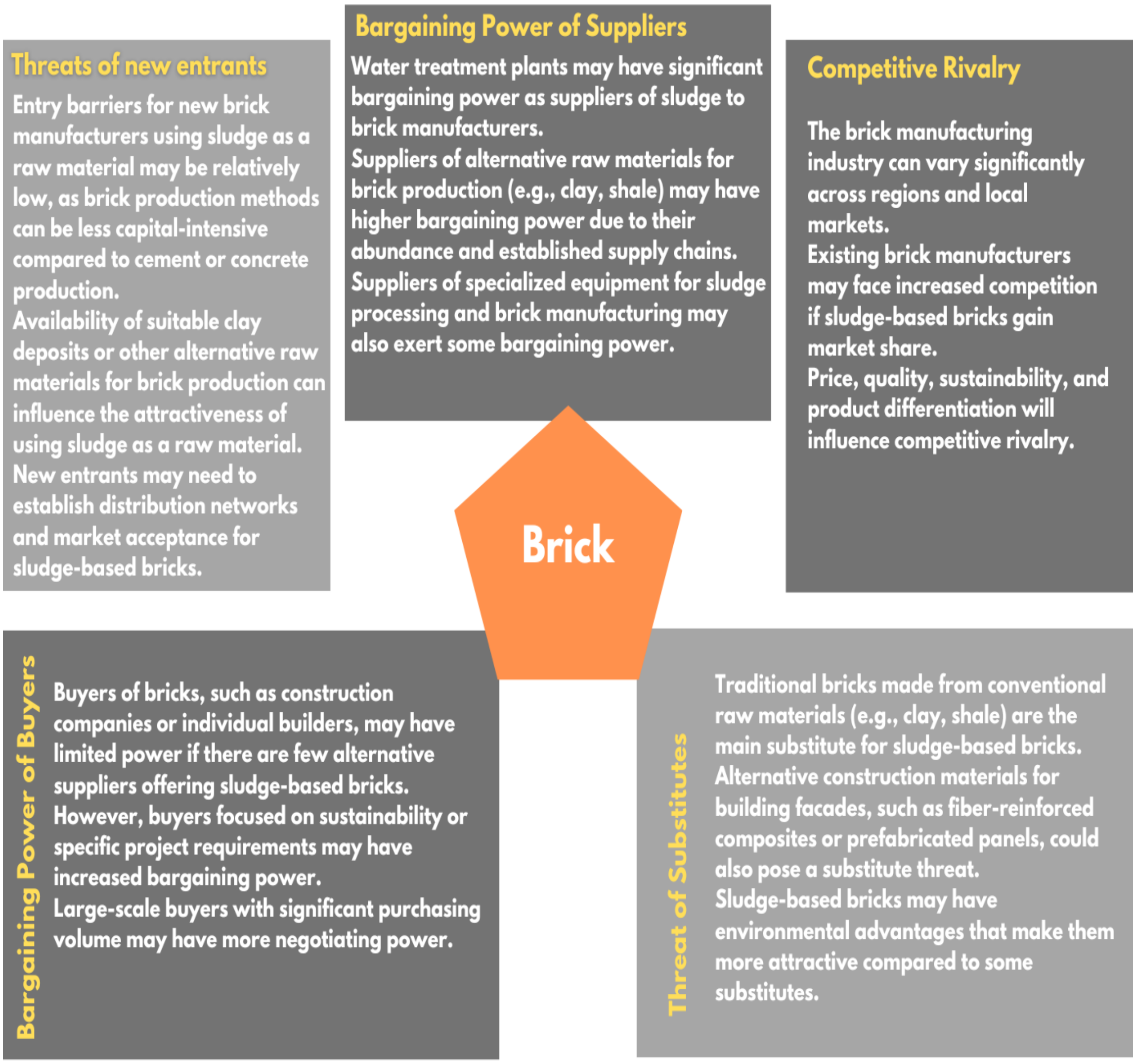
Cement buyers, such as construction companies and infrastructure developers, may have limited power if there are few alternative cement suppliers offering sludge-based cement.
However, buyers focused on sustainability or specific project requirements may have increased bargaining power.
Large-scale buyers with significant purchasing volume may have more negotiating power.

Traditional cement made from conventional raw materials is the primary substitute for sludge-based cement.
Alternative construction materials, such as geopolymers or low-carbon concrete, could also pose a substitute threat if they gain traction.
Sludge-based cement may have environmental advantages that make it more attractive compared to some substitutes.

Figure 14. The PFF of the WTS cement

Figure 15 shows the five porter's forces for the application of WTS in the production process of brick. As this is a less capital-intensive industry, new entrants may face fewer challenges. The availability of suitable clay deposits and other raw materials may create difficulties for new companies. They have to strengthen their relationship in the market and try to enhance public acceptance of WTS brick. The competitiveness of this industry varies significantly among different regions and local markets. If WTS brick production can successfully gain market share in the industry, existing manufacturers may face increased competitiveness, which is highly dependent on price, quality, and product differentiation.

Water treatment plants and suppliers of raw materials and specialised equipment for brick production may have high bargaining power due to their abundant supplies and relationships. On the other hand, brick buyers, including construction companies and local builders, may have limited bargaining power if there are few suppliers. Large-scale buyers, due to their high purchasing volume, have more negotiating power. Moreover, the main production substitute for the WTS brick is the traditional brick, followed by fiber-reinforced composites and pre-fabricated panels. Being environmentally friendly is one main advantage of the WTS brick.



Threats of new entrants

Entry barriers for new brick manufacturers using sludge as a raw material may be relatively low, as brick production methods can be less capital-intensive compared to cement or concrete production.
Availability of suitable clay deposits or other alternative raw materials for brick production can influence the attractiveness of using sludge as a raw material.
New entrants may need to establish distribution networks and market acceptance for sludge-based bricks.

Bargaining Power of Suppliers

Water treatment plants may have significant bargaining power as suppliers of sludge to brick manufacturers.
Suppliers of alternative raw materials for brick production (e.g., clay, shale) may have higher bargaining power due to their abundance and established supply chains.
Suppliers of specialized equipment for sludge processing and brick manufacturing may also exert some bargaining power.

Competitive Rivalry

The brick manufacturing industry can vary significantly across regions and local markets.
Existing brick manufacturers may face increased competition if sludge-based bricks gain market share.
Price, quality, sustainability, and product differentiation will influence competitive rivalry.

Bargaining Power of Buyers

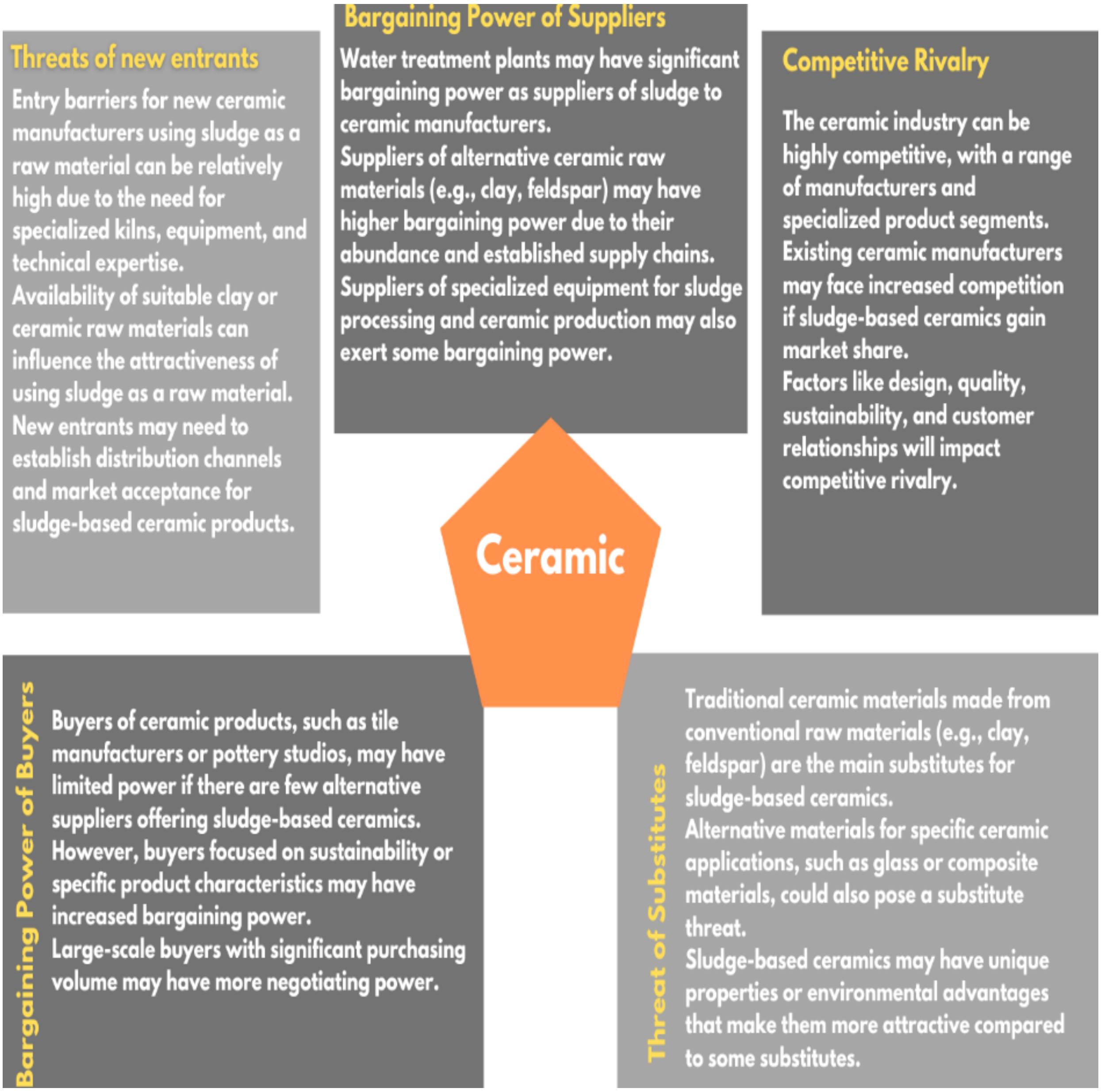
Buyers of bricks, such as construction companies or individual builders, may have limited power if there are few alternative suppliers offering sludge-based bricks.
However, buyers focused on sustainability or specific project requirements may have increased bargaining power.
Large-scale buyers with significant purchasing volume may have more negotiating power.

Threat of Substitutes

Traditional bricks made from conventional raw materials (e.g., clay, shale) are the main substitute for sludge-based bricks.
Alternative construction materials for building facades, such as fiber-reinforced composites or prefabricated panels, could also pose a substitute threat.
Sludge-based bricks may have environmental advantages that make them more attractive compared to some substitutes.

Figure 15. The PFF of the WTS brick

The porter's forces of the WTS ceramic production are illustrated in Figure 16. As special equipment, kilns, and technical expertise are essential in this industry, new entrants have a relatively hard start. They have to use their time to establish connections and gain market share to be successful. This is a highly competitive industry, as there are a range of different manufacturers with various sizes. Factors such as design, quality, sustainability, and customer service may influence the competitive rivalry. The bargaining power of WTPs is significantly high due to the limited amount of sludge disposal. Also, equipment and other raw material suppliers like clay and feldspar may have high bargaining power due to their established supply chains and the abundance of their materials. On the contrary, buyers of WTS ceramic productions, such as pottery studios and tile manufacturers, have relatively low bargaining power if there are limited sources offering WTS ceramic. However, buyers focused on sustainability criteria and large-scale purchasers have higher bargaining power. Furthermore, traditional ceramic products, followed by specific ceramic applications such as glass and composite materials, are considered the main threat to substitutes. Though WTS ceramic may have unique properties and be environmentally friendly, this can create an additional attraction for buyers.



Threats of new entrants

Entry barriers for new ceramic manufacturers using sludge as a raw material can be relatively high due to the need for specialized kilns, equipment, and technical expertise.
Availability of suitable clay or ceramic raw materials can influence the attractiveness of using sludge as a raw material.
New entrants may need to establish distribution channels and market acceptance for sludge-based ceramic products.

Bargaining Power of Suppliers

Water treatment plants may have significant bargaining power as suppliers of sludge to ceramic manufacturers.
Suppliers of alternative ceramic raw materials (e.g., clay, feldspar) may have higher bargaining power due to their abundance and established supply chains.
Suppliers of specialized equipment for sludge processing and ceramic production may also exert some bargaining power.

Competitive Rivalry

The ceramic industry can be highly competitive, with a range of manufacturers and specialized product segments.
Existing ceramic manufacturers may face increased competition if sludge-based ceramics gain market share.
Factors like design, quality, sustainability, and customer relationships will impact competitive rivalry.

Bargaining Power of Buyers

Buyers of ceramic products, such as tile manufacturers or pottery studios, may have limited power if there are few alternative suppliers offering sludge-based ceramics.
However, buyers focused on sustainability or specific product characteristics may have increased bargaining power.
Large-scale buyers with significant purchasing volume may have more negotiating power.

Threat of Substitutes

Traditional ceramic materials made from conventional raw materials (e.g., clay, feldspar) are the main substitutes for sludge-based ceramics.
Alternative materials for specific ceramic applications, such as glass or composite materials, could also pose a substitute threat.
Sludge-based ceramics may have unique properties or environmental advantages that make them more attractive compared to some substitutes.

Figure 16. The PFF of the WTS ceramic

DISCUSSION

The results showed that the alum present in WTS has the capability to be used in the cement industry [47]. Bignozzi [47] investigated the viability of incorporating WTS into the Portland cement production process by seeking out the best circumstances under which clay could be substituted with WTS. The new clinker showed that the compressive strength of the masonry has increased, and the setting time showed satisfactory results. Husillos Rodrguez et al. [48] also employed spray-dried WTS to evaluate using this additive in cement production. The powdery substance produced by the spray drying method has the same particle size as Portland cement. Organic matter made up between 13% and 14% of the substance, whereas minerals made up 35%. The bulk of the sludge's organic portion is comprised of fatty acids, which are a byproduct of the buildup of microbial biomass during the sludge-building process. By using a 12% clinker obtained through the spray process, Husillos Rodrguez et al. [48] discovered no variations in crystal size or composition between the test sample and the control. Thus, they reasoned, spray-dried WTS may serve as a partial substitute for limestone in the cement industry, in addition to replacing the clay. In other studies, Dahhou et al. [49] used alum sludge instead of limestone to form some clinkers and set a sintering range of 1300 to 1500 degrees Celsius. There was a significant presence of alite (C3S) and belite in all of the clinker compositions, and the compressive strengths and flexural of the cement pastes burnt at 1450 and 1500 °C were much greater than those of regular Portland clinker (C2S). However, most of the studies in this field have considered factors such as setting time, mechanical strength, mineralogical properties, and leaching tests. Although these parameters look necessary, they are not enough. Due to the presence of some compounds, including chloride and sulfate, that are harmful to concrete and are able to, for example, speed up the corrosion process of bars in concrete, more studies need to be conducted to assess the long-term durability and microstructure of WTS cement [40]. Kaosol [50] utilised WTS to create fine aggregate for concrete manufacturing. The research showed that using 10% to 20% WTS in the mixture in order to create pores for structural concrete and up to 50% WTS in the mixture for lightweight concrete can reduce costs without causing a major change in the concrete's properties. Sales et al. [51] investigated the usefulness of the utilising WTS in ultra-lightweight cement sample. They invented a combination of WTS, wood products, and lumber and achieved an acceptable amount for a specific mass for non-structural elements, water absorption, and compressive strength.

Tang et al. [52] conducted research on the production of LWA using sediment from reservoirs. Their proposed manufacturing process involved depositing, dredging, air drying, dewatering, crushing, heating, graining, stockpiling, conveying, and the packing. Synthetic aggregates were made using a rotary kiln. The test results showed that the reservoir sediments, with densities between 1.01 and 1.38 g/cm3, are a potential main resource. The manufactured aggregates matched the technical specifications of structural lightweight concrete and had a bulk density of less than 880 kg/m3 for coarse aggregates, as specified by ASTM C330. Additionally, Huang & Wang [53] suggested a method for producing lightweight aggregates from WTS generated during the chemical coagulant water treatment process. Through laboratory experiments, including two phases, Lightweight aggregates that conformed to ASTM C330 were successfully procured. A new method for using WTS as an internal curing agent for concrete was investigated by Cao and Kevern [54]. As an alternative to conventional internal curing agents like a superabsorbent polymer and prewetted lightweight fine aggregate, they employed lime sludge from a WTP. There was a 24% improvement in cement hydration and an 8% improvement in compressive strength after 7 days when sludge was added to the cement mortar mix, compared to the control mortar. At 28 days, autogenous shrinkage was also decreased by 25%. WTS's performance under the same conditions as the other two standard internal curing agents was comparable. Moreover, He et al., [55] investigated the impact of adding WTS ash into the concrete to improve the microstructure and strength of the material. By reducing the water-binder ratio and adding up to 10% WTS ash, they observed that the strength and shrinkage resistance improved.

ECONOMIC ASSESSMENT OF THE SLUDGE'S STRUCTURAL APPLICATIONS

Research regarding the economic assessment of the sludge's structural applications is so limited; however, Lundin et al. [55] analysed the economic consequences of four different recycling and disposal methods for municipal sewage sludge. Among agricultural applications, co-incineration with waste, incineration combined with phosphorus recovery (Bio-Con), and fractionation including phosphorus recovery (Cambi-KREPRO), the economic analysis showed that the agricultural application had the lowest cost, while co-incineration was the most expensive method. Zhou et al. [56] presented a new approach for the development of sludge cellulose plastic composite (SPC) recovered from wastewater treatment. They tried to replace the wood in wood-plastic composite (WPC) with SPC and conducted an economic assessment in line with circular economy goals. To increase the integration properties, they used two chemicals called maleic anhydride (MA) and vinyl trimethoxysilane (VTMS) agents. These helped to improve how well the SPC and WPC materials stuck together. The implementation of the eco-efficiency assessment of the study found that the SPC performed better in terms of environment and economy than the WPC. Sludge cellulose can be a better replacement for wood or natural fibers to make WPC. Chimphango et al. [57] studied if they could make boards that are strong, light, and good for the environment by using paper sludge (PS). The PS was made dry and combined with magnesium phosphate cement to create boards using a specific design called central composite design. The boards they made were not too thick or too thin, and they could be used inside buildings. Calcium carbonate was found to be the best filler among fly ash, calcium carbonate, and silica fume. By implementing an economic analysis, they looked at four different ways to get resources from different places, and they studied how much it would cost and how effective it would be to produce these composites. Then they combined all the ways together to see what might work best. The study found that if the cost of materials used to make a product went down, the price the product needed to be sold for to make a profit would also go down. The study found that the best choice for making money in the future was to do the combined plan. It was also the least expensive option.

CONCLUSION AND FUTURE STUDY

This study has made significant strides in the development of an intelligent and sustainable framework for the management of water treatment sludge, with a particular emphasis on integrating industrial ecology and eco-environmental considerations. Through extensive statistical computations and historical analyses, we gained valuable insights into sludge production and the operational efficiency of WTPs within the context of our case study. The comprehensive categorization of the literature on WTP sludge applications in construction materials has resulted in the creation of a robust database that can serve as a foundation for future meta-analytical investigations.

By extracting key parameters such as economic viability, environmental impact, ease of operation, durability, quality, and safety measures from various construction products, we established crucial benchmarks for the decision-making process. The integration of state-of-the-art MCDM algorithms, including the OWA, AHP, and TOPSIS, facilitated effective analysis and ranking of potential solutions, enhancing the efficiency and accuracy of our approach.

Furthermore, the implementation of PFF appraisal through questionnaires and descriptive statistical analyses provided a comprehensive conceptual model for assessing the competitive landscape within the industry. This strategic analysis enabled the identification of potential risks and opportunities within the realm of sludge management, paving the way for informed decision-making and proactive planning.

Moving forward, future research endeavours should focus on the practical implementation and validation of the proposed smart sustainable framework in real-world contexts, encompassing diverse water treatment plants and locations to gauge its adaptability and efficacy across varied settings. The incorporation of advanced AI and machine learning algorithms holds the promise of further enhancing the precision and efficiency of sludge management scheduling. Additionally, conducting comprehensive life cycle assessments and cost-benefit analyses will be imperative in providing a holistic evaluation of the environmental and economic implications associated with diverse sludge management strategies. To ensure the effective implementation and widespread adoption of the framework, collaborative efforts with key stakeholders, including WTP operators, professionals in the construction industry, and environmental organizations, will be crucial.

In conclusion, this study represents a notable contribution to the advancement of sustainable practices in water treatment sludge management. The proposed intelligent and sustainable framework, coupled with the application of cutting-edge MCDM algorithms and Porter's Five Forces analysis, offers a comprehensive and systematic approach to decision-making, while also taking into account industrial ecology and eco-environmental considerations. The successful adoption of this framework holds immense promise for enhancing the efficiency, sustainability, and ecological implications of water treatment sludge management in the years ahead.

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