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Zeolite mining industry in the Visegrad Group (V4) countries: a SWOT-AHP analysis of strategic, economic, and environmental factors

Introduction

The extraction of raw materials forms the foundation of industrial production, influences macroeconomic indicators, and is a key factor in international trade, impacting both socio-economic development and environmental areas (Baglioni and Campling 2017; Regueiro and Alonso-Jimenez 2021). The importance of efficient management and rational use of natural resources is emphasized by the United Nations, which has set the goal: "By 2030, achieve the sustainable management and efficient use of natural resources" (United Nations 2015).

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Among such resources are zeolites, which have numerous practical applications due to their unique adsorption, ion-exchange, molecular sieve, and catalytic properties (Bish and Ming 2001; Kunecki et al. 2021). Growing awareness of sustainability is a key, sustained force driving the global natural zeolites market. As environmental concerns intensify, zeolites are emerging as eco-friendly materials (Morante-Carballo et al. 2021; Grifasi et al. 2025). Beyond their environmental benefits, industrial minerals such as zeolites are increasingly recognized as "development minerals" (Franks 2020). Unlike globally traded high-value metals, their extraction generates strong local production linkages, substantial employment, and direct inputs for critical domestic sectors like construction and agriculture.

In recent years, synthetic zeolites have dominated the market. However, many studies and industries still focus on the need for practical applications of natural zeolites (Wdowin et al. 2014; Kunecki et al. 2021). Projections suggest that the global natural zeolites market size will expand from USD 13.27 billion in 2023 to approximately USD 17.11 billion by the year 2030 (Virtue Market Research 2023). The natural zeolites market also felt the reverberations of the COVID pandemic. Supply chains faltered, causing constraints in raw material accessibility and logistics. Moreover, industries reliant on natural zeolites, like construction and agriculture, faced temporary suspensions or reduced pace owing to widespread lockdowns and imposed limitations.

Despite these temporary disruptions, the fundamental demand for natural zeolites is sustained by their diverse applications. A comprehensive analysis identified key application areas for zeolites, including construction materials, animal feed, agriculture, catalysts, water treatment, healthcare, and gas filtration (VMR 2021). Additionally, smaller application segments such as household products, pet litter, cosmetics, and traction control agents were highlighted through an examination of offerings from primary producers, secondary processors, and re-sellers. Natural zeolites serve as essential raw materials in environmental engineering, forming the foundation for numerous technologies aimed at ecosystem treatment and protection.

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Consequently, the diverse applications of natural zeolites emphasize their critical role in advancing regional sustainability. Utilizing domestic natural zeolites rather than imported or synthetic alternatives significantly reduces transportation costs and adds substantial value to local enterprises and the regional economy (Alsawalha 2019). For resource-rich countries, the responsible extraction of zeolites provides essential, eco-friendly solutions that address pressing environmental challenges while directly stimulating local socio-economic growth.

However, fully unlocking this socio-economic potential is a complex endeavor. The viability and development of mining operations in the industrial minerals sector depend not only on the availability of resources but also on various other factors, including proximity to consumption centers, efficient transport infrastructure, favorable geological conditions, land use compatibility, societal acceptance, and environmental considerations (Kyle and Elliott 2019). These criteria are equally relevant to the natural zeolite mining industry, where deposits must be both economically and logistically viable to ensure effective, low-cost production and meet growing industrial demand.

The zeolite mining industry in parts of the V4 countries of Slovakia and Hungary represents an important segment of the European natural resources market. In the context of global sustainability challenges, analysis of the zeolite sector in these countries requires consideration of economic, environmental, and social aspects. This study is relevant as natural zeolite deposits in the V4 countries provide a valuable, eco-friendly raw material that could play a key role in addressing environmental challenges such as water purification, air filtration, and waste management – critical components of global sustainability efforts.

While natural zeolites are widely studied for their applications, there is a significant knowledge gap in the literature regarding the comprehensive evaluation of the zeolite mining sector in Central Europe. Previous studies have rarely integrated multidimensional strategic, economic, and environmental factors using quantitative Multi-Criteria Decision-Making (MCDM) tools, specifically for this region.

To fill this gap, this article aims to assess the potential and challenges of the natural zeolite mining industry in the countries of the Visegrad Group (V4), i.e., an informal regional form of cooperation between four Central European countries – Poland, the Czech Republic, Slovakia, and Hungary. Furthermore, it aims to support companies in strategic decision-making, enhance competitiveness, and promote long-term industry growth.

To achieve these objectives, the main factors relevant to the development of the V4 zeolite mining companies were identified and evaluated using SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis in combination with the Analytical Hierarchy Process (AHP). This methodological approach is an effective tool for prioritizing strategies and makes it possible to solve real MCDM problems (Afolayan et al. 2020). By integrating SWOT and AHP methods, the study aggregates knowledge, empirical evidence, and diverse opinions, offering insights into how well-prepared the sector is to face challenges and seize opportunities.

1. Methodology

The study employed a three-step methodology:
1) identification of relevant factors and integration into the SWOT analysis,
2) pairwise comparisons between SWOT factors and groups, and
3) AHP-based calculation process for generating rankings and recommendations.

1.1. Identification of relevant factors and integration into the SWOT analysis

SWOT analysis is a strategic management tool widely utilized in various fields (Helms and Nixon 2010), including for strategic planning in the raw materials sector (Hayati et al. 2023). It provides a systematic approach to evaluating both internal and external factors, potentials, and pitfalls, offering fact-based insight for decision-making and strategy formulation. The method includes internal factors, such as the strengths and weaknesses of an organization, project, product, technology, or sector that are under its control. It also considers external factors, such as opportunities and threats, which affect the evaluated entity but are beyond its control.

Meanwhile, SWOT analysis has shortcomings when used as a stand-alone assessment tool. One of the disadvantages of SWOT analysis is its subjectivity. While this approach allows for the simplification of complex issues by presenting a manageable list of grouped factors, this reduction requires human judgment, which can lead to inconsistency and lack of comprehensiveness (Helms and Nixon 2010). Another disadvantage of SWOT is the lack of hierarchy between factors and the absence of analytical tools to determine the importance of the factors (Spanidis et al. 2023).

In the first stage of this study, strengths, weaknesses, opportunities, and threats for the zeolite mining industry of the V4 countries were identified based on the analysis of scientific articles, grey literature, industry reports on the zeolite market, data provided by zeolite companies on websites, and experts' knowledge. In addition, the identification and refinement of the factors were supported by expert discussions conducted during workshops and webinars organized within the framework of a completed research project that underpins the present study.

To keep the number of factor comparisons at a manageable level at further stages of analysis (Saaty 1990), a reduction of factors was made, i.e., some of the related factors were listed as a single factor. This also affects a greater chance of responses from experts due to the reduced complexity of the questionnaire (Brudermann and Sangkakool 2017). Analysis of the collected materials and the use of experts' knowledge made it possible to prepare a set of 16 factors – 4 factors in each group of strengths, weaknesses, opportunities, and threats.

The resulting set of factors reflects expert judgments and perceptions rather than firm-level cost accounting data or quantitative benchmarking, which is consistent with the exploratory and decision-support character of the SWOT-AHP methodology. Accordingly,

the assessment aims to capture perceived strategic constraints and advantages of the zeolite mining sector rather than to provide a detailed empirical cost comparison between countries or producers.

1.2. Pairwise comparisons between SWOT factors and groups

The factors selected in the SWOT analysis were evaluated using a pairwise comparison within every SWOT group (each group needs 6 comparisons of factors – a total of 24 combinations), as well as a comparison of the four SWOT groups (6 combinations). The process of determining the relative importance of factors is accomplished by assigning values using the nine-step comparison scale developed by Saaty (Saaty 1990).

The scale includes only odd numbers, with a range of 9:1 meaning that factor X is absolutely preferred over factor Y, and a range of 1:9 meaning that factor Y is absolutely preferred over factor X. A range of 1:1 means that the two factors X and Y are equally important (Figure 1). This approach transforms subjective evaluations into numerical values that reflect the knowledge of the respondents.

The assessment was conducted by experts – stakeholders in projects and research related to natural zeolites in V4 countries – by completing a dedicated online questionnaire (Computer-Assisted Web Interview method). The study ultimately used 16 fully completed questionnaires received from experts with relevant scientific backgrounds and professional experience of at least 8 years.

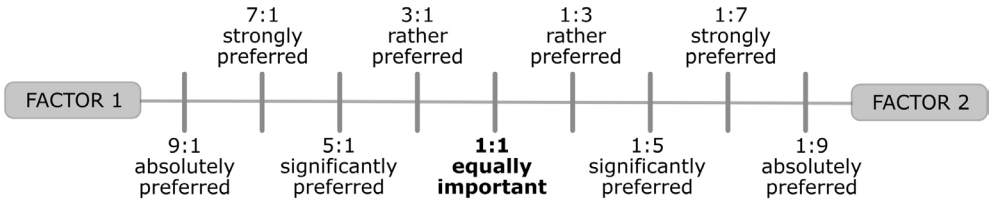

Fig. 1. Intensity of importance on an absolute scale implemented in the study

Rys. 1. Stopień ważności w skali bezwzględnej wykorzystanej w badaniu

1.3. AHP-based calculation process for generating rankings and recommendations

SWOT analysis is proposed in combination with the AHP method to determine the relative importance of each identified factor. While SWOT analysis is recommended as a hybrid method (Ghazinoory et al. 2011), improvements in the usefulness of this method have been made by using the MCDM technique (Kurttila et al. 2000). AHP ranking provides a quantitative extension of SWOT analysis and is used to prioritize SWOT elements.

To support decision-making the AHP method was used according to the methodology proposed by Saaty (Saaty 1990, 1999). AHP involves pairwise comparisons (step 2) to rank the relative importance of criteria and prioritize them using an eigenvalue calculation. However, it is noted that the results depend on the participating experts. The resulting averages of all respondents' ratings were used to create reciprocal matrices to determine the relative weights of the factors. Factor priorities (local priorities relative to other group factors) and SWOT category priorities (group priorities) were derived by multiplying each rating matrix by itself and calculating the right principal eigenvector. Further calculations also determined the global factor priorities by multiplying the local priorities by the group ones.

To assess whether the evaluations made are logically justified and whether respondents' answers are arbitrary, a consistency check was performed, with the calculated consistency ratio (CR) having to meet the condition CR < 10% (Saaty 1990).

2. Results

2.1. SWOT analysis

SWOT factors for zeolite mining companies from the V4 countries were identified based on various resources and experts' knowledge. They have been condensed into four main components within each group: strengths, weaknesses, opportunities, and threats.

2.1.1. Strengths

Within the SWOT analysis, strengths are internal advantageous characteristics or resources directly related to the zeolite mining entities from V4 countries:

[S1] ***High-quality zeolite deposits.*** One of the distinguishing strengths of the zeolite sector in the V4 countries is the presence of high-grade deposits of natural zeolite. The strategic location of the V4 countries, combined with the purest deposit of natural zeolite in Europe (e.g., Nižný Hrabovec and Kučin quarries can contain more than 80% of clinoptilolite), can be leveraged to build a sustainable competitive advantage in the market. The quality of the product is strictly dependent on its zeolite content, due to the desirable properties (Colella 2005). Both high-quality products with over 80 wt.% of zeolite (usually clinoptilolite) and materials with only 40 wt.% of zeolite (the rest being waste rock, e.g., clays, quartz, opal-CT, feldspars) are available on the global market (RMC 2025). Low-quality raw materials are most often used in construction, such as aggregate, and are often sold as zeolite material. In contrast, high-quality zeolite materials are used in high-value applications, which allows companies to make good returns and be highly competitive (Borsatto and Inglezakis 2012; U.S. Geological Survey 2024).

[S2] ***Diversified portfolio of zeolite products.*** Systematically introducing diversified and certified products into the portfolio has stabilized and subsequently increased the market share of V4 entities, including expanding exports through Europe to Southeast Asia and South America. V4 firms are characterized by an individualized approach to clients and the adaptation of products to many segments, as well as penetrating advanced markets. A competitive advantage that every firm must have to compete in the global market is a broad vision of products and the socio-environmental business landscape (Dashwood 2014; Yousefian et al. 2024). The zeolite products sold are dedicated to various sectors, such as agriculture, construction, industry, medicine, environmental protection, and domestic use, and are tailored to many applications in these areas.

[S3] ***Advanced quality management.*** Quality certifications, such as ISO 9001:2015, ISO 14001:2015, and FAMI-QS, along with in-house research laboratories, enable V4 companies to deliver high-quality products that comply with European standards. Continuous process monitoring and the implementation of measures for ongoing improvement of the management system allow for the supply of stable, high-quality, and safe products (Sfreddo et al. 2021). Certified enterprises with state-of-the-art manufacturing facilities and their research infrastructure incorporate the latest trends and regulations, offering environment-friendly solutions for long-term sustainability (Huang and Li 2018).

[S4] ***Strong domestic presence.*** Zeolite mining and processing entities have a strong position in the local market while building a worldwide presence. Slovakia currently does not import unprocessed natural zeolite, with more than 95% of its zeolite production being exported (VMR 2021). In Hungary, zeolite production is mainly for export, with only about one-third consumed in the domestic market. The absence of imports indicates that the application fields are suitably covered by the locally obtained materials and products.

Companies such as ZEOCEM Ltd. maintain a competitive market position, with gross margins above the average compared to other leading global enterprises (VMR 2021). High gross margins reflect robust management, operational efficiency, and the ability to generate profits from operations (Novy-Marx 2013). Slovak and Hungarian firms are well-positioned in the market and have the potential for further growth. Several firms in Poland and the Czech Republic process zeolite to sell and distribute their own branded zeolite materials. The leading producers of zeolite sold to these markets are the Slovak enterprises, which sell natural clinoptilolite in various size fractions.

2.1.2. Weaknesses

Another group is weaknesses, which are internal factors that can limit entities' effectiveness and hinder the achievement of their goals.

[W1] ***Labor costs.*** Compared to other regions, especially developing countries, labor costs in V4 countries can be relatively higher. Rising wages significantly affect

labor-intensive industries, reducing the competitiveness of companies in developed economies (Liuyi et al. 2023). It should be emphasized that labor costs are treated here strictly as an economic cost component affecting price competitiveness, and not as a normative assessment of labor standards or social protections, which are a necessary condition for responsible and sustainable mining operations. Various factors contribute to the increase in labor costs, including payroll tax rates, social security contributions, minimum wage regulations, urbanization, and population aging. This can lead to higher production expenses for zeolite and make it challenging to compete with producers from countries with lower wages, such as China or the USA (Trading Economics 2024). Within the SWOT-AHP framework, this factor reflects expert perceptions of cost-related constraints rather than an evaluation of labor policy or social conditions.

[W2] ***Material and logistics costs.*** Costs associated with processing, transporting, and insuring products can increase overall production expenses and affect price competitiveness in the global market. Energy consumption in mining operations represents a significant share of operating outlays, highlighting the intensive nature of energy use throughout various mining processes (Igogo et al. 2021). Additionally, high logistics charges can limit a firm's flexibility in adjusting product prices to competitive levels in the global market (Borsatto and Inglezakis 2012; Kar and Datta 2020).

[W3] ***Environmental impact of mining.*** Mining activities are associated with a decrease in environmental quality in the area of mineral deposits (Agboola et al. 2020). Open-pit mining can cause air, soil, and groundwater pollution, as well as noise emissions, which may lead to legal issues and negative public perception (Kafu-Quvane and Mlaba 2024). The pollution resulting from zeolite extraction through conventional open-pit mining is moderate, primarily due to increased dust and noise levels. Additionally, quarry operations result in significant landscape degradation and environmental costs connected with the reclamation of the area after extraction termination (Espinoza and Morris 2017; Sobczyk et al. 2020).

At the same time, zeolite mining companies strive to minimize environmental burdens in accordance with current directives. For example, air quality management areas are designated, and air pollution around quarries is monitored. Significant improvements in the environmental conditions around Slovak quarries are planned by 2050 (Drevko et al. 2018).

[W4] ***Competition in the internal market.*** Domestic consumption of natural zeolite in zeolite-producing V4 countries is low relative to their high production volumes, forcing mining entities to compete within a limited domestic market. As Domaracká et al. (2015) note, this intense local competition often drives companies to compete primarily on price, a challenge further exacerbated by a general lack of customer awareness regarding zeolite products.

Furthermore, the lack of differentiated cooperation networks and over-reliance on isolated efforts can hinder the market's full innovative potential (Visser and Atzema 2008). While

established collaborations typically drive innovation and joint problem-solving (Huang and Li 2018), the current absence of such strategic partnerships can weaken the position of V4 enterprises in the global market.

2.1.3. Opportunities

Opportunities are a group of external factors that can benefit companies and enable growth. Identifying these triggers allows entities to take advantage of market opportunities and increase their competitiveness.

[O1] ***Demand for adsorbents in diverse sectors.*** Increasing demand for adsorbents presents a potential growth opportunity for zeolite materials (Morante-Carballo et al. 2021). Due to its adsorption properties, zeolite can be an effective and cost-efficient solution in water purification processes, removal of toxic substances, improvement of feed production parameters, and many other applications. The growing demand for low-cost adsorbents further boosts interest in natural zeolite, paving the way for development and increased sales for producers of this raw material (Borsatto and Inglezakis 2012).

[O2] ***New applications of zeolites.*** Discovering new applications for zeolite can open up new markets and business opportunities. In recent years, zeolite research has undergone notable development, leading to advances in catalysis and adsorption processes (Morante-Carballo et al. 2021). Furthermore, this development has expanded the applications of zeolites to areas such as energy storage. This dynamic growth in the zeolite sector continues, promising further innovations and advancements in the future (Yan and Yu 2023).

[O3] ***Positive consumer trends.*** Consumers are increasingly seeking products that align with their environmental values, preferring those with lower impacts (Li et al. 2021). The rising interest in sustainability is likely to increase the demand for natural zeolite as an eco-friendly alternative (Grifasi et al. 2025). Promoting its applications can benefit producers, who can leverage this trend to attract new customers and markets.

[O4] ***Exploring new markets.*** Expanding into emerging markets, such as Southeast Asia or Central and South America, represents another opportunity. As the mineral industry becomes more globalized, increased international investments are reshaping market dynamics, allowing both large and small companies to operate in new regions (Upstill and Hall 2006). Strengthening advertising efforts, systematically introducing certified products into the portfolio, and improving export logistics will help stabilize and increase market share in international markets.

2.1.4. Threats

The last SWOT category is threats, i.e., external factors that can negatively affect companies' operations and challenge their stability and development. Identifying these threats helps entities prepare for potential challenges and develop strategies to mitigate their impact.

[T1] ***Regulatory constraints.*** Regulatory constraints affect various aspects of operations – from mining and processing to sales and export. An important role is played by intensifying environmental regulations, which may introduce new requirements or restrictions (Söderholm et al. 2015). Environmental standards can also be challenging, especially in light of increasing pressure for sustainable development. Zeolite companies must comply with ecological directives aimed at minimizing environmental burdens. ESG (Environmental, Social, and Governance) reporting challenges are becoming increasingly significant as investors and consumers value transparency and environmental responsibility more and more. Deregulation in various regions has also led to increased foreign investment and expanded mining operations, although this can introduce complexity as enterprises navigate differing legal frameworks (Upstill and Hall 2006; Dashwood 2014). Import and export regulations, including taxes and tariffs, can significantly impact costs and international sales opportunities. Changes in these regulations can result in greater trade barriers or rising operational expenses. Therefore, firms must continuously monitor the regulatory environment and be prepared to adapt to changing conditions.

[T2] ***High competition in established markets.*** The presence of many well-established players who have been operating in these markets for a long time leads to intense competition. This situation can put pressure on profit margins, as entities must compete not only on the quality of their products but also on price. The low cost of switching suppliers increases this dynamic, allowing customers to easily move between suppliers in search of better deals. Trade conditions that are favorable in some countries may not always reflect the commercial realities in others (Borsatto and Inglezakis 2012), making it challenging to maintain lasting customer relationships and achieve revenue stability.

The high level of regional concentration in the zeolite market means that a few firms can dominate the market, making it difficult for new players to enter and expand. These markets often operate based on strong business relationships and long-term contracts, which can pose a barrier for new companies trying to gain market share. Ultimately, the large number of suppliers in the zeolite market can lead to market saturation, where only enterprises offering significant cost advantages or unique added values will be able to sustain and grow their business.

[T3] ***Availability of substitutes.*** The increasing popularity of alternative substances also impacts the zeolite market. New materials that can offer comparable or better properties at lower prices add another layer of competition, potentially reducing the

market share of zeolite. This includes the abundance of alternative raw materials and synthesized zeolite materials. Raw substitutes for zeolites vary depending on the application; for example, diatomite or bentonite can compete with zeolite in applications such as construction, heavy metal removal, or animal feed (Šljivić et al. 2009; Eroglu et al. 2017; Kapeluszna et al. 2021).

The natural zeolite market also faces competition from synthetic zeolites (Yan and Yu 2023). Synthetic zeolites are a major alternative to natural ones, driven by rapid technological changes. They can be tailored to have specific physical and chemical properties and typically exhibit more consistent quality than their natural counterparts. Significant advancements include new zeolite structures and the development of innovative synthesis strategies. Competition is evident in applications where the controlled features of synthetic zeolites are more desirable. Thus, the natural zeolite market may be threatened, especially if synthetic zeolites offer better customization to customer needs and more competitive pricing (Król 2020).

[T4] ***Economic uncertainty and crises.*** Economic uncertainty poses a significant threat to the natural zeolite mining industry. Economic recessions, political changes, and associated crises such as wars or pandemics can substantially impact the demand for zeolite across various sectors, jeopardizing market stability and the industry's long-term growth (Humphreys 2019; Laing 2020). Key risks stemming from economic uncertainty include reduced demand and supply chain disruptions, financial and economic constraints, violations of regulations and sanitary standards, and an uneven pace of economic recovery.

2.2. AHP ranking

The AHP method enables all SWOT groups and factors to be prioritized and ranked according to their importance. When comparing SWOT groups, the highest values were given to those with a positive impact, i.e., strengths (0.40) and opportunities (0.27), which is reflected in the dominant positions of positive factors. The other two groups have even twice lower priorities – for threats it is 0.19, and for weaknesses it is 0.15 (Table 1).

Within the strengths group, the highest relative priorities are [S1] *High-quality zeolite deposits* (0.42) and [S2] *Diversified portfolio of zeolite products* (0.30). A significantly lower priority is achieved by [S3] *Advanced quality management* (0.21), while the factor [S4] *Strong domestic presence* (0.07) is relatively insignificant for the advantage of the analyzed zeolite V4 companies.

Among the weaknesses, [W1] *Labor costs*, [W2] *Material and logistics costs,* and [W3] *Environmental impact of mining* achieve similar relative priorities in the range of 0.29–0.33. Experts considered [W4] *Competition in the internal market* (0.07) as the least significant factor. According to the respondents, the weaknesses have the lowest impact on the development of the surveyed field.

Table 1. Individual priorities of SWOT factors established for the zeolite mining industry in the V4 countries

Tabela 1. Priorytety poszczególnych czynników SWOT ustalone dla przemysłu wydobywczego zeolitów w krajach V4

SWOT group	Factor symbol	Factor	Factor priority	Overall priority
Strengths Priority: 0.399	S1	High-quality zeolite deposits	0.42	0.17
	S2	Diversified portfolio of zeolite products	0.30	0.12
	S3	Advanced quality management	0.21	0.09
	S4	Strong domestic presence	0.07	0.03
Weaknesses Priority: 0.146	W1	Labor costs	0.29	0.04
	W2	Material and logistics costs	0.31	0.04
	W3	Environmental impact of mining	0.33	0.05
	W4	Competition in the internal market	0.07	0.01
Opportunities Priority: 0.266	O1	Demand for adsorbents in diverse sectors	0.33	0.09
	O2	New applications of zeolites	0.28	0.07
	O3	Positive consumer trends	0.30	0.08
	O4	Exploring new markets	0.09	0.02
Threats Priority: 0.189	T1	Regulatory constraints	0.22	0.04
	T2	High competition in established markets	0.15	0.03
	T3	Availability of substitutes	0.33	0.06
	T4	Economic uncertainty and crises	0.30	0.06

The main opportunities for V4 zeolite mining enterprises are [O1] *Demand for adsorbents in diverse sectors* (0.33), [O2] *New applications of zeolites* (0.28), and [O3] *Positive consumer trends* (0.30). The factor [O4] *Exploring new markets* is evaluated as being of relatively low importance for the future of this business (0.09).

The factor [T3] *Availability of substitutes* was considered the greatest threat (0.33). Simultaneously, [T4] *Economic uncertainty and crises* (0.30) are also important in terms of threats to the progress of V4 entities. The factors [T1] *Regulatory constraints* (0.22) and [T2] *High competition in established markets* (0.15) have no major influence.

Using the consistency ratio, the AHP results based on expert assessment can be considered sufficiently consistent, meeting the CR <10% assumption (Table 2).

The obtained results show that, in the experts' assessment, potential weaknesses and threats are less important than groups of opportunities and strengths (Figure 2). The overall priorities highlight the importance of [S1] *High-quality zeolite deposits* and [S2] *Diversified*

Table 2. Consistency ratios for AHP assessments

Tabela 2. Współczynniki spójności dla ocen AHP

Comparisons	CR [%]
Strengths	3.46
Weaknesses	0.84
Opportunities	6.51
Threats	8.57
SWOT factors	2.86

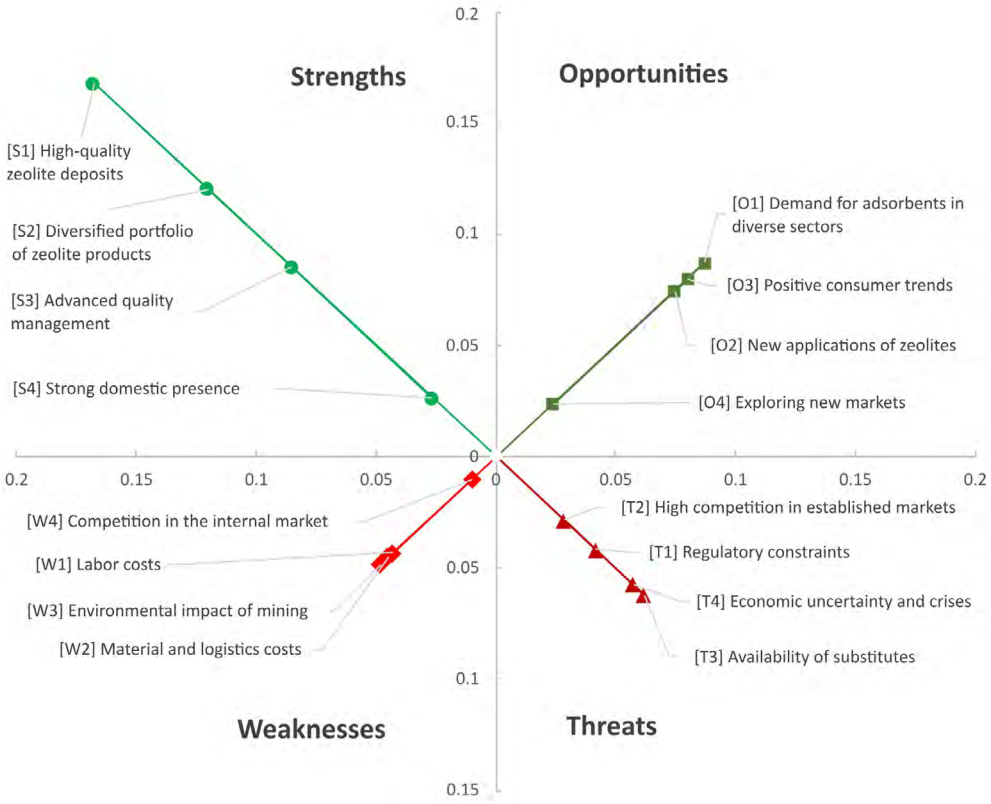

Fig. 2. Graphical interpretation of SWOT-AHP results. The lengths of the straight lines indicate the relative overall importance of the SWOT factors, with the outermost points representing the factors with the highest global priority. Overall priorities of strengths and opportunities dominate over weaknesses and threats

Rys. 2. Graficzna interpretacja wyników SWOT-AHP. Długości linii prostych odzwierciedlają względne, całkowite znaczenie czynników SWOT, gdzie punkty najbardziej oddalone od środka oznaczają czynniki o najwyższym globalnym priorytecie. Globalne priorytety mocnych stron i szans przeważają nad słabymi stronami i zagrożeniami

portfolio of zeolite products as the most significant factors for V4 zeolite mining companies among all those analyzed. The next dominant factors are also related to strengths – [S3] *Advanced quality management* as well as opportunities like [O1] *Demand for adsorbents in diverse sectors*, [O3] *Positive consumer trends,* and [O2] *New applications of zeolites*. Among the negative factors, the threats [T3] *Availability of substitutes* and [T4] *Economic uncertainty and crises* are the most influential, followed closely by [W3] *Environmental impact of mining*, which ranks higher than the lowest rated strength [S4] and opportunity [O4].

3. Discussion

The results of the SWOT-AHP analysis are useful in formulating potential strategies for the area of zeolite mining companies in the V4 countries. It is helpful to compare external against internal capabilities to identify possible courses of action. Strategies were identified based on the relative importance of SWOT factors, using the eight factors that received the highest priorities (Lee et al. 2021) (Table 3).

Table 3. Strategy selection based on calculated factor priorities using the SWOT-AHP method

Tabela 3. Wybór strategii w oparciu o priorytety czynników wyznaczone metodą SWOT-AHP

Internal / External		S	W
		S1 (0.17) | **S2** (0.12) **S3** (0.09) | S4 (0.03)	W1 (0.04) | W2 (0.04) W3 (0.05) | W4 (0.01)
O	**O1** (0.09) | **O2** (0.07) **O3** (0.08) | O4 (0.02)	S (S1, S2, S3) + O (O1, O2, O3)	–
		SO strategy	WO strategy
T	T1 (0.04) | T2 (0.03) **T3** (0.06) | **T4** (0.06)	**ST strategy**	WT strategy
		S (S1, S2, S3) + T (T3, T4)	–

The obtained priority values allow for a focused consideration of the strength-opportunity (SO) and strength-threat (ST) strategies among the discussed options. The SO approach is the most proactive, enabling enterprises to leverage key assets, such as high-grade deposits and product diversity, to enter new markets and develop novel applications for zeolite. Meanwhile, the ST strategy is essential in light of the availability of zeolite substitutes and global threats that may impact market stability. Diversification and investments in production efficiency are crucial for maintaining competitiveness in a rapidly changing market environment.

Given the lower priorities of the remaining factors, the weakness-opportunity (WO) and weakness-threat (WT) strategies are less significant.

The SO strategy involves leveraging strengths to maximize available opportunities. For zeolite mining firms in the V4 countries, this approach allows them to fully utilize their resources, such as high-quality zeolite deposits [S1], diverse product offerings [S2], and advanced quality management processes [S3], to meet growing market opportunities. These strengths can be used to capitalize on the growing demand for zeolite in various sectors [O1], enhancing competitiveness. The high quality of raw materials makes zeolites especially desirable for developing premium added-value products (Borsatto and Inglezakis 2012). High-grade zeolite deposits provide companies with a competitive advantage in markets that require products of premium purity and performance, such as pharmaceuticals, veterinary medicine, environmental protection, agriculture, and the chemical industry.

V4 region entities offer a diverse range of zeolite products, enabling entry into varied market segments and effectively taking advantage of development opportunities in new zeolite applications [O2]. Success in competition can be further enhanced by adopting environmentally friendly technologies. Zeolites are finding an expanding range of uses, from environmental protection to energy storage, positioning these firms to thrive in a dynamic, sustainability-focused market landscape.

Entities that invest in research and development can create innovative products and technologies that open up new markets and increase profitability (Upstill and Hall 2006; Sánchez and Hartlieb 2020). This allows enterprises to respond effectively to the growing demand for adsorbents, which are needed, for example, in animal food production where the natural origin of the raw material is also important.

Advanced quality management, supported by certifications such as ISO 9001:2015 or ISO 14001:2015, ensures continuous process improvement, enabling products to meet the highest quality standards. This is especially important in the context of positive consumer trends, where customers are increasingly looking for environmentally friendly products with proven reliability. Companies with a good quality management system can better adapt to these trends, building customer confidence and expanding their market (Herrmann et al. 2000). Important in this regard is to know the individual needs and to regularly monitor customer satisfaction in terms of the standards and safety of the products supplied.

The SO strategy can help firms increase their market share by diversifying their offerings [S2], investing in research and development to introduce additional applications for zeolite [O2], and enhancing marketing efforts for eco-friendly and innovative products in response to growing consumer interest [O3]. Aligning with the high prioritization of the SO strategy in the SWOT-AHP matrix, these actions will minimize the risk of stagnation and strengthen the competitive position of V4 firms. As part of the SO strategy, entities can pursue growth through an "organic growth strategy", using their resources and capabilities. To achieve profitable growth, enterprises should have integrated operations throughout the entire value chain, from extraction to initial processing and transport of zeolite.

The ST strategy is also crucial, particularly in protecting companies against external threats by leveraging their strengths. As reflected in our results, with high product quality [S1] and a diverse portfolio [S2], enterprises can face competition from substitutes [T3] and navigate economic crises [T4] more effectively. This strategy enables V4 firms to build stability and resilience in the face of unpredictable market shifts. The V4 natural deposits, which are rich in clinoptilolite, allow entities to compete with substitutes such as synthetic zeolites or other porous solid sorbents. The high quality of natural zeolites enables firms to offer products with superior physicochemical properties, creating a competitive edge over cheaper alternatives. By maintaining high product quality, enterprises can effectively mitigate the threat of substitutes, using their strengths to sustain market advantage.

Diverse products enable companies to be more flexible in responding to market changes and economic crises (Ding et al. 2023). When certain sectors, such as construction, face difficulties, firms can shift focus to other areas. At such times, agriculture or environmental protection may prove to be less susceptible to economic downturns, offering more stable opportunities. A diversified portfolio, along with targeting raw materials as zeolite products for various industries, helps zeolite businesses minimize risks associated with economic uncertainty.

Enterprises with strong quality management systems have greater operational stability, which is crucial during economic crises (Sfreddo et al. 2021). Adhering to quality standards allows firms to maintain their market position, even in challenging economic conditions, by building trust among customers.

Given that substitutes pose the greatest threat, a key element of the ST strategy will be the development of niche markets where substitutes have limited availability or do not offer the same quality. It is important to strengthen marketing efforts that highlight the advantages of natural zeolites compared to substitutes. In this context, firms should also focus on developing research departments or establishing close collaboration with institutions that are working on new zeolite applications in response to real market needs.

Furthermore, enterprises can rely on their strengths to focus on developing higher value-added products, which will help maintain competitiveness even amid intensified market competition and economic instability.

However, maintaining this competitiveness and financial stability is directly challenged by regulatory constraints [T1]. Although the AHP analysis assigned a moderate weight to this threat, its impact on day-to-day operations is undeniable. As highlighted in the broader mining literature, the regulatory environment, particularly taxation and royalties, can significantly increase operating costs and weaken the overall economic viability of mining operations (Yıldız 2020, 2022a). In the V4 countries, the fiscal regime for the mining sector is multidimensional and involves corporate income taxes, property taxes, mining area fees, and royalties for extracted minerals (Gałaś et al. 2021). According to Simonidesova et al. (2021), the tax burden varies across the region; while Slovakia and the Czech Republic rely heavily on corporate income and labor taxes, Poland and Hungary impose relatively higher property and capital taxes (Vartašova and Červená 2022). Furthermore, unpredictable tax

shifts can create severe hold-up risks for mining investors and represent a notable financial constraint for ongoing operations (Laporte and Quatrebarbes 2015; Kulczycka et al. 2017). Recently, legislative shifts, such as the implementation of consolidation packages in the Czech Republic, which restructured the royalty systems (Koudelková et al. 2025), and in Slovakia, which introduced new minimum corporate taxes and increased social security contributions (KR Group 2026), continue to elevate the overall financial pressure on enterprises. Nevertheless, despite these stringent regulatory and fiscal conditions, empirical evidence suggests that zeolite mining in the region's active deposits remains economically viable for operating businesses. As demonstrated by Šimková et al. (2019), such extraction projects maintain robust profitability for operators, generating a positive Net Present Value over the life of the mine, even after fully accounting for local taxes and royalties. Furthermore, Domaracká et al. (2015) emphasize that the economic viability of these mining enterprises is successfully secured by processing raw zeolites into high-added-value products, which ensures high profit margins and effectively offsets the rising costs of regulatory compliance.

This focus on value creation is also essential for international trade. Exports from V4 countries to Asian or American markets may lose significance due to the increasing impact of logistics costs, particularly for zeolites used in lower-added-value applications. Currently, V4 companies can expand their geographical reach by focusing on the sale of high-added-value zeolites rather than adopting the opposite approach of supplying large quantities of low-quality zeolite.

Nowadays, V4 companies are continuously advancing their professional standards. Investing in management quality, technology, and production processes, including their optimization, can also help improve efficiency and reduce production costs, which in turn will enhance the flexibility of firms in the face of economic crises.

SO and ST strategies are crucial for the long-term success of zeolite mining businesses, as they enable them to leverage their strengths for growth and defense against threats, while simultaneously implementing adaptive actions. Organic growth, in this context, is particularly important, as companies can naturally expand by investing in innovation, improving operational efficiency, and broadening their product offerings (Sánchez and Hartlieb 2020; Yousefian et al. 2024).

WO and WT strategies are less of a priority but may become important in the longer term, especially if firms aim to address their weaknesses and prepare for future challenges.

The WT strategy focuses on preventing situations where current weaknesses might increase the entity's vulnerability to external threats. This means optimizing production processes, which is especially crucial in the face of rising energy costs and a high share of labor expenses [W1]. As demonstrated in the broader mining literature, labor and engineering salaries constitute a substantial portion of total operating costs, reaching up to 42% in opencast rock mines (Trzaskuś-Żak and Fuksa 2008), while across the wider mining sector they account for approximately 22.7% of annual operating expenses on average, which represents a significant financial constraint (Yıldız 2022b). To mitigate these financial burdens, especially during periods of economic uncertainty [T4], companies must adapt

their operational organization, as changes in production scale strongly affect the structure of fixed and variable wage costs, which can otherwise lead to a disproportionate increase in labor expenses (Magda et al. 2005; Gawlik 2008).

Equally important to internal cost optimization is the need to defend against external administrative pressures. In this context, another critical aspect of the WT strategy involves navigating stringent environmental regulations [T1], particularly Environmental Impact Assessments (EIA) and waste directives, by systematically minimizing the ecological footprint of mining operations [W3]. As highlighted by Söderholm (2023) and Johnson et al. (2023), intensifying environmental standards and EIA procedures present substantial administrative and financial challenges that can impair the economic viability of mining. In certain non-EU jurisdictions, such as Turkey, excessively strict and abruptly implemented waste regulations have severely compromised economic feasibility, leading to widespread license abandonment and bankruptcies among mining enterprises (Yıldız 2021; Yıldız et al. 2024). However, despite similarly strict EIA and waste regulations in the V4 countries, such a negative scenario is effectively avoided through a proactive WT strategy. Unlike unpredictable regulatory environments, the V4 countries operate within a harmonized EU legal framework characterized by precise EIA qualification criteria and screening thresholds (Gałaś et al. 2015; Gałaś and Gałaś 2016). This predictability allows zeolite mining companies to anticipate compliance requirements. By implementing rigorous EIA reporting (Kasztelewicz and Ptak 2009) and adopting comprehensive environmental monitoring systems at the earliest stages of a project, V4 enterprises effectively mitigate their internal environmental weaknesses. Consequently, they neutralize the threat of regulatory penalties, ensuring that compliance costs do not compromise the overall economic viability of their extraction projects. By proactively addressing these environmental vulnerabilities, V4 zeolite enterprises successfully safeguard their operational continuity.

As a practical extension of this defensive approach, and considering the growing importance of sustainability, enterprises can implement eco-friendly solutions to further reduce the environmental impact of mining activities. Integrating environmental management into strategic planning processes can enhance a company's competitiveness and profitability (Huang and Li 2018). Improving the company's reputation as a responsible market player can also help build trust among customers and investors, which will be important as competition intensifies.

The introduction of energy-saving technologies and process automation can significantly reduce operational costs (García-Quevedo and Jové-Llopis 2021). In this context, it is also important to utilize electricity from renewable sources across all aspects of mining activities, such as extraction, transportation, processing, and management. Powering processes like raw material pre-processing or packaging, as well as equipment and vehicles, can be achieved using energy from proprietary photovoltaic farms. These actions not only reduce energy expenses but also lower the carbon footprint of zeolite products, which has a positive environmental impact. Furthermore, optimizing logistics [W2], such as through the use of intermodal transport, can reduce transportation costs and CO_2 emissions. A key factor in

protecting both the environment and human health is dust reduction measures. This may include the regular replacement of filters, adherence to environmental standards, and the use of advanced filtration systems.

It is also necessary to secure financial resources in case of crises [T4], which is an integral part of a defensive strategy. Maintaining price levels is crucial due to the competitive substitutes [T3] and the ease with which suppliers of the material can be changed.

The WO strategy allows zeolite mining companies in the V4 region to overcome their weaknesses while maximizing market opportunities. Proper investments and a strategic approach can transform current challenges into future successes. For example, enterprises can reduce production costs through investments in new technologies and improved resource management, aligning with advanced quality management, while also responding to the growing demand for zeolite-based products [O1]. By optimizing processes and improving management, entities can succeed in new markets [O4] despite existing weaknesses. In this context, recycling zeolite waste should also be prioritized to increase the economic viability of mining operations. However, successful mineral recovery from mine waste heavily depends on the sector's access to advanced processing technologies and adequate financial support, such as R&D subsidies, special funds, or financial instruments (Jędrusiak et al. 2023; Yıldız 2024). If direct mineral recovery from these wastes is not economically feasible due to technological or financial constraints, their application in agriculture offers a highly sustainable and cost-effective alternative. Recent comprehensive reviews highlight the economic and environmental viability of using zeolite mine wastes as soil conditioners and slow-release fertilizers, which effectively improve soil properties and agricultural yields (Eroglu et al. 2017; Yıldız 2026). Furthermore, from a circular economy perspective, the ability to safely recycle "spent" zeolites, those already utilized in applications such as wastewater treatment, creates a significant competitive advantage for mining firms by enhancing the lifecycle value of their products. Instead of being discarded, pollutant-loaded zeolitic sludge can be safely solidified and stabilized in cement matrices. Due to the excellent pozzolanic activity of zeolitic tuffs, this waste can be safely stabilized and utilized as supplementary cementitious materials in the construction industry (Colella 2005).

Investments in sustainable development and solutions that reduce the negative environmental impact of extraction [W3] can also positively influence how zeolite businesses are perceived in international markets, contributing to their long-term stability and growth. Efforts to mitigate the negative effects on local communities and the environment caused by the resource extraction process should include initiatives related to corporate social responsibility (Yousefian et al. 2024). By implementing these strategies, zeolite mining companies in the V4 countries will not only be able to survive but also thrive in changing market conditions, leveraging their strengths and adapting to emerging opportunities.

Conclusions

The zeolite mining industry in the V4 countries holds significant potential as reflected in the preponderance of strengths and opportunities identified in this study. AHP ranking revealed that high-grade deposits, a diverse product portfolio, and advanced quality management systems are key strengths of this sector. However, according to the SWOT analysis, high labor costs, environmental impacts, and intense competition pose challenges that must be addressed in strategic planning. Exploring new applications and adapting to evolving regulations will be essential for the long-term success of the zeolite industry in V4 countries.

The results of the secondary data investigation and experts' insights identify the drivers and barriers influencing the growth of zeolite mining firms within the V4 countries, outlining development pathways to meet current market and environmental demands while supporting a sustainable economy. Through targeted efforts, V4 companies can enhance the geographical reach of their specialty zeolite segment and solidify their position in a growing market. The SWOT-AHP analysis highlights critical strategies for development and adaptation that could underpin long-term success for zeolite mining firms in the region. The outcomes of the factor prioritization indicate that by implementing strength-opportunity and strength-threat strategies, enterprises can not only leverage their strengths effectively but also mitigate potential risks.

The findings highlight that adapting to a changing market through expanding product offerings, aligning with customer needs, driving innovation in zeolite applications, and optimizing operational processes forms the foundation for future growth and stability. This study also aims to encourage reflection on the future of the V4 zeolite mining sector, while discussions centered on strategic challenges and opportunities in these countries may also offer valuable insights for other entities, addressing a broad range of critical factors in their operations.

Regarding the theoretical and practical contributions of the study, this research theoretically fills a significant knowledge gap by integrating multidimensional strategic, economic, and environmental factors using a quantitative SWOT-AHP approach for the Central European zeolite mining sector. Practically, this study highlights the benefits of using natural zeolites, encouraging collaboration on innovative technologies and sustainable solutions. By assessing the strengths, weaknesses, opportunities, and threats of the industry, this study provides critical information for stakeholders to make informed decisions about efficient resource management, improve the sector's resilience to global market fluctuations, and align it with environmental and social sustainability objectives. Therefore, this research significantly expands the existing knowledge regarding the current status and future potential of zeolite mining in Central Europe, and its role in addressing both regional and global development challenges.

However, it is necessary to acknowledge the limitations of the study. Methodologically, the SWOT-AHP approach inherently relies on expert judgments and perceptions, which introduces a certain degree of subjectivity. Furthermore, regarding the subject matter, the

analysis focuses on a regional macro-level assessment rather than utilizing quantitative, firm-level cost accounting data or financial benchmarking. As a result, the specific operational and economic nuances of individual mining enterprises may be generalized.

To fill these academic gaps and further develop the topic, future research should focus on micro-level investigations, utilizing quantitative firm-level financial data and cost-benefit analyses to objectively verify the strategies proposed in this study. Methodologically, future studies could expand the decision-making framework by incorporating other quantitative tools, such as Life Cycle Assessment, to thoroughly evaluate the environmental impact of mining operations. Furthermore, given the identified opportunities regarding new zeolite applications, subsequent research should conduct detailed, firm-level economic feasibility studies on specific circular economy initiatives. Finally, while this study provides a macro-regional overview, further research could involve structured focus groups with local stakeholders and mining executives to translate these regional strategies into actionable, firm-specific operational plans.

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ZEOLITE MINING INDUSTRY IN THE VISEGRAD GROUP (V4) COUNTRIES: A SWOT-AHP ANALYSIS OF STRATEGIC, ECONOMIC, AND ENVIRONMENTAL FACTORS

Keywords

strategies, natural resources, mining industry, zeolites, SWOT-AHP

Abstract

This article assesses the potential and challenges of the natural zeolite mining industry in the Visegrad Group (V4) countries: Poland, the Czech Republic, Slovakia, and Hungary. Amid global sustainability challenges, the sector is gaining socio-economic importance due to the growing demand for eco-friendly materials with unique adsorption and catalytic properties. The Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis, combined with the Analytical Hierarchy

Process (AHP), enables the identification and ranking of the industry's key internal and external factors. The SWOT-AHP results indicate that high-quality deposits, a broad product portfolio, and advanced quality management are critical regional advantages. Conversely, high labor and logistics costs, the environmental impacts of extraction, and internal market competition were identified as weaknesses. Furthermore, economic uncertainty and the availability of substitutes represent significant threats to the industry's stability. Exploring new applications, expanding to diverse sectors (such as agriculture and water treatment), and adapting to consumer trends present major opportunities for growth. Strategic priorities highlight that a strengths-opportunities (SO) approach enables firms to proactively leverage key assets to meet the growing demand for environmental adsorbents. Concurrently, a strengths-threats (ST) strategy helps mitigate risks associated with zeolite substitutes and global economic fluctuations. The article provides evidence-based recommendations to enhance regional competitiveness and sustainable development, while encouraging collaborative innovations between enterprises, policymakers, and research institutions.

PRZEMYSŁ WYDOBYWCZY ZEOLITÓW W KRAJACH GRUPY WYSZEHRADZKIEJ (V4): ANALIZA SWOT-AHP CZYNNIKÓW STRATEGICZNYCH, EKONOMICZNYCH I ŚRODOWISKOWYCH

Słowa kluczowe

strategie, zasoby naturalne, przemysł wydobywczy, zeolity, SWOT-AHP

Streszczenie

W artykule ocenione są potencjał i wyzwania branży wydobywczej zeolitów naturalnych w państwach Grupy Wyszehradzkiej (V4): Polsce, Czechach, Słowacji i na Węgrzech. W obliczu globalnych wyzwań zrównoważonego rozwoju sektor zyskuje znaczenie społeczno-gospodarcze dzięki rosnącemu popytowi na ekologiczne materiały o unikalnych właściwościach adsorpcyjnych i katalitycznych. Analiza silnych i słabych stron, szans oraz zagrożeń (SWOT) w połączeniu z metodą AHP pozwala zidentyfikować i uszeregować kluczowe czynniki wewnętrzne i zewnętrzne branży. Wyniki SWOT-AHP wskazują, że wysokiej jakości złoża, szerokie portfolio produktów oraz zaawansowane zarządzanie jakością to kluczowe przewagi regionalne. Z kolei wysokie koszty pracy i logistyki, środowiskowe skutki wydobycia oraz wewnętrzna konkurencja rynkowa to główne słabe strony. Ponadto niepewność gospodarcza i dostępność substytutów stanowią poważne zagrożenia dla stabilności branży. Odkrywanie nowych zastosowań, ekspansja do różnych sektorów (jak rolnictwo i oczyszczanie wody) oraz adaptacja do trendów konsumenckich to ogromne szanse rozwoju. Priorytety strategiczne pokazują, że podejście oparte na silnych stronach i szansach (SO) pozwala firmom proaktywnie wykorzystać atuty do zaspokojenia rosnącego popytu na adsorbenty środowiskowe. Jednocześnie strategia oparta na silnych stronach i zagrożeniach (ST) pomaga łagodzić ryzyka związane z substytutami zeolitów oraz globalnymi wahaniami gospodarczymi. Artykuł dostarcza opartych na dowodach rekomendacji mających na celu wspieranie regionalnej konkurencyjności oraz zrównoważonego rozwoju, zachęcając do innowacyjnej współpracy między przedsiębiorstwami, decydentami politycznymi i instytucjami badawczymi.