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Examining the role of digitalization and technological innovation in promoting sustainable natural resource exploitation

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ABSTRACT

In the era of technological advancement, the potential of digitalization and technical innovation to revolutionize sustainable resource exploitation has become a focal point. The promises of reduced environmental impact, heightened efficiency, and improved socio-economic outcomes underscore the transformative power that digitalization holds for resource management. To this extent, the fuzzy Analytical Hierarchy Process (AHP) and fuzzy VIsekriterijumsko KOmpromisno Rangiranje (VIKOR) methods are used to examine challenges and come up with possible solutions for the mining sector in Pakistan to adopt digital transformation. The study identifies several key challenges, sub-challenges, and strategies, giving readers a thorough grasp of digital transformation. These challenges and sub-challenges are evaluated and ranked according to their relative weights using the fuzzy AHP approach. The fuzzy VIKOR method is applied to determine strategies that can help overcome these challenges and promote digitalization and technological innovation in the sustainable exploitation of natural resources. The results of fuzzy AHP show that policy and regulation, infrastructure, and human capital are key challenges. The findings of fuzzy VIKOR indicate that robust policy development, investment in Research and Development (R&D), and leveraging global trends and partnerships are key strategies to overcome the challenges. These findings provide valuable insights for policymakers, researchers, and practitioners, offering new perspectives on integrating digital technology into the natural resource sector to foster sustainable development.

1. Introduction

Digitalization and technological innovation have revolutionized various facets of life, ushering in an era of unprecedented change and progression (Vial, 2019). As the world grapples with the aftermath of the Corona Virus Disease 2019 (COVID-19) pandemic, these technological advancements have proved instrumental in crafting resilient and adaptive systems (Abidi et al., 2022). However, exploitative practices have often led to detrimental environmental effects (Ali et al., 2022). Sustainability, therefore, has emerged as an unavoidable path, rather than a choice, especially in the post-COVID-19 era. Ensuring the sustainable exploitation of natural resources is imperative to replenish them, minimize environmental harm, and meet the needs of a growing global population (Solangi and Jianguo, 2023).

Pakistan, a developing country with a rich array of natural resources ranging from arable land to mineral resources, stands at a critical juncture in this context (Ahmed et al., 2020a,b). It has the potential to leverage its resource wealth for economic development. However, without sustainable practices, this could lead to irreversible environmental damage. Furthermore, given its vulnerability to climate change impacts, it is imperative for Pakistan to incorporate sustainable practices in resource exploitation. The path to sustainable natural resource exploitation lies at the intersection of economic growth, environmental protection, and social equity, forming what is commonly referred to as the triple bottom line of sustainability (Dai and Solangi, 2023). Embarking on this journey within the context of Pakistan entails navigating a complex interplay of factors, including the nation's diverse ecological systems, developmental imperatives, and socio-economic

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disparities. Crucially, economic growth in many developing countries, Pakistan being no exception, is intricately tied to the utilization of natural resources as a fundamental revenue stream. However, the challenge lies in deftly balancing the exploitation of these resources to propel economic development while simultaneously ensuring their sustainable management. Industries such as mining represent a significant part of the national Gross Domestic Product (GDP) and employ a few portion of its population (Jiskani et al., 2022).

Furthermore, the significance of these resources for the energy sector, coupled with their sustainable exploitation, directly influences energy security and affordability (Ali Shah et al., 2021). Therefore, interventions promoting sustainability in resource exploitation must carefully consider the economic implications and strive to foster economic growth. The environmental facet of sustainability in resource exploitation underscores the imperative to minimize adverse environmental impacts associated with these activities. Pollution, habitat destruction, and climate change are all interconnected with unsustainable resource exploitation. In the context of Pakistan's vulnerability to climate change impacts, strategies should be devised to promote efficient resource use, minimize waste, and mitigate environmental harm (Ajani and van der Geest, 2021). From a social perspective, sustainable resource exploitation must account for its impact on local communities. Many of these resources are situated in areas with indigenous populations or marginalized communities, often bearing the brunt of environmental degradation, leading to displacement or adverse effects. The role of digitalization and technological innovation should not only aim to minimize harm but also strive to deliver benefits to these communities, thereby fostering social equity (Mele et al., 2022).

Digitalization and technological innovation can play a critical role in achieving this balance. With the advent of Industry 4.0, technologies like the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), robotics, and blockchain are transforming traditional practices in natural resource exploitation (Bai et al., 2020; Javaid et al., 2022). They offer numerous benefits, including increased efficiency, reduction in waste, enhanced safety, providing mechanisms to decrease the environmental footprint (Magazzino, 2023). These technologies, coupled with advanced analytical techniques, ensure the sustainability of practices. However, the successful integration of these technologies and analytical methods in Pakistan's context is contingent upon several factors. These include infrastructure development, technical skills availability, regulatory frameworks, and the investment climate, among others. Therefore, a holistic approach is needed, which not only focuses on technological incorporation but also addresses these enabling factors.

In this regard, the study aims to explore the role of digitalization and technological innovation in promoting sustainable natural resource exploitation in Pakistan. It seeks to understand the potential of these technologies, and the applicability of hybrid fuzzy Multi-Criteria Decision Making (MCDM) approaches, i.e., Analytical Hierarchy Process (AHP) and VIekriterijumsko KOmpromisno Rangiranje (VIKOR) in guiding sustainable practices. The hybrid MCDM approaches combined with fuzzy set theory, allowing for the handling of both quantitative and qualitative data, and dealing with the inherent uncertainty and vagueness in the decision-making process (Stojčić et al., 2019). These approaches allow decision-makers to assess the challenges and solutions in Pakistan and propose recommendations to enhance sustainable practices in natural resource exploitation. The overarching goal is to contribute to the discourse on sustainable practices, offering insights that can guide policymaking and practice in the country, ultimately leading to a balance between economic development, environmental protection, and social equity.

This study delves into the complexities of sustainable natural resource exploitation in Pakistan, exploring the potential of digitalization and technological innovation. It also sheds light on the challenges that need to be overcome by determining strategies. Consequently, the objectives of this study are:

- to identify the current challenges and strategies in natural resource exploitation in Pakistan. The focus will be on the sustainability of these practices and their impact on the economy, environment, and society;
- to evaluate and rank the challenges using the fuzzy AHP method in implementing digitalization and technological innovations for sustainable resource exploitation in Pakistan;
- to prioritize the key strategies using the fuzzy VIKOR method to overcome the challenges that these technologies present for improving sustainability and propose ways to leverage them.

In a broader context, this study aims to contribute to the ongoing discourse on sustainability in Pakistan. By shedding light on sustainable practices in resource exploitation, it aspires to pave the way for a future where economic development, environmental protection, and social equity can coexist and thrive harmoniously.

The remainder of the paper follows this structure: Section 2 illustrates the related literature. Section 3 briefly shows Pakistan's mineral sector together with the design strategy. Section 4 provides the empirical methodology. Section 5 gives the empirical results and their discussion. Section 6 concludes, by proposing some policy implications.

2. Literature review

Several studies explored the current practices of natural resource exploitation and their sustainability implications. Shahbaz et al. (2012) discussed the environmental degradation in Pakistan as a consequence of economic growth and energy consumption, emphasizing the urgent need for sustainable practices. It suggests that the responsible use of natural resources is not only necessary for the environment but also for the economy (Idrees and Majeed, 2022). Moreover, the emphasis on sustainability has increased since COVID-19. According to Ibn-Mohammed et al. (2021), the epidemic has served as a wake-up call, compelling countries to reevaluate their approaches to resource exploitation and pursue more environmentally friendly solutions.

Digital technologies have the potential to change the use of natural resources. Javaid et al. (2022) show how Industry 4.0 technologies – such as IoT, AI, and ML may boost productivity, cut waste, and encourage sustainable practices in the mining sector. Similar findings were presented by Kunz (2016) in the context of water resource management. The potential of blockchain technology for increasing transparency and traceability in natural resource supply chains has also been discussed extensively in Agrawal et al. (2021) and Calvão and Archer (2021). This technology could play a pivotal role in verifying the sustainability of resource exploitation practices. The earlier study delved into the potential of blockchain technology for enhancing transparency and traceability in resource supply chains (Iansiti and Lakhani, 2017). The previous research highlighted the challenges in digital transformation for resource exploitation, which discusses information systems innovation in the context of environmental sustainability (Melville, 2010). Furthermore, a prior study underscored the pivotal role of free and open-access satellite data in biodiversity conservation. This highlights the significance of digital technologies, particularly satellite remote sensing, in facilitating improved environmental monitoring and informed conservation efforts (Turner et al., 2015). Besides, scientists pointed out the broader field of strategic management of technology and innovation. While not specific to natural resource exploitation, it provides insights into the challenges and strategies related to technological innovation in various domains (García Manjón, 2020).

In terms of decision-making frameworks, the application of hybrid fuzzy MCDM approaches has gained momentum. These approaches offer a systematic way of handling the inherent uncertainty and subjectivity in decisions related to natural resource exploitation (Xu and Solangi, 2023). They enable the evaluation of several factors, such as social, environmental, and economic ones (Xu et al., 2023). Bakhtavar et al. (2019) and Khosravi et al. (2021) provided examples of how to pick sustainable mining methods using a hybrid fuzzy MCDM methodology. They emphasized that by allowing for the evaluation of various solutions according to their sustainability, this methodology helps decision-makers make well-informed decisions.

The literature underscores several challenges in applying digitalization and technical advancements for sustainable resource extraction, including skills gaps, infrastructure deficiencies, and regulatory concerns (Manny et al., 2021; Onyango and Ondiek, 2021). Adding to this complexity is the unique environment of Pakistan, characterized by socio-economic imbalances and specific developmental requirements. Despite these challenges, there is a widespread acknowledgment that these technologies hold substantial potential to contribute to the goals of sustainable development, offering opportunities for social justice, environmental preservation, and economic expansion (Mondejar et al., 2021). Recent studies indicate a clear trend towards the application of technological innovation and digitalization to support sustainable natural resource use. These technologies present intriguing possibilities for enhancing sustainability, particularly when integrated with decision-making frameworks like hybrid fuzzy MCDM techniques. However, the existing literature also highlights significant obstacles that must be addressed to ensure the successful implementation of these technologies (Huang et al., 2024).

While there is extensive literature on the role of digitalization and technological innovation in promoting sustainable natural resource exploitation, several research gaps can be identified. Most studies focus on developed countries with advanced technological infrastructure (Park and Choi, 2019; Marti and Puertas, 2023; Radicic and Petković, 2023). Notwithstanding, a significant gap emerges in the literature specifically focused on developing countries like Pakistan, where the context and challenges might be different. There is less emphasis on a holistic perspective of natural resource exploitation across the mineral sector. While the literature has touched upon the potential of digital technologies and hybrid fuzzy MCDM approaches in sustainability (Tanveer et al., 2023; Yüksel and Dinçer, 2023), no study on the practical challenges and solutions related to implementing these technologies and methods in a developing country context can be detected.

The aftermath of the COVID-19 pandemic has brought a new paradigm to the forefront, which requires reassessment of previous strategies and the exploration of new approaches. Research is sparse, specifically in the application of digitalization and technological innovation for sustainable resource exploitation. Moreover, the literature lacks sufficient insight into how policy and regulatory frameworks in developing nations like Pakistan can be shaped to facilitate the adoption of digital technologies and innovative methods for sustainable resource exploitation. The social aspects, particularly in terms of how technology can be used to ensure social equity in resource exploitation, are not well-explored. In the scholarly arena, a noticeable gap persists in terms of quantitative and empirical research that substantiates the practical impacts and feasibility of hybrid fuzzy MCDM methods, specifically the AHP and VIKOR, within the domain of sustainable natural resource exploitation. To address these research voids, this study takes a focal point on the intricate landscape of Pakistan. Specifically concentrating on the mining sector within the broader spectrum of natural resource exploitation, the research embarks on a comprehensive exploration and assessment of the challenges and opportunities associated with the application of these hybrid fuzzy MCDM methods. By undertaking empirical research, the study seeks to offer valuable insights into the practical implications and effectiveness of these decision-making tools, providing a perspective specifically tailored to the unique context of sustainable resource exploitation in Pakistan.

3. Analysis of Pakistan's mineral sector

Pakistan boasts extensive mineral reserves that span an expansive outcrop area of 600,000 square kilometers. Within this geological wealth, a total of 92 minerals have been identified, with 52 of them being actively mined for commercial purposes, yielding a collective annual production capacity of 68.52 million metric tons (Farooqui, 2021). This sector exhibits a steady growth rate, typically ranging from 2 to 3 percent annually. The mineral sector in Pakistan holds great promise, boasting an average annual growth rate of 2–3 percent. This sector is a significant contributor to the economy, with over 5000 operational mines, 50,000 small and medium-sized enterprises, and providing direct employment to approximately 300,000 workers.

Pakistan's mineral wealth includes the world's second-largest salt mines, the fifth-largest reserves of copper and gold, the second-largest coal deposits, and estimated billions of barrels of crude oil (ICSC, 2023). Despite these abundant resources, the mineral sector's performance has been uninspiring. Alarmingly, Pakistan's mineral exports account for only about 0.1 percent of the world's total exports. In the year 2020, Pakistan's total mineral and metals exports reached around $1.18 billion, significantly lower than the world's total of $1490 billion (United Nations, 2023). Fig. 1 presents the estimated mineral resources in Pakistan.

Across the globe, many countries have effectively utilized their mineral reserves to drive economic expansion. Pakistan might adopt similar strategies by taking a cue from neighboring India, which gained $29 billion in 2021 from the export of jewelry and diamonds and $4 billion from the sale of other ores and value-added minerals. India's ascent to the position of second-largest global producer of crude steel in 2019 – having produced 111.2 million metric tons – is a striking illustration of the potential in the mineral sector (PIB Delhi, 2020). In a similar vein, countries such as Brazil have become global mining giants, generating steady profits from mineral exports. With the help of these successful examples, Pakistan must try to adopt their tactics and use its mineral riches as a boost to the country's economy. To date, though, the country has not made the most of this opportunity to propel the needed transformation.

It is imperative to explore all avenues for leveraging mineral resources to expedite wealth and value creation. Furthermore, the nation's diminished competitiveness on the global stage can be attributed to the mining sector's insufficient adoption of digitization and technological innovation. Notably, Pakistan's inclination to predominantly export raw commodities, without fully harnessing the potential for value addition that could significantly boost revenue, is a crucial aspect. To enhance Pakistan's competitiveness in the global market, the mining sector should wholeheartedly embrace digitalization and updated technology. The adoption of contemporary mining methods such as remote sensing, data analytics, and automated equipment has the potential to maximize resource extraction, reduce operating costs, and elevate safety standards.

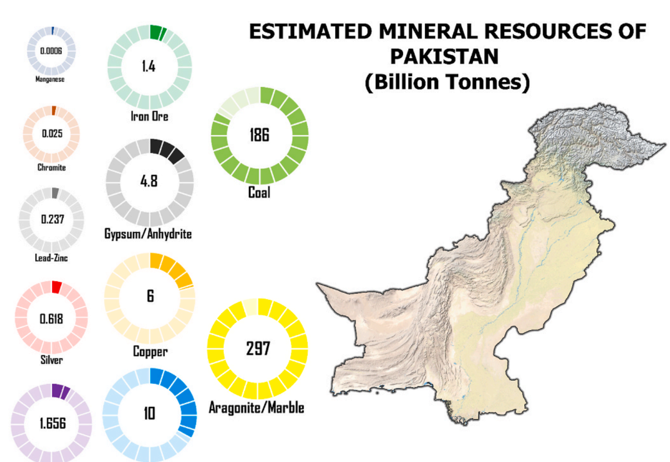

Fig. 1. Estimated Pakistan's mineral resources.
Source: Farooqui (2021).

3.1. Digitalization and technological innovation challenges in sustainable resource exploitation

The integration of digitalization and technological innovation for sustainable natural resource exploitation entails numerous challenges. Following an exhaustive literature review, we have identified several key challenges and corresponding sub-challenges, outlined in Table 1. Understanding and addressing these challenges is crucial for devising effective strategies and frameworks that can facilitate the successful integration of digital technologies in the pursuit of sustainable resource exploitation.

Table 1
Challenges and sub-challenges of digitalization and technological innovation for sustainable natural resource exploitation.

Challenge	Sub-challenge	Description
Infrastructure	Inadequate technological infrastructure	In many parts of Pakistan, basic infrastructure such as reliable electricity, internet connectivity, and data centers are lacking or unreliable, which can hinder the implementation of digital technologies.
	Lack of capital investment	The implementation of advanced technologies often requires substantial capital investment, which can be a significant hurdle, especially for small and medium enterprises.
	Obsolescent equipment	Outdated machinery and equipment can pose challenges to the integration of advanced technologies.
	Environmental constraints	Natural factors like extreme weather conditions, difficult terrains, and remote locations can impact the establishment of necessary technological infrastructure.
Human capital	Skills deficit	There may be a lack of skilled workforce who can understand, operate, and maintain the advanced technologies.
	Resistance to change	Workers and managers may resist the adoption of new technologies due to fear of job loss or discomfort with change.
	Lack of training programs	Insufficient training programs to upskill the existing workforce can act as a barrier to technology adoption.
	Inadequate research and development	Lack of focus on research and development can hinder innovation and adaptation of digital technologies.
Policy and regulatory	Lack of regulatory clarity	Absence of clear regulatory guidelines can create uncertainty for companies looking to adopt digital technologies.
	Data privacy and security concerns	With the adoption of digital technologies, concerns related to data privacy and security arise which require clear policy responses.
	Inconsistent policy environment	Inconsistent or frequently changing policies can create an unstable environment that discourages investment in technology.
	Lack of incentives	Absence of incentives or support from the government can limit the adoption of sustainable practices and technologies.
Social and cultural	Digital divide	The digital divide, characterized by unequal access to technology, can exacerbate social inequalities.
	Social acceptance	Resistance from local communities or society at large towards technological changes can act as a barrier.
	Job displacement concerns	Advanced technologies may lead to job losses in the short term, creating unrest.
	Cultural barriers	Cultural beliefs or traditional practices can sometimes act as hurdles to the acceptance of new technologies.

Effectively addressing these challenges and sub-challenges demands a multi-faceted approach that involves collaboration among stakeholders from various sectors. This collaborative effort should engage representatives from the government, industry, academia, and local communities. By fostering a comprehensive and inclusive dialogue, we can harness diverse perspectives, expertise, and resources to develop holistic solutions that navigate the complexities associated with the integration of digitalization and technological innovation for sustainable natural resource exploitation.

3.2. Strategies for sustainable resource exploitation

The challenges in implementing digitalization and technological innovation for sustainable natural resource exploitation are indeed substantial. Consequently, this study has identified eight distinct strategies to address these challenges. Fig. 2 presents a comprehensive list of significant strategies, each tailored to mitigate specific obstacles and enhance the prospects of successful integration of digital technologies in sustainable resource exploitation. These strategies encompass a spectrum of approaches, from policy interventions and capacity building to fostering collaborative partnerships and leveraging cutting-edge technologies.

3.2.1. Collaborative initiatives (ST1)

Forming collaborative initiatives such as public-private partnerships can be a significant strategy (Fraser, 2021). These partnerships can stimulate shared investment in necessary technological infrastructures and enable the exchange of knowledge, fostering a robust ecosystem for digital innovation in natural resource sectors.

3.2.2. Investment in renewable energy (ST2)

The challenge of energy shortages can be turned into a solution by investing in renewable energy technologies for sustainable development (Kul et al., 2020). Not only do these renewable energy technologies provide a solution to power digital infrastructures, but they also contribute to Sustainability Development Goals by reducing carbon emissions.

3.2.3. Emphasizing research and development (ST3)

Encouraging research and development can foster technological innovation tailored to local needs (Ediriweera and Wiewiora, 2021). It can also lead to discovering more efficient and sustainable ways of exploiting natural resources, positioning Pakistan as a leader in sustainable practices.

3.2.4. Enhanced training and education (ST4)

Developing comprehensive education and training programs to build

Fig. 2. The key strategies.

a digitally competent workforce is a key strategy (Bergamo et al., 2022). This involves prospectuses that cover the necessary technical skills and promote a culture of innovation and lifelong learning.

3.2.5. *Robust policy development (ST5)*

The creation of stable, clear, and forward-thinking policy frameworks can provide a favorable environment for digital transformation (Li et al., 2023). Such policies may encourage investment in digital technologies and ensure that the benefits of digitalization are shared equitably.

3.2.6. *Promotion of digital literacy (ST6)*

Enhancing digital literacy at all societal levels can increase acceptance of new technologies (Kabakus et al., 2023). It also equips people with skills to participate in and benefit from the digital economy, thus reducing social inequalities.

3.2.7. *Community engagement (ST7)*

Involving local communities in technology deployment and decision-making processes can ensure that interventions are socially acceptable and beneficial (Segerstedt and Abrahamsson, 2019). It can also mitigate potential social concerns and facilitate smoother technology adoption.

3.2.8. *Leveraging global trends and partnerships (ST8)*

Pakistan can capitalize on global trends and international collaborations to accelerate its digital transformation. This includes partnerships for technology transfer, capacity building, funding, and learning from best practices in sustainable development (Pandey et al., 2022).

The identified strategies offer pathways to effectively address the challenges linked with digitalization and technological innovation in the sustainable exploitation of natural resources in Pakistan. Implementing these strategies necessitates coordinated efforts from various stakeholders and a steadfast commitment to invest in the future.

4. Hybrid fuzzy-based methodology

The study employs a hybrid fuzzy-based AHP and VIKOR as comprehensive decision-making tools to address the challenges and strategies for promoting digitalization and technological innovation in sustainable natural resource exploitation in Pakistan. This methodological approach provides a systematic framework to navigate the complex challenges associated with technology adoption for sustainability (Stojčić et al., 2019). In this research, the fuzzy AHP method assesses the challenges and sub-challenges, while the fuzzy VIKOR method prioritizes key strategies related to digitalization and technological innovation for sustainable natural resource exploitation in Pakistan. Fig. 3 illustrates the applied methodology.

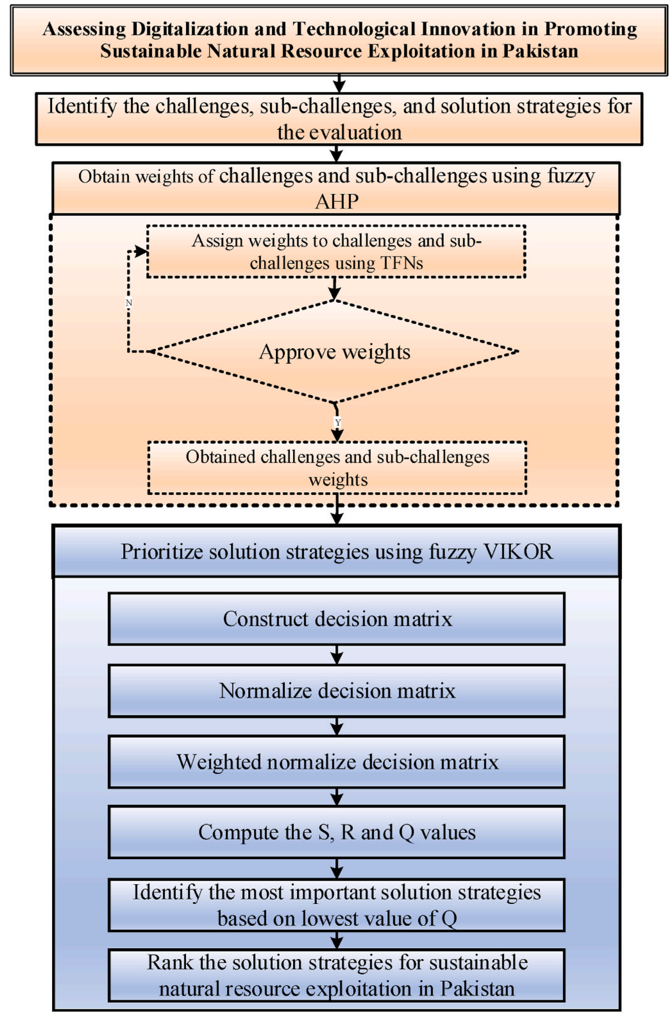

Fig. 3. Hybrid fuzzy-based methodology.

4.1. *Fuzzy AHP method*

AHP is a well-known MCDM method, which was introduced by Saaty (1990). However, in the current study, we used fuzzy-based AHP method, since assigning fuzzy numbers to the criteria employed in the decision-making process is one way that address the handling of imprecise and uncertain information (Ajrina et al., 2020). In particular, when dealing with complicated and unpredictable scenarios, this enables a more accurate scheme of the decision-making problem. The Triangular Fuzzy Numbers (TFNs) scale is presented in Table 2.

Table 2
Triangular Fuzzy Numbers scale.

Code	Linguistic variable	TFNs
1	Equally preference	(1, 1, 3)
2	Weak preference	(1, 3, 5)
3	Strong preference	(3, 5, 7)
4	Very strong preference	(5, 7, 9)
5	Extremely strong preference	(7, 9, 11)

The fuzzy AHP process involves several steps (Gogus and Boucher, 1998), including:

Step I. Construct the Triangular Fuzzy Matrix (TFM):

$$X_i = (l_i, m_i, u_i) \tag{1}$$

Then, the first TFM is created with the middle TFM:

$$X_m = [x_{ijm}] \tag{2}$$

Next, the second TFM is established for the upper and lower bounds of TFN using a geometric mean approach:

$$X_g = \left[\sqrt{x_{iju} x_{ijl}}\right] \tag{3}$$

Step II. Create and compute the weight vector and lambda max based on Saaty's method.

Step III. Create the Consistency Index (CI):

$$CI_m = \frac{\lambda_{max}^m - n}{n - 1} \tag{4}$$

$$CI_g = \frac{\lambda_{max}^g - n}{n - 1} \tag{5}$$

Step IV: Create the Consistency Ratio (CR):

$$CR_m = \frac{CI_m}{RI_m} \tag{6}$$

$$CR_g = \frac{CI_g}{RI_g} \tag{7}$$

The pairwise comparisons are regarded as consistent if the CR is less than an established threshold, which is set to 0.10. Here, the RI scale is employed, which was developed by Gogus and Boucher (1998).

4.2. The fuzzy VIKOR method

The fuzzy VIKOR approach can be applied in situations where understanding about the decision problem is hazy, partial, and uncertain (Klir, 2001). Among a range of options, the fuzzy VIKOR method aids in determining the optimal compromise solution. In order to make a final decision and cope with competing criteria and objectives, this method is especially helpful (Solangi et al., 2019a). Using TFNs can be highly beneficial in the presence of uncertainty (Shukla et al., 2014). Table 3 displays the TFNs rating scale that is commonly used in MCDM situations.

A fuzzy number is defined by a trio X = (x, y, z). The membership function of TFN is described as:

$$\mu_X(x) = \left\{ \begin{array}{c} 0, x < 1 \\ \frac{x - x}{y - x} \ \text{if} \quad x \le x \le y \\ \frac{z - x}{z - y} \ \text{if} \quad y \le x \le z \\ 0, x > 0 \end{array} \right\} \tag{8}$$

The rest of the fuzzy set process is developed according to Kim and Chung (2013). Besides, the following are the several steps of the fuzzy VIKOR approach (Ahmed et al., 2020a,b):

Step I. Construct the Fuzzy Performance Matrix (FPM):

$$\widetilde{D} = \begin{matrix} O_1 \\ \vdots \\ O_n \end{matrix} \begin{bmatrix} C_1 \, C_2 \cdots C_n \\ \widetilde{p}_{11} \widetilde{p}_{12} \cdots \widetilde{p}_{1n} \\ \widetilde{p}_{21} \widetilde{p}_{22} \cdots \widetilde{p}_{2n} \\ \vdots \vdots \vdots \vdots \\ \widetilde{p}_{m1} \widetilde{p}_{m2} \cdots \widetilde{p}_{mn} \end{bmatrix}$$

$$\widetilde{W} = (w_1, w_2, w_3), \sum_{j=1}^{n} w_j = 1 \tag{9}$$

Step II. Establish the values for the cost and benefit criterion:

$$\widetilde{p}_i^+ = \max_j \widetilde{p}_{ij}, \widetilde{p}_i^- = \min_j \widetilde{p}_{ij} \text{ for } i \in l^b \text{ (benefit criteria)}$$

$$\widetilde{p}_i^+ = \min_j \widetilde{p}_{ij}, \widetilde{p}_i^- = \max_j \widetilde{p}_{ij} \text{ for } i \in l^c \text{ (cost criteria)} \tag{10}$$

Table 3
Linguistic variables fuzzy number.

Code	Linguistic Variable	TFNs
1	Very Bad (VB)	(0.00, 0.05, 0.15)
2	Bad (B)	(0.10, 0.20, 0.30)
3	Fairly Bad (FB)	(0.20, 0.35, 0.50)
4	Fairly (F)	(0.30, 0.50, 0.70)
5	Fairly Good (FG)	(0.50, 0.65, 0.80)
6	Good (G)	(0.70, 0.80, 0.90)
7	Very Good (VG)	(0.85, 0.95, 1.00)

Step III. Compute the normalized Fuzzy Decision Matrix (FDM) $\widetilde{D}_{ij}$:

$$\widetilde{D}_{ij} = \frac{\widetilde{p}_i^+ (-) \widetilde{p}_{ij}}{z_i^+ - l_i^-} \text{ for } i \in l^b$$

$$\widetilde{D}_{ij} = \frac{\widetilde{p}_{ij} (-) \widetilde{p}_i^+}{z_i^- - l_i^+} \text{ for } i \in l^c \tag{11}$$

Step IV. Compute the values $\widetilde{S}_j = (\widetilde{S}_j^x, \widetilde{S}_j^y, \widetilde{S}_j^z)$ and $\widetilde{R}_j = (\widetilde{R}_j^x, \widetilde{R}_j^y, \widetilde{R}_j^z)$:

$$\widetilde{S}_j = \sum_{i=1}^{n} \widetilde{W}_i (\times) \widetilde{D}_{ij} \tag{12}$$

$$\widetilde{R}_j = \max_i \widetilde{W}_i (\times) \widetilde{D}_{ij} \tag{13}$$

Step V. Compute the values $\widetilde{Q}_j = (\widetilde{Q}_j^x, \widetilde{Q}_j^y, \widetilde{Q}_j^z)$:

$$\widetilde{Q}_j = v \frac{\widetilde{S}_j (-) \widetilde{S}^+}{S^{-z} - S^{+x}} (+) (1 - v) \frac{\widetilde{R}_j (-) \widetilde{R}^+}{R^{-z} - R^{+x}} \tag{14}$$

here $\widetilde{S}^+ = \min_j \widetilde{S}_j$; $S^{-z} = \max_j S_j^z$; $\widetilde{R}^+ = \min_j \widetilde{R}_j$; $R^{-z} = \max_j R_j^x$.

Steps VI and VII. Defuzzify $\widetilde{S}_j$, $\widetilde{R}_j$ and $\widetilde{Q}_j$ values.
Step VIII. Provide a solution for the alternative, which is the measure $\widetilde{Q}_j$ optimal solution.

This decision-making methodology provides a systematic, flexible, and robust approach to assess the challenges and strategies in the context of digitalization and technological innovation for sustainable natural resource exploitation.

4.3. Survey respondents

The respondents comprise a diverse group of individuals who are closely associated with the natural resource exploitation sectors in Pakistan and have a keen understanding of the impact of digitalization and technological innovation. The twenty-five respondents belong to the following four categories: 1) individuals from government departments related to natural resources, technology, and sustainability. These experts provided insights into the policy and regulatory landscape, as well as government initiatives to promote digitalization and sustainable practices; 2) representatives from industry engaged in natural resource exploitation, such as mining. It can offer a practical perspective on the current challenges and solutions in implementing digital technologies. 3) scholars from universities/research institutes focusing on natural resources, digital technologies, and sustainability. They can bring in-depth theoretical knowledge and an understanding of the latest research trends. 4) representatives from local communities impacted by natural resource exploitation activities. This can provide a perspective on social and cultural aspects, as well as the impacts at the grassroots level. Incorporating a varied group of respondents is essential for gaining a thorough understanding of the challenges and strategies involved in implementing digitalization and technological innovation for sustainable natural resource exploitation in Pakistan. The insights collected through a webmail survey from these respondents will be instrumental in fueling the hybrid fuzzy MCDM methodology. This inclusive method ensures a strong analysis of the research problem, drawing from diverse perspectives to enrich the study's findings comprehensively.

5. Results and interpretation

The AHP and VIKOR in their fuzzy form are powerful tools to handle complex decision-making problems. In this study, the fuzzy AHP method is used to analyze the main challenges and sub-challenges based on their importance. The weights provided correspond to the relative importance of each challenge category, with higher weights implying greater importance. Moreover, the fuzzy VIKOR method is applied to prioritize the significant strategies for implementing digitalization and technological innovation for sustainable natural resource exploitation in Pakistan. Fig. 4 presents the hierarchical structure of the research.

5.1. Ranking and interpretation of the challenges using fuzzy AHP

In this section, the fuzzy AHP method is used to assess and rank the key challenges (Table 4). The findings show that "Policy and Regulatory" challenges are ranked first (w = 0.274), indicating that issues related to policy and regulation are seen as the most critical barriers to implementing digitalization and technological innovation. This may include inconsistent or outdated policies, lack of clear guidelines for technology adoption, inadequate protection of data privacy and security, and regulatory uncertainty (Dehghani et al., 2022). Adequately facing these challenges is crucial because policies and regulations set the framework within which all other activities take place. Besides, "Infrastructure" challenges come second (w = 0.263), indicating that there are significant hurdles related to the basic technological and physical infrastructures necessary for digital transformation. This might involve inadequate internet connectivity, insufficient power supply, lack of necessary hardware and software, and limited access to modern

Table 4
Ranking of main challenges based on their importance.

Main challenges	Weight	Rank
Infrastructure	0.263	2
Human Capital	0.247	3
Policy and Regulatory	0.274	1
Social and Cultural	0.216	4

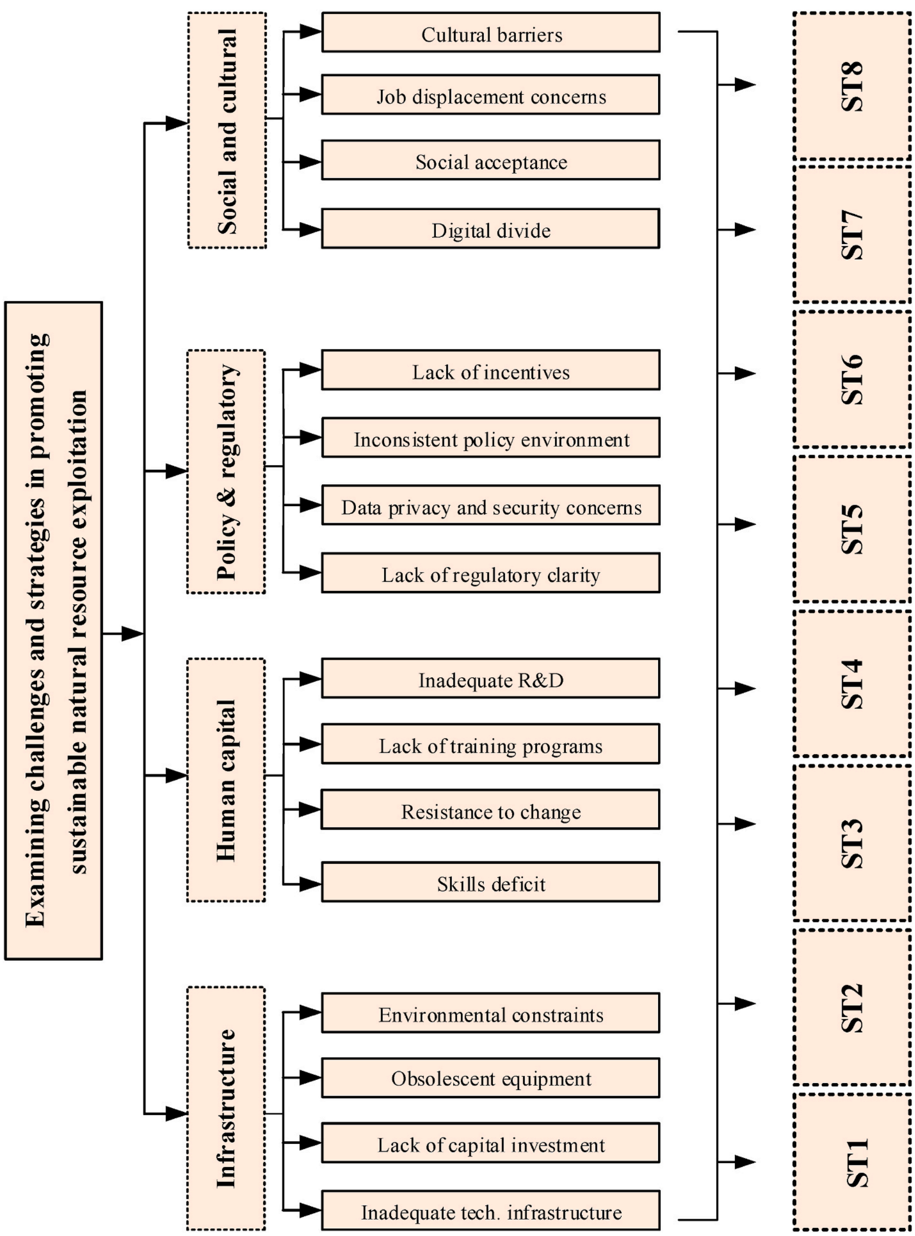

Fig. 4. The hierarchically structured methodology.

technologies in remote areas. Furthermore, "Human Capital" challenges are ranked third (w = 0.247). These are the issues tied to the skills and abilities of the workforce and might include a lack of necessary technical skills, limited digital literacy, and resistance to change among workers. Finally, "Social and Cultural" challenges received the lowest score (w = 0.216), but still represent significant obstacles to digital transformation. They involve societal attitudes towards technology, cultural norms that may resist change, and potential social impacts of technology adoption, such as job displacement. While these challenges rank lower in terms of their weight, addressing them is crucial to ensuring a socially sustainable digital transformation.

5.2. Ranking and interpretation of the sub-challenges using fuzzy AHP

Fig. 5 provides the results for the challenge "Policy and regulatory". The results reveal that "Inconsistent Policy Environment" is considered the main sub-challenge (w = 0.271), suggesting that the policy environment's inconsistency represents the most substantial barrier to the implementation of digitalization and technological innovation. Inconsistencies could arise from changes in government, frequent shifts in policy directions, or conflicting regulations among different government departments. The "Lack of Regulatory Clarity" is prioritized as the second key sub-challenge (w = 0.256), indicating a significant issue in understanding what the regulations require. Moreover, "Data Privacy and Security Concerns" (w = 0.244) reflects apprehensions about the potential misuse of data or breaches of data security in the digital transformation process (Gebremeskel et al., 2023). With the increased use of digital technologies, there is a vast amount of data generated, and ensuring its privacy and security is paramount. Lastly, the "Lack of Incentives" sub-challenge represents the lowest ranked (w = 0.229) even though a crucial factor. The absence of sufficient incentives can discourage businesses from investing in digital technologies and pursuing sustainable practices. Incentives could include tax breaks, subsidies, or other forms of governmental support.

Fig. 6 provides the results for the challenge "Policy and regulatory". The results indicate that the lack of capital investment sub-challenge receives the highest weight (0.268), implying that capital investment is crucial for developing and enhancing the necessary infrastructure for digitalization and technological innovation. Lack of funding or financial resources can lead to inadequate technological infrastructure, use of obsolescent equipment, and inability to address environmental constraints (Kul et al., 2020). "Inadequate Technological Infrastructure" is identified as the second important sub-challenge (w = 0.255), which reflects the fact that Pakistan's current technological infrastructure might not be sufficiently robust to support extensive digitalization in the natural resource sector. Likewise, "Environmental Constraints" is measured as the third key sub-challenge (w = 0.247), which emphasizes the need for infrastructural adaptations to mitigate environmental impacts. It may refer to limitations in current infrastructure to comply with environmental regulations, incorporate renewable energy sources, or ensure environmentally-friendly waste management (Huang et al., 2023). Finally, the "Obsolescent Equipment" sub-challenge (w = 0.230) highlights the problem of outdated or aging equipment that is inefficient, unreliable, and unable to support new digital technologies. It can hinder the process of digitalization and potentially lead to increased operational costs and environmental harm.

In Fig. 7 the results for the challenge "Human Capital" are given. The "Inadequate Research and Development" sub-challenge (w = 0.259) reflects the critical importance of R&D in driving technological innovation and digitalization. Indeed, the lack of robust R&D might result in a lack of innovation, limited ability to adapt to new technologies, and poor problem-solving capacity. "Resistance to Change" is the next key sub-challenge (w = 0.254), which represents the social and psychological barriers to digital transformation. It includes reluctance among workers to adopt new technologies, fear of job displacement due to automation, and cultural preferences for traditional methods. Besides, the "Lack of Training Programs" sub-challenge comes in third place (w = 0.247), implying that a lack of appropriate training programs is a significant barrier to upskilling the workforce and preparing them for the digital age (Murphy et al., 2021). This could be due to limited availability, poor quality, or lack of relevance of training programs. The issue of "Skills Deficit", though ranking last, is still a crucial sub-challenge (w = 0.240). It refers to the shortage of individuals in the workforce with the necessary technical skills to implement and manage digital technologies.

Fig. 8 summarizes the findings for the challenge "Social and Cultural". The outcomes show that the "Digital Divide" sub-challenge is ranked first (w = 0.264), suggesting that the disparity in access to digital technologies and internet services is a significant barrier to digitalization in Pakistan's natural resource sector. The digital divide can be due to socioeconomic factors, geographical location, education level, age, or other demographic attributes. The "Social Acceptance" sub-challenge receives the second score (w = 0.259), reflecting the importance of society's approval and acceptance of digital transformation in the natural resource sector. The public's perception of technology, understanding of its benefits, and trust in digital systems all play a role in social acceptance (Tan and Solangi, 2023). Then, "Cultural Barriers" is ranked third (w = 0.245) and indicates that traditional beliefs, norms,

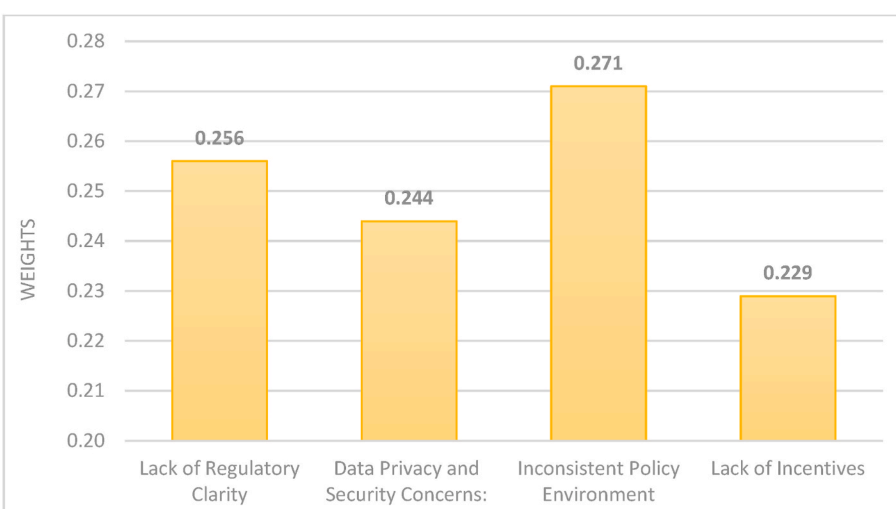

Fig. 5. Ranking for the sub-challenge "Policy and Regulatory".

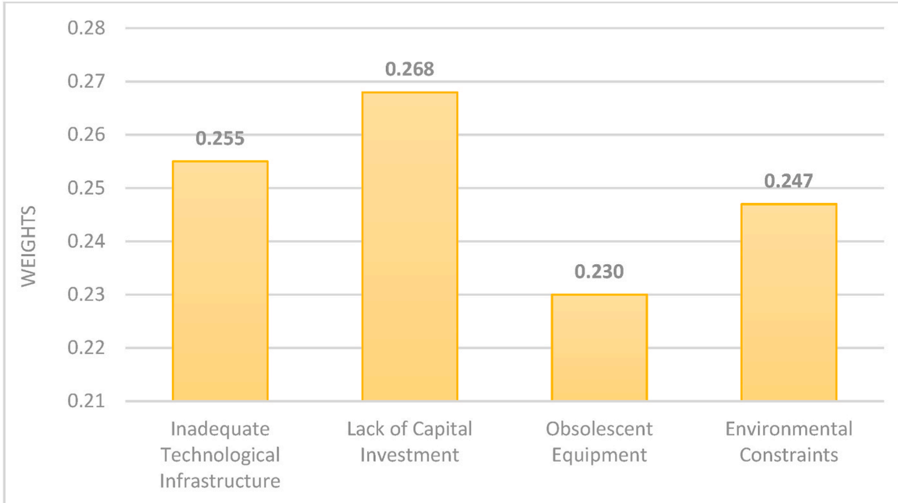

Fig. 6. Ranking for the sub-challenge "Infrastructure".

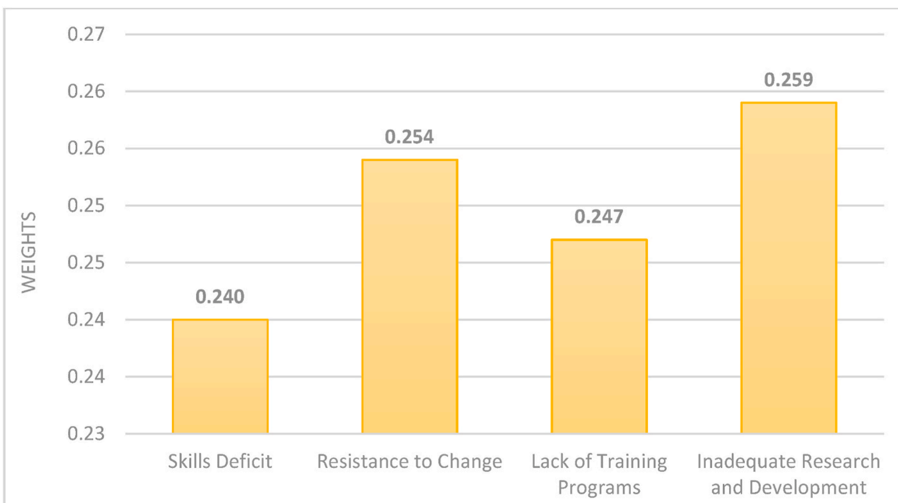

Fig. 7. Ranking for the sub-challenge "Human Capital".

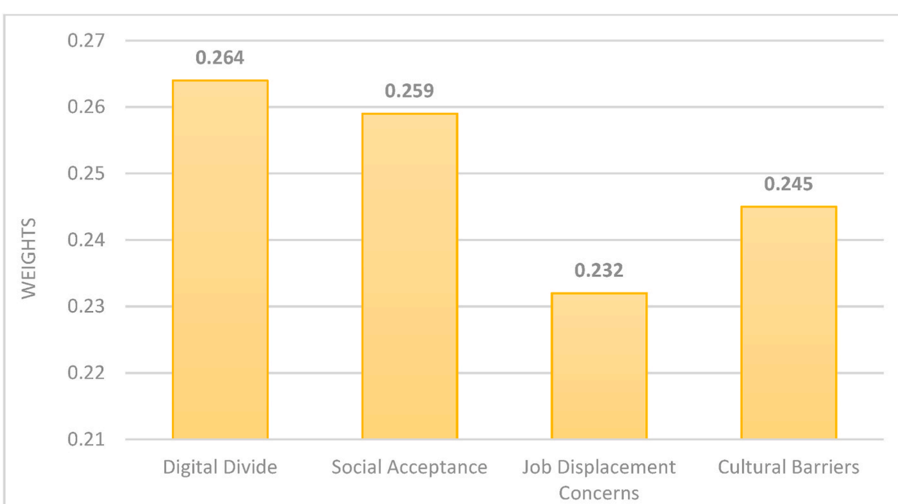

Fig. 8. Ranking for the sub-challenge "Social and Cultural".

and practices can pose significant obstacles to the adoption of digital technologies. Additionally, the "Job Displacement Concerns" sub-challenge should be considered the fourth sub-challenge (w = 0.232). The fear of job loss due to automation and the implementation of new technologies can lead to resistance to change and slow down the pace of digital transformation.

5.3. Ranking and interpretation of the strategies using fuzzy VIKOR

Table 5 displays the prioritization order of strategies based on S, R, and Q values due to the fuzzy VIKOR method. Additionally, the final ranking of solution based on the lowest Q values is given in Fig. 9.

"Robust Policy Development" is identified as the key solution (Q = 0.057), indicating that developing robust policies can substantially enhance digitalization and technological innovation. These policies can offer a consistent and clear framework for operation, provide incentives for sustainable practices, and mitigate policy and regulatory challenges. "Emphasizing Research and Development" is considered the second important strategy (Q = 0.066), reflecting the significant potential of R&D in driving innovation and technological advancements. By investing in R&D, new and efficient technologies can be developed for sustainable natural resource exploitation. R&D can also provide solutions to specific challenges such as environmental constraints and obsolete equipment. Furthermore, "Leveraging Global Trends and Partnerships" is placed third (Q = 0.071), signifying that aligning with global trends and forming strategic partnerships can help overcome many of the challenges faced in the process of digitalization. These trends and partnerships can provide access to new technologies, capital, skills, and markets, and can help address challenges such as lack of capital investment, skills deficit, and inconsistent policy environment. Next, "Investment in Renewable Energy" is recognized as the fourth solution (Q = 0.083): investing in renewable energy sources like solar and wind power can help mitigate environmental constraints, reduce dependency on non-renewable resources, and create sustainable energy infrastructure for digital technologies. Besides, "Collaborative Initiatives" is prioritized as the fifth important strategy (Q = 0.098), highlighting collaborative initiatives between various stakeholders, such as government, businesses, academia, and civil society, that can support the digital transformation process. Moreover, "Promotion of Digital Literacy" (Q = 0.104), "Enhanced Training and Education" (Q = 0.109), and Community Engagement" (Q = 0.113) strategies are still relevant.

5.4. Discussion

The digitalization and technological innovation process in sustainable natural resource exploitation brings forth considerable challenges and extensive opportunities and solutions, especially in the context of Pakistan. This study employs fuzzy AHP and fuzzy VIKOR methods to underscore these aspects and their impacts.

Initially, the findings of the fuzzy AHP method indicated that policy and regulation are the key challenges, emphasizing the critical role of clear, consistent policies and regulations in driving digitalization in the natural resource sector. The sub-challenge of the inconsistent policy environment further substantiated this point, reiterating that policy inconsistencies and regulatory ambiguities can lead to uncertainty and hinder investment in new technologies. This was followed closely by infrastructure challenges, indicating that issues like lack of capital investment and inadequate technological infrastructure are substantial barriers to digital transformation. Among the human capital challenges, inadequate research and development stood out, indicating the pressing need to invest in R&D to drive innovation and stay abreast with global advancements. Social and cultural challenges were found to be equally important, with the digital divide being the most significant barrier. This reveals a socio-economic disparity in digital access that can hinder inclusive digital transformation.

Regarding strategies, the fuzzy VIKOR method identified robust policy development as the most crucial, indicating that well-formulated policies can establish a supportive framework for digitalization and sustainable practices. Following closely is the emphasis on research and development, underscoring the potential of R&D in propelling technological advancements and offering solutions to specific challenges. Further, leveraging global trends and partnerships was also highlighted, suggesting that synergizing with global advancements and forging strategic partnerships can enhance access to new technologies, skills, and markets (Pandey et al., 2022).

Our findings align with and expand upon previous research on the digitalization of natural resource exploitation. A common thread across studies is the acknowledgment of several key challenges that must be addressed for successful digital transformation, particularly in developing countries like Pakistan. Prior research has highlighted infrastructure, human capital, policy and regulation, and social and cultural challenges as barriers to digital transformation (Manny et al., 2021). The results provide a more nuanced understanding of these challenges and their interconnections in the context of Pakistan's natural resource sector. For instance, Manny et al. (2021) highlighted the importance of infrastructure in enabling digital transformations. Our findings confirm this, emphasizing the significance of capital investment and technological infrastructure. Similarly, our study resonates with prior research by Huang et al. (2023) on the crucial role of R&D in driving technological advancements and innovation, highlighting this as a top priority for overcoming human capital challenges. The results also support the research by Guaita Marti and Puertas (2023) on the importance of a clear and consistent policy environment, reiterating this as a critical challenge and an opportunity for digital transformation in the natural resource sector (Li et al., 2023). Furthermore, the challenges of the digital divide and social acceptance that our study identified resonate with the findings of Aditya et al. (2023) and Yu et al. (2018), who pointed out the importance of addressing these social and cultural factors for ensuring inclusive and equitable digital transformation. On the opportunity front, our results confirm and build upon the insights from previous studies. For instance, the strategies identified in our study, such as robust policy development, investment in R&D, and leveraging global trends and partnerships, are well-established in the literature (Muğaloğlu et al., 2023; Solangi et al., 2019b; Solangi and Jianguo, 2023).

One of the key insights from this study is the interconnectedness of the challenges and opportunities. Addressing infrastructure challenges requires capital investment, which is linked to policy clarity and incentives. Similarly, overcoming human capital challenges like skills deficit and resistance to change is closely tied to the promotion of digital literacy and enhanced training and education. Highlighting the imperative of a holistic and integrated approach to the digital transformation of Pakistan's natural resource sector, this study emphasizes the need for collaborative efforts involving the government, businesses, academia, civil society, and local communities. Through such joint initiatives, there is potential to foster innovation, enhance capacity building, and establish a shared vision, ultimately driving forward the process of digital transformation. Therefore, this study adds to the existing body of

Table 5
Ranking of strategies based on S, R, and Q values.

Strategy	S	R	Q	Rank
Collaborative Initiatives (ST1)	0.248	0.039	0.098	5
Investment in Renewable Energy (ST2)	0.276	0.038	0.083	4
Enhanced Training and Education (ST3)	0.263	0.043	0.109	7
Emphasizing Research and Development (ST4)	0.212	0.037	0.066	2
Robust Policy Development (ST5)	0.224	0.035	0.057	1
Promotion of Digital Literacy (ST6)	0.284	0.042	0.104	6
Community Engagement (ST7)	0.276	0.044	0.113	8
Leveraging Global Trends and Partnerships (ST8)	0.269	0.038	0.071	3

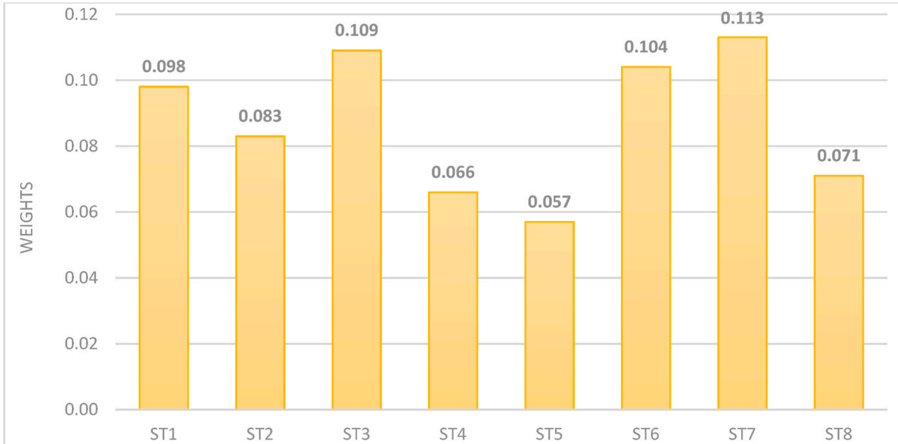

Fig. 9. Best strategies based on the lowest value of Q.

knowledge by not only reaffirming the findings of previous studies but also providing a more detailed and context-specific understanding of the challenges and opportunities for digital transformation in the sustainable exploitation of natural resources in Pakistan.

5.5. *Theoretical and practical implications*

The utilization of hybrid fuzzy AHP and fuzzy VIKOR techniques provides a reliable framework for decision-making, considering the complexities and uncertainties in the evaluation process. Through Pakistan as a case study, this research contributes to advancing our theoretical understanding by addressing challenges and proposing solutions. It sheds light on the effective application of technology innovation and digitalization in developing countries, taking into consideration specific socio-economic and environmental factors. The outcomes offer policymakers valuable guidance for formulating consistent laws and regulations that foster an environment supportive of digitalization and technological progress in the sustainable use of natural resources (Zhao et al., 2023). The theoretical and practical implications enrich our knowledge base, providing valuable insights for policymakers, industry professionals, and researchers dedicated to promoting sustainable resource exploitation through digitalization. Addressing identified challenges and seizing opportunities can pave the way for a more sustainable and digitally empowered future in the natural resource sector.

6. Conclusions and recommendations

This research has investigated how digitalization and technological innovation contribute to the promotion of sustainable natural resource exploitation in Pakistan. Utilizing the fuzzy AHP and fuzzy VIKOR approach, it systematically analyzes the challenges and proposes solutions in this particular field.

The empirical analysis identifies four main challenges i.e., infrastructure, human capital, policy and regulatory, and social and cultural, each with various sub-challenges. Policy and regulatory challenges, along with infrastructure challenges, carry the highest weights, emphasizing their crucial role in facilitating digital transformation. Key sub-challenges include the digital divide, inconsistent policies, lack of capital investment, and inadequate research and development. The study advocates for robust policy development, prioritizing research and development, and leveraging international collaborations to address these challenges and foster digitalization.

The study employs fuzzy AHP and fuzzy VIKOR to methodologically deepen the examination of challenges and strategies in digital transformation. Achieving digitalization and technological advancement for sustainable natural resource use in Pakistan is complex, but strategic planning, robust policies, and collaboration can overcome challenges and maximize opportunities. The study emphasizes the potential of digital transformation for sustainable resource use, providing a roadmap. While focused on Pakistan, its findings extend to other developing countries undergoing digital transformation.

6.1. *Policy recommendations*

After analyzing the challenges and solutions of digitalization and technological innovation for Pakistan's sustainable natural resource utilization, the following recommendations are formulated:

o Establish a robust and supportive policy and regulatory framework to facilitate digital transformation in the natural resource sector.
oEncourage investments in crucial technological infrastructure, such as reliable internet connectivity, power supply, and data storage facilities.
oAllocate resources to support research and development initiatives aimed at innovating sustainable technologies for natural resource exploitation.
oDevelop comprehensive training programs to bridge the skills gap and enhance digital literacy among the workforce involved in natural resource exploitation.
oFoster collaboration among government agencies, businesses, academia, civil society organizations, and local communities to promote innovation, knowledge sharing, and capacity building.
oPromote awareness and address social acceptance challenges by engaging with local communities, addressing cultural barriers, and alleviating concerns related to potential job displacement.
oIntroduce financial and non-financial incentives to motivate businesses to adopt sustainable practices and invest in digital technologies.
oEstablish robust mechanisms to monitor and evaluate the progress of digital transformation initiatives, measure their impact on sustainability goals, and identify areas for improvement.

6.2. *Limitations and future research*

Like any research, this study is not without limitations, which in turn provide opportunities for future research. This study primarily focuses on Pakistan's sustainable natural resource sector. While the findings are highly relevant and provide in-depth insights into this context, they may not be directly applicable to other countries or sectors. Thus, future research could extend the scope by exploring digitalization and sustainable natural resource exploitation in different geographical and sectoral contexts.

Moreover, the hybrid fuzzy MCDM approach used in this study offers a robust and systematic analysis of the challenges and opportunities. However, it is predominantly a quantitative method and may not capture the full depth and nuances of subjective experiences and perceptions. Future studies could use qualitative methods, such as interviews or case studies, to gain more in-depth insights into the issues at hand.

The perspectives incorporated in this study are from select stakeholder groups. The views of other stakeholders, including rural communities, marginalized groups, or international organizations, may provide additional insights. Future research can incorporate a broader range of stakeholder perspectives. Moreover, the study represents a snapshot of the situation in a dynamic environment. Given the rapid pace of technological advancements and policy changes, the identified challenges and opportunities may evolve over time. Future research should aim to regularly update these findings to reflect the changing context.

Finally, the study focuses on the challenges and opportunities but does not assess the impacts of digitalization on the sustainable exploitation of natural resources. Future research can focus on measuring these impacts, examining, for example, the environmental, economic, and social outcomes of digital transformation. Therefore, addressing these limitations in future research will not only enhance our understanding of the subject matter but will also contribute to more effective policymaking and practice in the field of digitalization and sustainable natural resource exploitation.

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CRediT authorship contribution statement

Pang Jianing: Data curation, Formal analysis. **Keke Bai:** Resources, Validation. **Yasir Ahmed Solangi:** Data curation, Investigation, Methodology, Software. **Cosimo Magazzino:** Project administration, Supervision, Validation, Visualization, Writing – review & editing. **Kamran Ayaz:** Conceptualization, Writing – original draft.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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