

Digital Solutions for the Management of Wastewater Storage for the Mining Industry

Leah Ledwaba¹ and Makgopa Tshehla²

¹Da Vinci Institute

²Graduate School of Business Leadership, University of South Africa

Abstract

Managing wastewater in the mining sector presents considerable issues, with extensive ramifications for operations. This study seeks to provide a comprehensive digital solution to improve the effective management of wastewater storage, with a particular emphasis on Platinum Group Metals mining. Mining is a significant danger to water safety in arid places such as South Africa, necessitating new solutions. This study adopted qualitative methodologies to discern emergent themes. The findings indicate that technologies like big data and artificial intelligence may significantly enhance the efficiency of wastewater management. Significantly, technological failures often stem from fundamental difficulties like organisational and cultural obstacles, rather than the solutions themselves. Legal and regulatory compliance exacerbates treatment procedures. This study presents a conceptual framework that amalgamates digital technology with pragmatic solutions to tackle these difficulties. The framework improves management and compliance in wastewater operations via a systematic approach, encouraging the implementation of digital technologies in the mining industry to address present and future requirements.

Keywords: Compliance, digital technologies, operational efficiency, sustainability, wastewater storage management

1. Introduction

The few water resources in South Africa intensify difficulties for mining firms, especially with wastewater treatment (Northey *et al.*, 2019; Masindi *et al.*, 2022). Mining operations substantially increase pollution levels, with coal (Simpson *et al.*, 2019) and gold mining (Chetty *et al.*, 2021; Agboola *et al.*, 2020; Verlicchi & Grillini, 2020) polluting water resources long after the cessation of activities. This often results in acid mine drainage, which presents health hazards to adjacent communities (Yuan *et al.*, 2022). The mining sector is mainly dependent on water and is under growing pressure to manage wastewater efficiently as clean water resources diminish. This complexity underscores the pressing need for investment in effective technologies and approaches (Litvinenko, 2020). The use of digital technology in Chilean mining has improved operational efficiency and competitiveness, outpacing other sectors (Castillo-Vergara *et al.*, 2024). Nevertheless, some locations exhibit hesitance, referencing substantial initial expenses, integration difficulties, and a lack of qualified personnel (Sishi & Telukdarie, 2020; Nuur *et al.*, 2020). By prioritising innovation and using digital technology while mitigating environmental risks, mining companies may realise substantial advantages.

Efficient wastewater storage systems, a subset of wastewater systems, are essential for sustaining operational effectiveness and preserving the industry's social license to operate. Efficient wastewater management is essential for environmental preservation, adherence to regulations, and operational

effectiveness (West & Brye, 2019; Tumane *et al.*, 2021). Appropriate storage safeguards adjacent land and water resources, alleviating environmental concerns. The mining sector encounters obstacles, including antiquated infrastructure (Sishi & Telukdarie, 2020), regulatory limitations and insufficient storage capacity, particularly for tailings. These issues may be resolved by improving wastewater storage management with digital technologies that provide real-time data analytics and automated controls. Digital solutions have shown efficacy in Lean Six Sigma initiatives (Pongboonchai-Empl *et al.*, 2024), international manufacturing endeavours (Ferreira *et al.*, 2023), and the construction sector in Ghana (Maqbool *et al.*, 2023). Advanced technologies such as digital twins, sensors, artificial intelligence, the Internet of Things, integrated digital models, and machine learning may enhance operational efficiency, responsiveness, and sustainability, therefore assuring long-term viability and showcasing a commitment to responsible resource management in the mining sector.

2. Literature Review

The digital technologies that were identified in the literature reviewed are grouped according to their application and purpose, under three classifications, namely data management and analysis, simulation and visualisation, and integration and operational management.

2.1. Data Management and Analysis

Data management and analysis are essential in wastewater management, big data, and analytics

¹ Corresponding Author

Email address: 17430@davinci.ac.za

(Kannan *et al.*, 2024). Data management and analysis convert raw data into valuable insights for decision-making by operational teams (Jain *et al.*, 2021). Due to the large datasets that require storage, cloud computing enables efficient storing and processing (Kagan *et al.*, 2021), which is a precursor to the big data analytics process (Kagan *et al.*, 2021). In addition, the use of generative AI in data analysis enables organisations to forecast results, streamline operations, and refine decision-making processes, thus augmenting the efficiency and efficacy of wastewater systems (Garrido-Baserba *et al.*, 2020). Ghahramanieisalou and Sattarvand (2024) encourage the use of advanced analytics together with generative AI since it has the potential to foster collaboration across various industries. Artificial intelligence solutions are being developed to aggregate and analyse data from wastewater systems, facilitating resource recovery and source separation, which can benefit mining businesses (Sarc *et al.*, 2019). Further, Sarc *et al.* (2019) propagate the use of AI to optimise water operations and extract vital information on health and lifestyle patterns from wastewater data. Despite these promising benefits, the study of Boikanyo and Gomwe (2024) cautions that the integration of AI into overall business systems is complex, resource-intensive and time-consuming. A dichotomy exists in the practical operations of the mining business, requiring a balance between innovation, efficiency, and minimising operational disruptions.

2.2. Simulation and Visualisation

Simulation and visualisation tools accurately simulate wastewater storage management data and scenarios to increase system understanding (Cammarano *et al.*, 2023; Tain *et al.*, 2024). Operators can assess performance and forecast faults using real-time digital twins. GIS and robotics expand data collection and analysis, while AR and MR show complicated data and scenarios for training and decision-making. Advanced management tools assist stakeholders in improving efficiency and problem-solving. For mining applications like automated geological mapping and rockfall trajectory modelling, Cammarano *et al.* (2023) and Ghahramanieisalou & Sattarvand (2024) use GIS to gather, assess, and integrate geographic data, and precise 3D models aid environmental analysis and decision-making (Ghahramanieisalou & Sattarvand, 2024). UAVs and robots simplify digital technologies (Ghahramanieisalou & Sattarvand, 2024). Human input varies for autonomous robots and UAVs—automation and optimisation in mining and manufacturing. Tian, Yu, & Gu (2024) suggest that industrial robots and humans may boost mining production and safety.

Real-time digital twins replicate, monitor, and optimise physical systems. Technology data is utilised to construct and assess predictive maintenance and decision-making models (Ghahramanieisalou & Sattarvand, 2024; Tian, Yu, & Gu, 2024). According to

Cammarano *et al.* (2023), digital twins may integrate geotechnical analysis, fleet management, and risk evaluation for dynamic mining decision-making and risk assessment. Augmented and Mixed Reality (AR) technologies overlay digital information on the real environment, creating immersive experiences that improve training, visualisation, and operational efficiency for operating teams (Kunyska *et al.*, 2024). Mine crews learn complicated processes like wastewater management using these technologies, as explained by Kunyska *et al.* (2024).

2.3. Integration and Operational Management

Optimising wastewater management requires seamless coordination between systems and processes via integration and operations (Martini & Roni, 2021). Specifically, the streamlining of management and resource distribution across the many operational units, while concurrently guaranteeing the prompt provision of goods and services. The automation of activities enhances operational efficiency by reducing human involvement and mistakes.

In most instances, an Enterprise Resource Planning (ERP) system is the backbone of back-office processing of most operations, such as finance, human resources, and materials management (Sishi & Telukdarie, 2020). ERP systems oversee mining capital and resources. Industry 4.0 and ERP are being explored to create semi-autonomous mines characterised by real-time efficiency and communication (Sishi & Telukdarie, 2020). Sishi and Telukdarie (2020) identified two major flaws in ERP systems: their inability to interface with emerging technologies to improve process efficiency and control, as well as their limitation in presenting data to lower-level teams.

Bi *et al.* (2022) explain how mining supply chain management enhances the flow of materials and information from extraction to delivery, as well as how system integration enhances efficiency. The integration of supply chain management with ERP enhances data accuracy, decision-making, resource allocation, and process optimisation. Mining companies need connectivity for adaptability and profitability. IoT and Big Data-enabled supply chain management solutions may enhance mining efficiency and sustainability by increasing supply chain visibility and control. Supply chain management systems streamline data and supplies. Enterprise Resource Planning enhances data precision and decision-making efficacy. In contemporary supply chain management systems, the Internet of Things and Big Data enhance visibility and control, hence enhancing efficiency and sustainability. Onifade *et al.* (2023) advocate that automation enhances resource allocation and minimises work, hence increasing the benefit to operational efficiency. In the case of wastewater management, it assists in conserving, reducing non-production water, and preserving infrastructure. The overall benefit is that of

enhancing safety, productivity, and environmental impact that could be caused by human intervention, reducing expenses and augmenting revenues.

3. Theoretical Framework

The challenges and inefficiencies identified in the literature review are financial and cost barriers; technology and infrastructure limitations; people change management and skills development; and legislative and regulatory. As a result, the theoretical frameworks identified in the literature reviewed are discussed in relation to the challenges and inefficiencies identified.

3.1. Financial and Cost Barriers

Both Real Options (RO) and Multi-Criteria Decision Making (MCDM) theories provide unique but complementary viewpoints in overcoming financial and cost barriers to the adoption of digital solutions. RO is defined as a financial decision-making and investment framework that views investment initiatives as options rather than obligations (Ismael *et al.*, 2024). This method acknowledges investment uncertainty and provides a systematic framework for analysing management flexibility over time. RO, as explained by Ismail *et al.* (2024), emphasises both adaptability and risk mitigation in decision-making concerning capital projects, such as the adoption of digital solutions. In contrast, (Sarc *et al.*, 2019) implied that MCDM proposes a holistic approach that promotes the participation of various stakeholders, resulting in various viewpoints in the evaluation of measures such as cost, benefits, risks, and compliance with regulations in initiatives such as the adoption of digital solutions.

3.2. Technology and Infrastructure Limitations

The theoretical frameworks identified are Technology Organisation Environment (TOE) for the contextual analysis; Diffusion of Innovation (DOI) to investigate the innovation characteristics; Unified Theory of Acceptance and Use of Technology (UTAUT) to establish user acceptance as well as usage; Risk Management theory for risk analysis and mitigation thereof and DeLone and McLean IS Success Model for the evaluation of deployment success. Min *et al.* (2021) explained the transmission of innovation through new ideas and technologies using DIT. Corporate employees accept technology due to innovation, communication, introduction, and social institutions (Musa & Gugong, 2024). These variables affect digital technology adoption by altering perceptions of the innovation's value and use.

Internal and external aspects must be considered when analysing technology adoption in a business (Crabbe, 2023). According to Ediriweera & Wiewiora, the 2021 TOE framework highlights technical, organisational, and environmental factors that are key in influencing

technology adoption. TOE emphasises organisational processes, structures, and tactics that influence technology adoption. Agile and digital organisations boost value chain collaboration and efficiency, which is crucial to success (Li *et al.*, 2022; Sanda & Johansson, 2011). Effective use of open data platforms and stakeholder involvement in environmental risk management show how external impacts may promote innovation (Taborda *et al.*, 2024; Li *et al.*, 2022). The TOE framework provides a structured view of innovation adoption. However, success depends on technology, organisational agility, and environmental adaptability (Ediriweera & Wiewiora, 2021), emphasising the need for a balanced approach to digital transformation in the mining industry.

The UTAUT is widely used to evaluate digital solution adoption across various industries (Ismail *et al.*, 2024). UTAUT integrates the Theory of Reasoned Action, Technology Adoption Model, and Theory of Planned Behaviour to describe the technology adoption dynamics. According to Kwarteng *et al.* (2022), UTAUT emphasises performance expectation, which evaluates users' perceptions of how technology will enhance their work performance. Secondly, effort expectation measures the ease of use of technology. Thirdly, social influence measures the perceived approval of technology use by peers and authority figures. Lastly, conducive circumstances measure the perceived organisational support and available technological infrastructure. These four constructs may influence technology usage and behaviour in technology adoption initiatives. The technology implementation situation may impact each dimension's relative effect. Subsequently, according to Schorr (2023), UTAUT2 was introduced, and it added consumer-oriented elements to the original model, making it more applicable and offering more insights into user behaviour in different circumstances. Ismail *et al.* (2024) highlighted criticism of the UTAUT that includes issues of complexity, contextual constraints, stability, disregard for emotional aspects, methodological rigour, and an emphasis on post-adoption behaviour.

The ISSM is a key theoretical framework for evaluating information systems in business intelligence, e-learning, and risk management. The ISSM takes a multi-dimensional approach to system, information, service, user satisfaction, net benefits, and user engagement, building on DeLone and McLean (Dash *et al.*, 2023). This complete model shows how these aspects affect information system success and their interdependence. Dash *et al.* (2023) further explain how ISSM blends the TAM and Expectation-Confirmation Theory and adapts to current difficulties by adding elements and resolving applicability concerns. According to Dash *et al.* (2023), several studies have used the ISSM to assess system performance in real-world settings, proving its applicability and usefulness.

Despite criticism about the need for more dimensions and robustness of measuring instruments, the ISSM remains a crucial tool for organisations seeking to improve their information systems and results. Ismail *et al.* (2024) posit that regular use of ISSM in technology adoption initiatives aided businesses in identifying areas for improvement as well as enhancing both user demands and the alignment of technology solutions to organisational strategies.

3.3. *People Change Management and Skills Development*

Effective change management must include both organisational strategy and individual staff requirements as explained by Tomičić-Pupek *et al.* (2023). Further, this dual emphasis guarantees that businesses can adjust while simultaneously supporting workers throughout the change. At the organisational level, leaders play a pivotal role in shaping attributes that support the successful deployment of technology as posited by Tomičić-Pupek *et al.* (2023), Dash *et al.* (2023) and Arumugam *et al.* (2023). Further, Arumugam *et al.* (2023) outlined critical attributes essential for successful leadership in technology adoption initiatives, encompassing robust communication faculties, proficient leadership practices, the confidence leaders instil in their workforce, and the primary quality of leadership. With these attributes, both Arumugam *et al.* (2023) and Dash *et al.* (2023) advocate that employees are likely to be appropriately supported in acquiring the relevant capabilities by leaders.

3.4. *Legislative and Regulatory Challenges*

RBV of a firm is a pivotal strategic management framework emphasising the critical role of a firm's internal resources and capabilities in achieving competitive advantage and superior performance (Fedorovna *et al.*, 2022). Emerging in the mid-1980s, RBV has been widely applied across disciplines such as marketing, supply chain management, and the creative industries. Bals and Rosca (2022) explain how the theory posits that sustainable competitive advantage arises from resources that are valuable, rare, inimitable, and non-substitutable (VRIN). This perspective provides a foundation for understanding how firms can leverage unique assets to outperform competitors. Further, by focusing on strategic capacity, RBV underscores the importance of a company's unique expertise and capabilities in enhancing competitiveness, particularly in industrial sectors (Lubis, 2022). Fedorovna *et al.* (2022) explain how the transformation of resource allocation processes using digital technologies connects with the RBV framework by emphasising the strategic use of digital resources to boost organisational growth and competitiveness. Despite its robustness, RBV faces criticism for potentially overlooking external factors like market dynamics and competition, and for not fully addressing rapid technological and consumer preference changes.

Nevertheless, it remains a foundational theory in strategic management, offering valuable insights into the central role of resources in firm success.

Institutions impact social, organisational, and political conduct (Kahupi *et al.*, 2024). Beyond constitutional and legal settings, historical, sociological, and rational choice views benefit political analysis, sports management, strategic management, and the digital economy (Agyei-Ababio *et al.*, 2023). Institutional theory explains how laws, industry standards, and societal norms influence the adoption of technology. Kemal and Shah (2023) say institutions may overlook human agency and rapid digital development. Agyei-Ababio *et al.* (2023) claim the theory shows external institutional impacts but overlooks the dynamic nature of organisational innovation and regional culture.

RBV and TOE (Agyei-Ababio *et al.*, 2023) highlight individual actors and their ability to transform organisations (Kemal & Shah, 2023). TOE shows how employees and decision-makers react to technological and environmental changes, impacting new technology adoption. According to Kemal and Shah (2023), TOE includes dynamic interactions between technology, organisation, and environment, making it more straightforward to adapt to fast-paced changes and comprehend how organisations react to breakthroughs. RBV asserts that workers compete using their skills, knowledge, and social capital, making human agents vital for resource activation and management. Reducing these limits may maintain institutional theory relevant to the mining sector's social and organisational processes.

4. *Research Methodology*

The study subject involves defining the conceptual framework for the adoption of digital solutions in tackling the persistent issues of wastewater storage management in the mining industry, focusing on enhancing operational efficiency, guaranteeing regulatory compliance, and promoting sustainability. The study used a qualitative, exploratory approach first to identify the relevant theoretical frameworks that underpin the study; then identify the challenges and inefficiencies in the application of digital technologies for wastewater management within the mining industry; and then to examine the various technologies employed in wastewater management and the mining sector; and finally to define the conceptual framework to guide mining businesses through the complexities of integrating digital solutions into their wastewater management practices. A systematic literature review was performed by scanning the EBSCOhost database and Google Scholar for publications published between 2019 and 2025. The search string for the first round was wastewater management. Excluded articles were those authored in languages other than English, duplicate submissions, and book chapters. Articles were filtered

based on the digital technologies used in wastewater management and those utilised by the mining sector. The systematic literature review included an examination of existing literature to synthesise available information, which is intrinsically challenging due to the fragmented nature of current research and the multidisciplinary aspects of the issue (Snyder, 2019) (Figure 1).

Technologies such as big data, AI, and data management are transformational by improving operational efficiency and decision-making (Kannan *et al.*, 2024; Jain, 2021). In the adoption of these technologies, the barriers and challenges identified are financial and cost barriers (Ediriweera & Wiewiora, 2021); technology and infrastructure limitations (Crabbe *et al.*, 2022); people change management, and

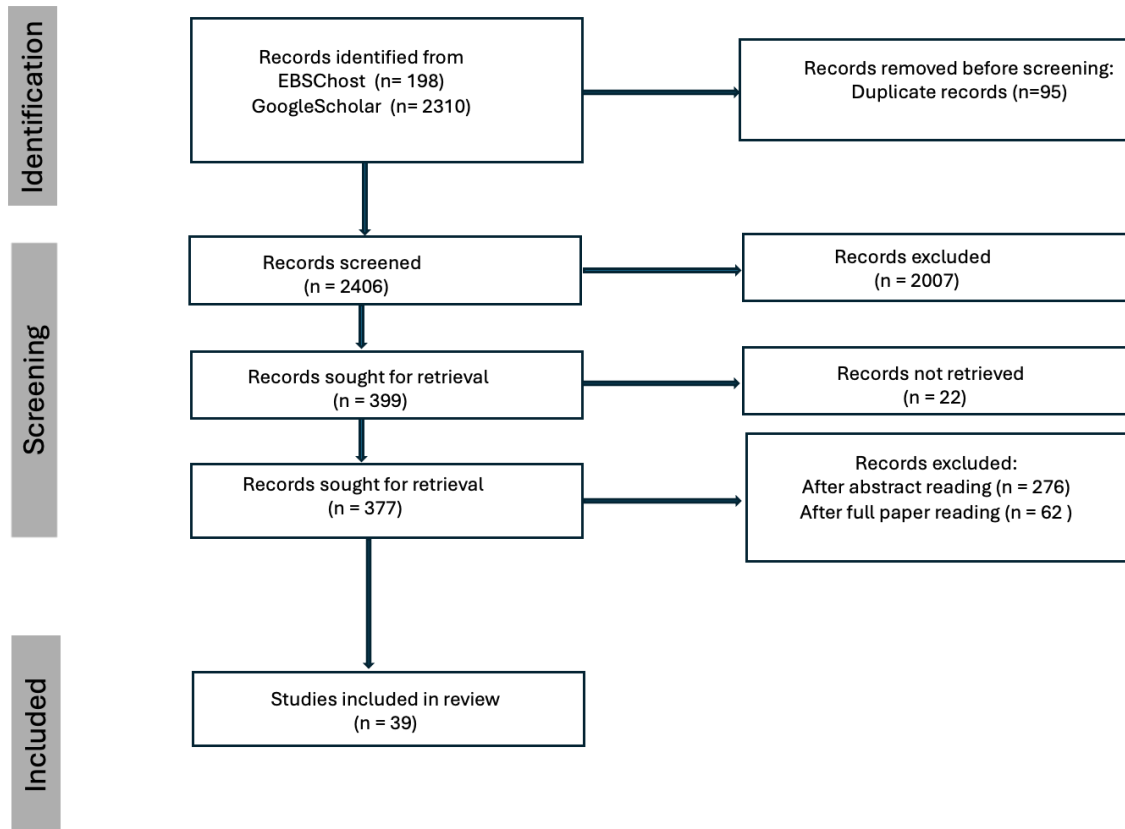


Figure 1: Prisma 2020 flow diagram for identification of studies for review

This study's literature review strategy provided a comprehensive foundation for understanding the current state of digital solutions in wastewater storage management in the mining industry. This strategy not only identifies existing knowledge gaps but also lays the groundwork for future research initiatives aimed at enhancing operational efficiency and sustainability in wastewater storage management.

5. Findings and Discussion

The consensus in the articles reviewed is that there is a benefit to digital solutions in managing wastewater, although the specifics of wastewater storage management are not addressed. Discussions were primarily for the deployment of digital technologies within the water management, wastewater treatment and overall mining operations. These digital technologies are classified into three areas, namely data management and analysis, simulation and visualisation, and integration and operation management.

skills development (Mokganya *et al.*, 2024); and legislative and regulatory challenges (Crabbe *et al.*, 2022).

In overcoming the identified challenges, a conceptual framework based on theoretical frameworks identified in the literature review is essential for the deployment of digital technologies in wastewater management, especially in the mining industry. Figure 2 depicts such a framework by indicating how each theoretical framework addresses the challenge identified in the literature review.

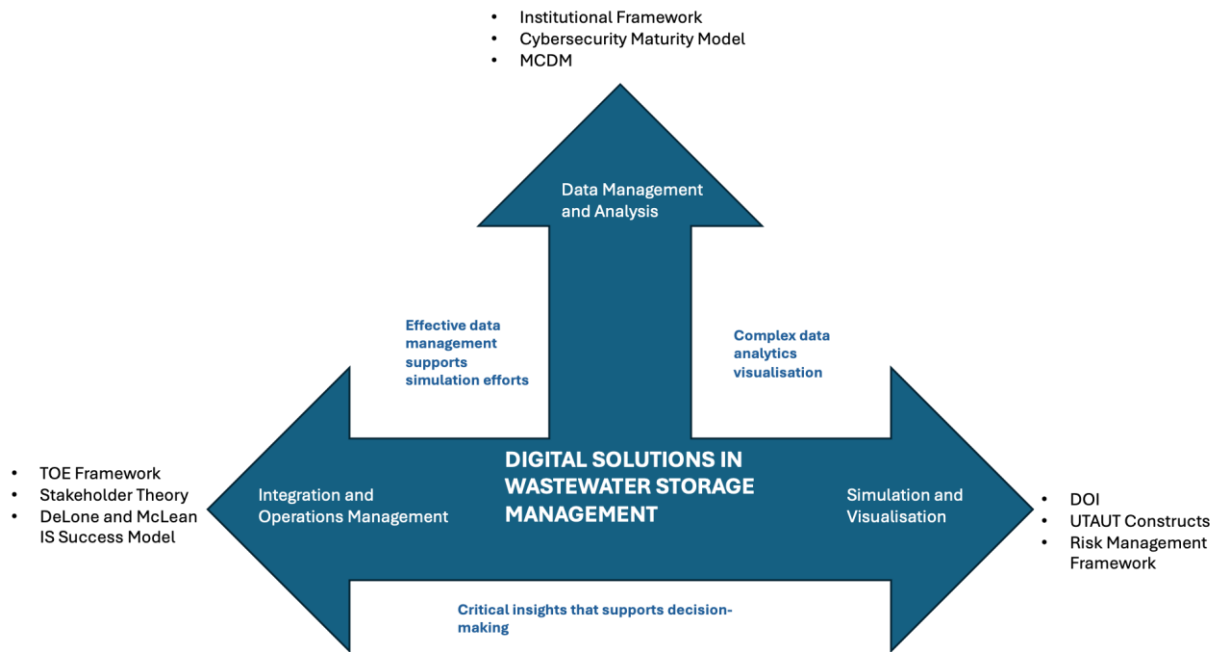


Figure 2: Conceptual Framework for the adoption of digital solutions in the management of wastewater storage management

6. Conclusion and Further Research

The environmental impacts of mining activities depend on wastewater storage management. This study shows that digital technologies may improve wastewater management inefficiencies. Many mining businesses are incorporating new technology into their current frameworks. While industry, telecommunications, and tourism have profited from digital revolutions, caution is advised. Staff alignment and support are crucial to such projects' success. Thus, revolutionary programs must emphasise technology-personnel partnership for meaningful outcomes. This study's conceptual framework helps organisations navigate the intricacies of digital wastewater management systems. This study uses TOE, TAM, DOI, Institutional Theory, and RBV to show the complexity of the challenges. Interdisciplinary qualitative and quantitative research is

needed to discover crucial success factors that may enable these transitions and to identify which digital solutions can be successfully integrated to achieve desired results. The scarcity of literature on digital technology in wastewater management highlights the need for more research. Innovation and sustainability in wastewater management need collaboration between major and small-scale miners and government agencies. A strong conceptual framework will improve understanding of these dynamics and guide practical implementation tactics, helping the mining sector manage wastewater storage.

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