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Sustainable Tailings Management in Sedimentary Phosphate Beneficiation: A KPI-Oriented Literature Review and Gap Analysis

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Abstract- ***Sedimentary phosphate ore processing produces large amounts of fine phosphate tailings and washing sludges that create a number of problems in phosphate ore processing plants. Sedimentary phosphate ore processing tailings are known to create problems such as high water retention capacity, slow settlement rates, and intricate geochemical composition that may include ecologically hazardous elements like cadmium, uranium, and arsenic. Most of the research in phosphate ore processing has concentrated on increasing the efficiency of individual operations in phosphate ore processing plants, such as flotation, thickening, and tailings deposition, without considering the integration of the phosphate ore processing plant and mine tailings management system. As a result, decision support tools that integrate operation performance and sustainability in phosphate ore processing and tailings management have not been well explored in phosphate ore processing plants. This paper presents a Key Performance Indicator (KPI) literature review and gap analysis on sustainable tailings management in sedimentary phosphate ore processing. This paper aims to provide a literature review and gap analysis based on various literature works and provide an approach to improving operational performance using Key Performance Indicators (KPI). The Key Performance Indicators (KPIs) identified in this paper are grade optimization and efficiency improvement in order to increase the life of phosphate ore processing plants, thickener water recovery optimization using improved underflow density and water clarity in thickener overflow, and tailings deposition to reduce Tailings Storage Facility (TSF) risk and structural stability. Sustainability in phosphate ore processing and tailings management is another constraint identified in this paper as it is one of the cross-cutting issues related to Key Performance Indicator (KPI). A structured gap matrix has also been presented in this paper to identify gaps in the literature and provide quantified validation methods. The integrated Key Performance Indicator (KPI) approach is presented in this paper as future research with emphasis on plant-scale validation, dynamic water mass modeling, and Key Performance Indicator (KPI) dashboards with auditable sustainability metrics in accordance with current tailings management practices.***

Index Terms- ***Phosphate Beneficiation; Sedimentary Phosphorite; Tailings Management; KPI Framework; Thickener Water Recovery; Tailings Storage Facility; Circular Economy; ESG Governance***

Highlights

Introduces a KPI-oriented framework linking phosphate beneficiation performance with sustainability outcomes.

- Synthesizes recent literature on tailings recovery, thickener water optimization, and TSF risk reduction.
- Develops a structured gap matrix connecting research gaps with measurable performance indicators.
- Examines cross-cutting themes including potentially toxic elements, recycled water chemistry, and circular-economy pathways.
- Proposes an implementation roadmap aligned with global tailings governance standards such as GISTM.

I. INTRODUCTION

Phosphate is one of the raw materials that is utilized in the world fertilizer market and is of critical importance in maintaining high levels of agricultural productivity. A significant part of the world's phosphate resources is represented by phosphate in sedimentary phosphorites and is subjected to a number of methods of mineral processing. One of the major challenges faced in the mineral processing of phosphate is the production of a significant amount of fine tailings and washing sludges in the processing of sedimentary phosphate ores. The production of fine tailings in the mineral processing of sedimentary phosphate ores is considered to be one of the most complex challenges in phosphate mining systems. The presence of a significant amount of clay

particles, carbonate particles, and mineral particles in phosphate tailings is a common aspect in all cases. This is considered to be one of the most complex challenges in phosphate mining systems. It is considered that a significant amount of fine tailings in the mineral processing of sedimentary phosphate ores is one of the most complex challenges in phosphate mining systems. It is generally considered that a significant amount of fine tailings in the mineral processing of sedimentary phosphate ores represents unrecovered phosphate values. This is considered to be one of the major risks with regard to loss of resources. It is considered that an increase in the water content of tailings results in an increase in the number of tailings storage facilities. This is considered to be one of the major risks in tailings management. This is considered to be one of the major risks in tailings management. Potentially toxic elements like cadmium, uranium, and arsenic are considered to be a major risk in tailings management. However, in recent years, there has been a large awareness of risks that are involved in the management of tailings. It is considered that there has been a large increase in this regard with regard to catastrophic failures of mine tailings dams. It is considered that there is a system of governance in the mining industry. It is considered that it places large emphasis on aspects such as transparency, risk management, and environmental responsibility. It is considered that the most significant initiative with regard to this is the development of a global industry standard on tailings management (GISTM), which includes a framework of tailings governance. In this regard, it is considered that international organizations have developed guidelines that place large emphasis on aspects such as managing risks and environmental responsibility with regard to tailings management. It is considered that the system of governance with regard to this indicates that there is a need to demonstrate improvements with regard to mining companies' performance with regard to water efficiency, reduction of tailings, and structural stability of storage facilities. Despite all these improvements, it is observed that most of the literature on phosphate minerals and tailing has been fragmented in terms of unit operations. Many studies have been carried out to enhance the phosphate mineral flotation reagent system, particle size control, and slime handling to enhance the phosphate mineral recovery. Many studies have also been carried out to enhance the thickening process, flocculation process, and rheology to enhance the recovery of water from the slurry of tailing. Many geotechnical and environmental studies have also been carried out to enhance the stability, consolidation, and environmental aspects of tailing storage facility. Although all these studies are significant and have provided significant insight into the scope of improvement of unit operations, there has been no system in place to link all these improvements to sustainability and governance outcomes. This is because it is fragmented in nature and hence creates difficulties in assessing the impact of decisions made by mine operators and researchers. For example, if improvements are made to the recovery rates of the flotation circuits, it may have an impact on the particle size of materials. Similarly, if improvements are made to the underflow density of thickening circuits, it may have an impact on the rheology of tailings. Without such a system in place, it may cause suboptimal decisions to be made, which may not utilize the full scope of optimization of sustainability outcomes. In view of such challenges associated with effectively managing sedimentary phosphate mine tailings, there has been great interest in the use of Key Performance Indicator (KPI) frameworks in effectively managing mine tailings. This is due to its potential to provide an opportunity to provide performance metrics and its relationship with strategic performance measures such as resource optimization, environmental performance, and safety performance. In relation to the phosphate industry, there are various operational performance metrics that may be considered effective KPIs in effectively managing phosphate mine tailings. Such metrics may include grade of the tailings, underflow density, water recovery efficiency, and deposition properties of the tailings. Such a framework may be effectively integrated to form a comprehensive framework for effective mine-to-tailings management. Therefore, this study is a literature review and gap analysis with regard to KPI-based framework to develop effective and efficient approaches to effectively manage sedimentary phosphate mine tailings. Such a literature review may be synthesized with regard to three KPIs operationalized as follows: 1. Tailings grade optimization and efficiency of recovery with regard to its implications on resource utilization and

mine life extension. 2. Thickener water recovery optimization with regard to underflow density, water clarity in the overflow, and composition of water. 3. Tailings deposition strategies and structural risks with regard to the performance of TSFs. In addition to these key KPIs, there are three key themes, which have been recognized as being of significant importance, and which have implications for the performance of the phosphate mining industry with particular emphasis on more sustainable approaches to resource utilization. These include the performance of potentially toxic elements, the composition of recycled water in the process, and the development of the circular economy with emphasis on the valorization of phosphate wastes. By taking into consideration the aforementioned, with the context of the current study, it is considered that there is more scope for making connections between the results of the research on the laboratory scale and the more effective implementation of the results obtained. The main aim of the current review is to identify key issues and problems, taking into consideration the context of the process, and at the same time to propose more integrated and consolidated approaches to the development of the current research with more scope and opportunity for more sustainable approaches to phosphate mining.

II. RESEARCH METHODOLOGY

For conducting this research study, it is proposed to use the structured narrative literature review method with a Key Performance Indicator (KPI) focused analytical framework for conducting research in sustainable tailing management practices in sedimentary phosphate mining systems. This research methodology is based on the identification of literature and its analysis to create a research methodology that is capable of establishing links with mineral processing performance and sustainability. This methodological framework is created with the aim of addressing one of the major limitations of existing literature in the subject area, where research is focused on addressing various aspects of phosphate mining or tailing management individually without creating a framework that links various aspects of mineral processing performance with water management and tailing storage risks. Hence, it is proposed to create a KPI-focused framework for creating an integrated platform of existing literature for conducting research in sustainability in mining activities.

2.1 Literature Search and Data Sources

For conducting literature review and analysis for creating the research methodology for conducting research in sustainability in phosphate mining activities, it is proposed to use major academic data sources like Scopus, Web of Science, ScienceDirect, Springer Link, and Google Scholar, which are rich sources of literature in the subject areas of mineral processing, water management in mining activities, and sustainability in mining activities. For conducting a literature review and analysis for creating the research methodology for conducting research in sustainability in phosphate mining activities, it is proposed to use credible sources of literature, such as guidelines in mining activities and conferences.

The process of literature search makes use of specific combinations of keywords such as the mining of phosphate, processing of phosphate, management of tailings, and the aspect of sustainability. Some of the keywords for the literature search are as follows:

- Phosphate Beneficiation
- Sedimentary Phosphorite Processing
- Flotation Tailings Treatment
- Thickener Water Recovery
- Tailings Storage Facility Stability
- Mine Tailings Sustainability
- Tailings Rheology and Deposition
- Phosphate Waste Valorization

The Boolean logic ‘AND,’ ‘OR,’ and other combinations of these logical operators are used to narrow down the literature search results to obtain literature that discusses the relationships between the interactions of phosphate processing, tailings management, and sustainability.

The literature search results are mainly restricted to literature published between 2014 and 2025, which discusses the recent developments in the processing of phosphate, the recovery of water, and the management of the tailings. Some literature published between 1960 and 1990, which discusses the rheology of mineral tailings, paste tailings, and the geotechnics of tailings, are included to obtain an

overview of the theoretical aspects of the management of the tailings.

2.2 Study Selection Process (PRISMA-Lite Approach)

In order to ensure transparency and reproducibility of the research work, it has been suggested to adopt the PRISMA-lite approach for literature selection and screening. Although the present study does not explicitly mention the literature review method, it has been suggested to adopt the PRISMA-lite approach for literature selection and screening.

The literature selection process has been divided into four stages:

Identification Stage

The literature screening process has been initiated by adopting the literature screening process, which involved the use of a number of academic databases to identify literature publications related to phosphate mining, its beneficiation, and treatment technologies for the treatment of tailings, and the management of tailings storage facilities. Around 120 publications were obtained during the literature search process.

Screening Stage

The literature screening process has been continued by eliminating duplicate publications and literature publications not related to sedimentary phosphate mining. The literature screening process has been done based on the title and abstract of the literature publications, which resulted in the elimination of literature publications related to the generation and treatment of tailings and the associated environmental impacts. Around 95 publications were obtained during the literature screening process.

Eligibility Assessment
The literature screening process has been continued by adopting the literature screening process, which resulted in the selection of literature publications providing technical insights on the operational performance, water recovery, and risks associated with the tailings storage facilities. Around 60 publications were obtained during the literature screening process.

Final Inclusion
A set of literature publications, i.e., around 30-35 literature publications, has been obtained for literature analysis and synthesis in the KPI framework. The literature publications were related to the management of phosphate tailings and included empirical data and experimental and conceptual insights on the KPIs for the sustainable management of phosphate tailings.

2.3 KPI-Based Analytical Framework
For literature analysis and synthesis in the KPI framework, literature is categorized into three operational KPIs concerning sustainability issues in phosphate tailings management.

KPI 1: Optimization of Grade of Tailings and Efficiency of Recovery

This KPI is used for measuring and evaluating the level of efficiency in phosphate recovery during the beneficiation process. Phosphate grade in the tailings is an indication of phosphates not recovered during the process. Phosphates not recovered during the process can be considered as loss of resources. Literature concerning phosphates in flotation selectivity, particle size distribution in desliming methods, and secondary phosphates is considered under this category.

Optimization of this KPI will reduce wastes generated and extend the longevity of phosphate mine sites.

KPI 2: Efficiency of Water Recovery and Density Optimization

This KPI is used for measuring and evaluating thickener water efficiency in thickening units. Thickening is considered crucial in linking mineral processing and tailings management. Thickening is used for controlling water volumes being recycled back to the plant and density transported for storage.
Literature concerning flocculation, feedwell, settling, underflow density optimization, and water clarity of thickener overflow is considered under this category.

Optimization of this KPI will reduce water usage and extend mine longevity in water-scarce areas.

KPI 3: Tailings Deposition Strategy and Reduction of Storage Risks

This KPI is used for measuring and evaluating thickener efficiency concerning geotechnical and environmental issues in tailings storage facility sites. Deposition of tailings in tailings storage facility sites is crucial in beach slope formation, consolidation rates, and stability.

Literature regarding rheology of tailings, deposition strategies, consolidation of tailings, seepage control, and stability of dams were considered under this category of KPIs. Improvement in thickener performance would reduce structural risks in TSFs.

2.3 Gap Analysis Framework

Once this literature is coded in reference to these KPIs, a structured gap analysis would be conducted to determine areas of research that are not yet complete or sufficiently integrated.

The framework that would be followed in order to perform this gap analysis is as follows:
1. Theme presented in literature
2. Scientific evidence and insights
3. Limitations and gaps in literature
4. Proposed KPIs and methods to validate

This framework would allow us to convert academic research results into quantifiable plant-level metrics that could be monitored in a plant or mine site setting. Such results could be obtained using plant-scale testing, mass balance reconciliation, water quality analysis, rheology, and long-term geotechnical monitoring techniques.

2.5 Sustainability Integration and Governance Alignment

The final component of this proposed methodology is the integration of sustainability and governance into operational performance analysis. Each of these proposed KPIs would be analyzed in reference to key sustainability drivers such as:

• Reduction of freshwater usage
• Improvement of resource efficiency of minerals
• Reduction of tailings storage volumes
• Improvement of structural safety of TSFs
• Improvement of environmental monitoring and compliance

Integration of sustainability drivers into operational performance analysis would allow us to develop a series of proposed KPIs that could then be integrated into the above framework and allow us to develop quantifiable metrics for Environmental, Social, and Governance (ESG) performance in accordance with the latest and most stringent of tailings management standards such as GISTM.

III. LITERATURE REVIEW AND SYNTHESIS OF KEY PERFORMANCE INDICATORS (KPI) OF PHOSPHATE TAILINGS MANAGEMENT

Phosphate tailings management, obtained in the process of beneficiating sedimentary phosphate ore, has been identified to be an important research area in the mining industry, particularly in light of the increasing demand for environmental management, water conservation, and sustainability. Sedimentary phosphate ore has been identified to contain a high amount of clay, silica, carbonates, and fine materials, which are creating problems in the process of beneficiating phosphate ore, thereby creating the need for phosphate tailings management, which has been identified to have a slow settling rate, a high amount of water, and variability in composition. This has created an important interface in mineral processing and environmental management. For the purpose of developing an understanding of the sustainability of phosphate tailings management, literature has been synthesized to identify Key Performance Indicators (KPI) of sustainability of phosphate tailings management. Literature has been synthesized to identify the three critical elements of phosphate tailings management, which are critical to the sustainability of this process, and these are phosphate recovery, water recovery, and deposition of phosphate tailings in tailings storage facilities.

3.1 KPI-1: Optimization of Grade of Tailings and Recovery of Phosphate

The efficiency of the recovery of the phosphate is critical in ensuring the sustainability of the process of beneficiating the phosphate ore. This is ascertained based on the grade of the tailings, which is based on the composition of the phosphate content in the tailings. The high grade of the phosphate content in the tailings indicates inefficient use of the process, which leads to inefficient use of the critical natural resource. According to some literature sources, it is essential to optimize the process in order to ensure efficiency in the recovery of the phosphate content in the sedimentary ore. For example, it was indicated that the process is efficient if there is consideration of the liberation, selection, and control of the particle sizes. The desliming is considered as one of the methods used in the process in order to ensure efficiency in the process. The desliming is considered as one of the methods that lead to inefficient use of the process, which leads to the loss of the fine phosphate content. Another factor considered as being critical in the process is the use of the process in the entrainment of the fine particles contained in the ore during the floatation process. For example, it has been indicated that the use of the combinations of the chemicals is considered as being critical in the optimization of the selection of the fine particles contained in the ore during the floatation process. The use of the secondary minerals, which are rare earth and uranium contained in the ore, is indicated as being essential based on the high demand for the product. However, when one thinks about the issue of sustainability, there are various benefits that are attached to making phosphate rock more efficient. It is important to make phosphate rock more efficient since it would help in reducing the ore that is required in order to produce a constant level of concentration in the recovery process. This is important since it would help in increasing the life of the ore and the level of waste that is generated in the process. It is also important to consider how it would affect other areas of the process, such as thickening and dewatering of the tailings.

3.2 KPI-2: Thickener Water Recovery and Density Optimization

Water is another key component in the issue of sustainability in the phosphate rock mining and processing industry. Water is required in large quantities in order to wash, classify, and float. Water is also recovered in the process of tailings and is important in the process in order to ensure the efficiency of the water usage process. Thickeners are considered to be important equipment used in the process of solid particles and water separation during the process of transporting tailing slurries to TSFs. The efficiency of thickeners is dependent on several operational parameters. These operational parameters include the dosage of flocculants and hydrodynamics of the feedwell. Generally, the flocculants used in thickeners are polymers. This is because it is considered to be of importance so that efficiency can be achieved in terms of density and hence efficiency in the process of water recovery. The maximization of efficiency ensures that the volume of water pumped to TSFs is minimal. This is considered to be of importance so that sustainability can be achieved in terms of cost and hence sustainability in TSFs. It is considered to be of importance to understand that thickeners are dependent on several parameters. One such parameter is the chemistry of recycled water. This implies that there is always the possibility of salt, reagent, and suspended solids being added to the recycled water. This implies that there is always the possibility of interference in the floatation and flocculation process during the process of beneficiation. Improvement of efficiency in thickeners is considered to be of importance so that sustainability can be achieved in terms of water and hence the impact on the environment is minimal.

3.3 KPI-3: Tailings Deposition and Storage Facility Risk

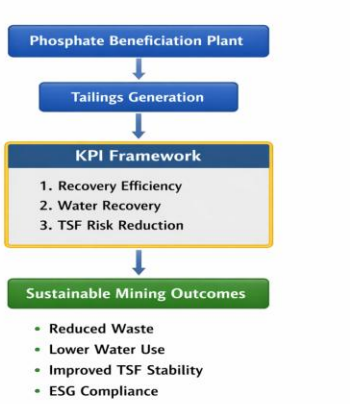
The last process in the management of phosphate mining tailings is the deposition of mining materials in TSFs. The physical and environmental integrity of TSFs is a function of the physical characteristics of mining tailings deposited in TSFs, which include mining tailings particle size, density, consolidation, and pore water pressure. The process of deposition also affects the slopes of beaches, drainage, and solid content in TSFs. For instance, using dense mining

tailings is useful in improving the consolidation process, which in turn reduces the risks of ponding in TSFs. Such a process also enhances the physical integrity of TSFs and reduces the risks of dam failures. Thickened or paste mining tailings, on the other hand, are useful in creating operation risks, especially due to increased slurry viscosities. Mining tailings rheology is thus a significant factor in determining the most suitable deposition process in TSFs. On the environmental side, risks include those of releasing PTEs such as cadmium, uranium, and arsenic into the environment. These are significant risks since they are capable of causing harm to human life and the environment in general. Risks are a result of the potential toxicity of these elements and are likely to occur when there is a geochemical change, especially when exposed to oxidizing conditions or pH. However, the current governance structure of mining tailings recognizes the need to monitor and assess risks and to ensure transparency in TSFs management. For instance, the current global industry standard on mining tailings management, which has been developed and accepted by the mining industry, requires mining firms to establish a monitoring system and to consider a risk-based approach in TSFs management.

Table 1: Key Performance Indicators for Sustainable Phosphate Tailings Management

KPI Category	Operational Focus	Sustainability Impact
Tailings Grade Optimization	Phosphate recovery, flotation selectivity	Resource efficiency and mine-life extension
Thickener Water Recovery	Underflow density, overflow clarity	Reduced freshwater consumption
TSF Deposition Risk	Tailings rheology, consolidation, deposition strategy	Improved structural safety and environmental protection

Conceptual Diagram: KPI Framework for Sustainable Tailings Management



Gap Analysis Matrix and Research Opportunities

The literature review has shown that, despite the significant amount of individual research on various elements of the phosphate mining process, the majority of the literature has been fragmented, with many researchers focusing on the efficiency of the flotation process, the performance of the thickening process, or the deposition of the tailings independently, without fully considering the interactions between these processes. Such gaps in the literature imply that decision-making models that could effectively link the mineral recovery process, the water process, and the tailings process are limited. The gap analysis matrix has been developed to identify the gaps in the literature and propose measurable operational indicators to be used in the development of more effective and more sustainable tailings management systems. The gap analysis matrix has been developed to link four elements of the analysis: the research theme, the existing knowledge, the gaps in the literature, and the Key Performance Indicators (KPI) to be used in the evaluation of the performance of the operation. The gap analysis has shown that the development of more effective and more sustainable tailings management systems for the phosphate mining industry is primarily an integration challenge, as the improvement of one aspect of the process could influence the performance of the other operational stages. For example, improving the recovery of the phosphate could influence the thickening process, as the production of finer particles could influence the thickening process. Similarly, the improvement of the thickening process could influence the deposition

process, as the improvement of the underflow density could influence the rheology of the tailings, which could influence the deposition process in the TSF.

Table 2: Gap Analysis Matrix for Sustainable Phosphate Tailings Management

Research Theme	Current Literature Coverage	Identified Research Gap	Proposed KPI	Validation Method
Tailings phosphate losses	Studies analyze flotation performance and tailings grade as indicators of recovery efficiency	Limited integration between recovery optimization and long-term mine planning	Tailings Grade KPI (P_2O_5 concentration in tailings)	Plant mass balance analysis and flotation monitoring
Desliming processes	Research highlights importance of slime removal to improve flotation selectivity	Lack of decision frameworks for optimal desliming cut-off size	Desliming Loss Index (DLI)	Particle size distribution and mineral liberation analysis
Fine particle flotation	Research focuses on reagent systems and entrainment control	Weak integration with downstream thickening and water recovery processes	Flotation Selectivity Index	Controlled plant trials with reagent optimization
Thickener performance	Studies analyze flocculant dosage, feedwell design, and settling dynamics	Limited understanding of scale-up effects from laboratory to plant operations	Underflow Density KPI	Thickener performance monitoring and operational trials
Recycled water chemistry	Literature recognizes effects of water chemistry on flotation and flocculation	Insufficient monitoring of dissolved contaminants in recycled process water	Recycled Water Quality Index	Routine chemical analysis of process water
Site water balance	Studies recognize influence of rainfall and evaporation on tailings ponds	Lack of dynamic models linking plant water recovery with TSF water inventory	Seasonal Water Stress KPI	Water balance modeling and meteorological monitoring
Tailings rheology	Research addresses yield stress and paste tailings technology	Limited operational guidelines linking rheology with pumpability and deposition	Pumpability Window KPI	Rheological testing and pipeline pressure monitoring
Tailings deposition strategies	Studies analyze deposition methods such as spigot or central discharge	Weak linkage between thickener performance and deposition design	TSF Loading KPI	TSF volume reconciliation and beach slope monitoring
Long-term consolidation	Research examines consolidation and pore pressure dissipation in tailings dams	Lack of long-term datasets for predictive modeling	Consolidation Performance KPI	Geotechnical instrumentation and monitoring
Potentially toxic	Studies identify presence	Limited lifecycle	PTE Risk Index	Geochemical

Research Theme	Current Literature Coverage	Identified Research Gap	Proposed KPI	Validation Method
element mobility	of Cd, U, and As in phosphate tailings	evaluation of contaminant mobility in recycled water systems		modeling and leachate monitoring
Circular economy utilization	Research explores production of geopolymers and construction materials from tailings	Limited industrial-scale validation and life cycle analysis	Valorization Rate KPI	Pilot-scale material testing and life cycle assessment
Secondary mineral recovery	Studies suggest potential recovery of rare earth elements from tailings	Lack of economic evaluation frameworks for secondary recovery	Secondary Recovery KPI	Bench-scale recovery experiments
ESG governance integration	Global standards emphasize risk transparency and monitoring	Lack of operational metrics translating technical performance into ESG reporting	ESG Translation KPI	Sustainability dashboards and monitoring systems

IV. DISCUSSION OF KEY RESEARCH GAPS

The gap analysis has shown that there are various gaps in the key areas where research and operational innovations need to be done. For example, there is the need to develop integrated process models which can simultaneously evaluate mineral recovery, water management, and tailings deposition performance. Currently, the research has been focused on evaluating each of these processes individually. For example, thickening and flotation process research has been done individually. This has been making it difficult to evaluate the sustainability impact of mining processes on the environment. Another gap analysis indicates that scaling up laboratory results to plant operations has been a challenge. For example, thickening and flotation process research has been done individually under controlled laboratory conditions. However, it has been difficult to ascertain whether the results obtained in the laboratory are representative of what happens at the plant operations. Therefore, there is the need to consider the plant-scale validation of process optimization strategies in thickening and flotation process research. The gap analysis has shown that there is a need to research the impact of mining processes on the environment, particularly with regard to recycled water chemistry and the presence of potentially toxic elements. For example, there is a need to consider the movement of contaminants through the tailings storage facilities. There is also the need to consider the integration of KPI with sustainability governance frameworks. For example, the Global Industry Standard on Tailings Management has shown the need for measurable performance indicators that can be used to demonstrate environmental accountability and operational transparency. The KPI framework has the potential to enable mining companies to become more accountable for the environment.

V. CROSS-CUTTING SUSTAINABILITY THEMES IN PHOSPHATE TAILINGS MANAGEMENT

While various operational performance indicators like efficiency in recovery, water recovery efficiency, and stability in deposition of tailings offer a basic framework for measuring and monitoring the effectiveness of a phosphate ore beneficiation process, there are various overarching sustainability drivers that impact all aspects of a phosphate ore sedimentary deposit tailings management process. These overarching sustainability drivers impact how phosphate ore beneficiation interacts with various environmental processes, resource efficiency strategies, and global governance strategies. In terms of phosphate ore sedimentary deposit tailings management, there are three overarching

sustainability drivers that impact all aspects of the phosphate ore sedimentary deposit tailings management process. These include the mobility of PTEs, recycled water chemistry, and circular economy strategies for the valorization of the tailings. In addition to that, in modern times, it is essential to integrate various technical processes in a mining process with ESG strategies that promote transparency and resource efficiency.

5.1 Mobility of Potentially Toxic Elements (PTEs)

It is widely known that phosphate ore deposits often contain various trace elements that impact various environmental processes in a negative way when released into an ecosystem. Among the most common PTEs known to impact various environmental processes in a negative way are cadmium (Cd), uranium (U), and arsenic (As), which are known to be present in phosphate ore in trace amounts and impact various environmental processes in a negative way when released into an ecosystem. Research on the processes of PTEs in the management of phosphate ore sedimentary deposit tailings has shown that the movement of PTEs in the process of phosphate ore sedimentary deposit tailings management is influenced by various factors such as pH, redox, and water chemistry. Such processes are recognized to have the potential to influence water resources in a negative manner if the process is not effectively controlled and managed. However, the risks associated with the process of phosphate ore sedimentary deposit tailings management can be controlled and managed effectively through the development of strategies for the effective and efficient management of the tailings. Such strategies include the testing of the leachate and geochemical modeling, which would enable the mine companies to effectively understand the potential risks associated with the process of phosphate ore sedimentary deposit tailings management. Moreover, the effective control and management of the process of deposition of the tailings and water would be effective in controlling the risks associated with the potential for PTE contamination, which would be useful in providing effective and stable conditions for the storage of the tailings. The incorporation of PTE monitoring indicators into the KPI system would be effective in the context of sustainability, as the mine companies would be in a position to effectively control and manage the process of monitoring their performance and would be in a position to comply with the relevant laws and regulations. Moreover, the development of the concentration and the process of PTE contamination would be effective in the context of controlling the risks associated with the process of storage of the tailings.

5.2 Recycled Process Water Chemistry

Recycling of water is an integral part of any sustainable mineral processing plant, more so in arid and semi-arid regions where water is in short supply. In phosphate processing plants, considerable quantities of water are used in washing, flotation, and classification circuits. Recycling of water through thickening of the tailings streams is likely to reduce water demand in such plants and is essential for water-efficient mining. It is believed that recycled water used in mineral processing plants may impact the performance of various unit operations in phosphate processing plants. As water is recycled and reused in various circuits within the plant, salts and solids tend to build up in the water recycling circuits. There is also the possibility of residual reagent buildup in recycled water used in various circuits within the plant. For instance, the buildup of ions in water recycled in various circuits may impact the performance of various unit operations in phosphate processing plants. For example, ions in recycled water may impact the performance of various unit operations in phosphate processing plants. For example, ions in recycled water may impact the performance of various unit operations in phosphate processing plants. For example, ions in recycled water may impact the performance of various unit operations in phosphate processing plants. For example, ions in recycled water may impact the performance of various unit operations in phosphate processing plants. For example, ions in recycled water may impact the performance of various unit operations in phosphate processing plants. For example, ions in recycled water may impact the performance of various unit operations in phosphate processing plants. For

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5.3: Circular Economy and Tailings Valorization

Besides environmental risk management of tailings, there is an emerging focus on the potential of sustainable tailings management to support other aspects of mining activity, such as valorization of mining by-products. For instance, phosphate mining wastes may be rich in materials such as silica, carbonates, clays, and phosphates that may be utilized to produce materials of great use to various industries. Research has been conducted to ascertain whether phosphate wastes may be utilized to produce materials such as geopolymer bricks and cement. Such materials may be of great use to various industries and may be an opportunity to generate economic value from mining wastes. For instance, geopolymer technology may be utilized to produce building materials from wastes through a series of chemical reactions. In addition, it may be possible to produce bricks or other components of building materials from wastes through a mixture of other industrial wastes that may be utilized to produce bricks or other materials that may be considered environmentally friendly. However, there is still a number of barriers to be addressed before the potential of sustainable tailings management may be fully utilized to generate economic value from mining wastes. For instance, there is a need to ascertain whether it is possible to produce materials of acceptable quality to be utilized as construction materials. In addition, there is a need to ascertain whether it is economically viable to produce materials from wastes on a large scale.

5.4: ESG Governance and Tailings Management

Today's mining activities are being assessed based on Environmental, Social, and Governance (ESG) criteria. Investors, as well as local and central governments, are looking at mining companies' commitment to environmental sustainability and long-term sustainability.

In the context of tailings management, for example, global guidelines such as the Global Industry Standard on Tailings Management (GISTM) underscore the importance of monitoring and reporting tailings risks. These governance guidelines require mining companies to establish effective management systems for monitoring the performance of tailings facilities over the life cycle. Mining companies can use the integration of KPI-based monitoring systems and ESG reporting to establish connections between mining performance and sustainability metrics. For example, metrics such as water intensity, tailings generated per unit of production, and tailings storage facility stability can provide useful insights into the environmental performance of mining companies. Mining companies can use the integration of operational KPIs and governance guidelines to improve their ability to demonstrate responsible resource management.

VI. IMPLEMENTATION ROADMAP AND FUTURE RESEARCH DIRECTIONS

As can be deduced from the gap analysis and KPI-oriented synthesis methodology developed in this research, it is evident that sustainable tailings management in sedimentary phosphate beneficiation can only be realized if there is a holistic approach to this concept, considering innovation, monitoring, and governance. Although several research works have been done to try to address the issue of phosphate tailings management, it is essential to develop

implementation strategies that can help bridge the gap, which often exists, between research and implementation in different mining industries. Therefore, this proposed implementation roadmap is a clear indication of critical research and development priorities that can help in the move towards a more sustainable phosphate tailings management system in the future. One of the most important priorities in the move towards developing a more sustainable phosphate tailings management system is to develop integrated modeling tools to help in the assessment of the different interactions that may occur in the phosphate tailings management system. Most of the optimization strategies developed in the literature are mostly aimed at optimizing different processes such as flotation, flocculation, and thickening. Integrated modeling tools can help in developing a holistic approach to the different interactions that may occur in the phosphate tailings management system. This can be important in helping the mining operators to assess the different interactions that may occur in the phosphate tailings management system. For example, such integrated modeling tools can help in assessing the different effects of fluctuations in the recovery process, such as the effect of such fluctuations on tailings particle size distribution, water recovery, and tailings storage facility behavior. The second critical priority would be the validation of optimization strategies for the operation of phosphate tailings treatment plants. Most of the technologies that have been proposed in the literature, with the aim of addressing the phosphate tailings treatment, have been validated based on laboratory-scale studies. Although laboratory-scale studies are critical in the development of new technology, there is a need to validate the laboratory-scale studies with pilot-scale and plant-scale studies. This will be critical in addressing the potential variability in the performance of the plant, with the aim of validating the laboratory-scale studies in the development of solutions to the problems encountered in the phosphate mining industry. The other critical area of future research would be the development of a better understanding of the rheology and deposition properties of the tailings. The rheology of the tailings has been recognized as critical in the development of solutions to the potential problems encountered in the development of the relationship between the thickener underflow density and the performance of the thickener. Similarly, the pumping and deposition properties of the tailings are critical in the development of solutions to the potential problems encountered in the tailings storage facilities. As such, the future research should be directed towards the development of operational guidelines for the thickener underflow density in relation to the rheology of the tailings, with the aim of providing mining companies with the optimal balance between water recovery efficiency and pumpability. Another important direction for future research is related to developing a better understanding of monitoring and modeling tailings behavior. The monitoring and modeling of tailings behavior is very important in ensuring that mining companies are able to attain optimal performance in terms of sustainability. For example, instrumentation of geotechnical monitoring is very important in developing a better understanding of monitoring consolidation behavior and pore pressure dissipation in tailings storage facilities. This is important in ensuring that mining companies are able to attain optimal performance in terms of stability in tailings storage facilities. Aside from carrying out technical research regarding better utilization of phosphate tailings, more emphasis should be put into carrying out research regarding establishing circular economy solutions regarding better utilization of phosphate tailings. Although it has been ascertained through carrying out tests on a lab scale regarding better utilization of phosphate tailings, more emphasis should be put into carrying out life cycle assessments and tests regarding better utilization of phosphate tailings in construction materials. Lastly, in order to effectively execute strategies regarding sustainable tailings management, it is essential to integrate performance indicators into operations with a broader governance system. It is essential to develop a monitoring system with key performance indicators, which are essential in ensuring that mining operations are able to realize sustainability benefits from technical improvements. In addition, it is essential to integrate these monitoring systems with broader international governance systems, such as the Global Industry Standard on Tailings Management.

VII. CONCLUSION

Sustainable management of phosphate tailings during the beneficiation process has become an essential issue in the mining industry with the increasing environmental concerns, water scarcity, and strengthened global governance requirements. The sedimentary phosphate tailings produced during the mineral processing have unique physical and geochemical characteristics, which are characterized by high water retention and settling rates, as well as the presence of potentially toxic elements. The unique characteristics of phosphate tailings have made tailings management an essential part of efficiency and sustainability in phosphate mining systems. This paper has presented a literature review and gap analysis based on KPIs with the aim of synthesizing available literature and exploring avenues for improving sustainability in phosphate tailings management. The gap analysis showed that available literature has mainly focused on specific technical processes, including flotation optimization, thickening efficiency, and tailings placement strategies. However, sustainable tailings management involves an integrated approach to considering the interrelation between mineral processing efficiency, water management processes, and tailings facility stability. Three major operational performance indicators were identified as being central to sustainable phosphate tailings management, and they are tailings grade optimization, thickener water recovery efficiency, and tailings deposition stability. The KPIs offer an opportunity to provide measurable links between mineral processing efficiency and environmental outcomes and tailings management practices. The application of this framework is to highlight the opportunity to advance sustainable phosphate tailings management through the organization of existing research. Through the gap analysis, it was identified that there are significant research opportunities, which include developing integrated process models, validating laboratory-based technologies at the plant scale, improving tailings rheology and deposition characteristics, and expanding research into circular economy-based solutions for phosphate tailings management. Furthermore, there is an opportunity to advance sustainability-based tailings management practices through the integration of operational-based KPIs with sustainability-based governance frameworks, such as the Global Industry Standard on Tailings Management. The KPI-based framework presented in this research provides an opportunity to advance scientific research into practical operational improvements. The opportunity to advance sustainable phosphate tailings management is presented through the application of this framework to provide links between technical and sustainability-based outcomes, which can provide more sustainable and environmentally responsible phosphate mining systems.

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