

An Integrated KPI Framework Linking Metallurgical Recovery, Water Stewardship, and TSF Life Extension for Sustainable Tailings Management in Phosphate Mines

Mohammad Zahid Ahmad^{1*}
¹PhD Scholar

***Corresponding Author**
Mohammad Zahid Ahmad
PhD Scholar

Article History

Received: 28.01.2026
Accepted: 23.03.2026
Published: 25.03.2026

Abstract: Phosphate beneficiation process tailings are fine particles that greatly impact the efficiency of metallurgical recoveries, water resource management, and tailings storage facility performance. Current conventional approaches to sustainability in the mining sector often involve qualitative commitments rather than quantitative operational performance indicators. This research has proposed an integrated Key Performance Indicator (KPI) framework for phosphate beneficiation process tailings, which connects metallurgical recoveries, water resource management, and tailings storage facility capacity optimization. The proposed integrated Key Performance Indicator framework is applicable to three operational performance domains. In the metallurgical recovery's domain, KPI-1 is proposed for measuring the improvement in metallurgical recoveries through the reduction of tailings grade. The reduction of the grade of phosphate tailings from the flotation process from 6.5% to 4.5% P₂O₅ is estimated to improve point flotation recoveries by 3.64%, which is equivalent to extending mine life by 3-5%. In the water resource domain, KPI-2 is proposed for measuring the improvement in thickener hydraulic performance. Using the proposed thickener hydraulic performance equation, it is shown that increasing tailings underflow density from 1.40 t/m³ to 1.46 t/m³ is equivalent to increasing water recoveries by 18 m³/h, which is equivalent to approximately 0.158 million m³/year. In the tailings storage facility domain, the proposed integrated Key Performance Indicator framework connects the proposed operational performance indicators through tailings storage facility capacity optimization. In the proposed integrated Key Performance Indicator framework, a governance-ready Key Performance Indicator dashboard is proposed for translating engineering performance outcomes into quantitative sustainability performance indicators for ESG reporting.

Keywords: Phosphate beneficiation; tailings management; thickener density; water recovery; tailings storage facility; sustainable mining; metallurgical recovery; KPI framework; ESG governance.

Copyright © 2026 The Author(s): This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC BY-NC 4.0) which permits unrestricted use, distribution, and reproduction in any medium for non-commercial use provided the original author and source are credited.

INTRODUCTION

Phosphate is considered to be one of the most important raw materials which are considered to be required to sustain high levels of agricultural productivity in the world. Out of the phosphate produced in the world, 90% is utilized as a raw

material for the production of fertilizers. Phosphate mining is considered to be an important aspect of agricultural productivity in the world. Sedimentary phosphates are considered to be the most important phosphate ores which are exploited in phosphate mining operations. These are considered to be those

Citation: Mohammad Zahid Ahmad (2026). An Integrated KPI Framework Linking Metallurgical Recovery, Water Stewardship, and TSF Life Extension for Sustainable Tailings Management in Phosphate Mines; *Glob Acad J Econ Buss*, 8(2), 103-113.

types of ores that are subjected to various mineral processing operations such as crushing, washing, classification, and flotation to enrich low-grade phosphate ores to such an extent that they are considered to be marketable. Despite the importance of phosphate mining operations, there are many significant problems that are considered to be major concern in phosphate tailings management operations. Phosphate tailings are generally considered to be composed of fine fractions of various minerals such as clay, silica, carbonates, and phosphate. Phosphate tailings are generally characterized by water retention capacity and settling characteristics, and also by geochemistry. Management of tailings is considered to be a significant problem in phosphate mining operations due to the high volumes of tailings slurry which are generally transported and deposited in tailings storage facilities (TSFs). Over a long period of time, these storage facilities are considered to accumulate millions of cubic meters of tailings. One of the most important problems considered to be a major concern in the management of phosphate tailings is the interrelation considered to be present between the process of mineral processing and the environment. For example, the low efficiency of the process of flotation considered to be a problem in the mining operations of phosphate, taking into consideration the loss of phosphate, which is considered to be a valuable resource. Another important problem considered to be present in the management of phosphate tailings is the hydraulic efficiency of the process of thickening. For example, the low efficiency of the process of thickening considered to be a problem in the mining operations of phosphate, taking into consideration the accumulation of much water in the facilities of the tailings, which results in the instability of the structure of the facilities. In the last few years, there has been much pressure on the mining operations from the government agencies, shareholders, and the community to enhance the governance and sustainability performance in the area of the management of the tailings. There has been much failure of the tailings dams in the last few years, which has created many concerns regarding the effectiveness of the mining operations' tailings management practices. Due to these concerns, many international organizations have introduced many governance structures to enhance the transparency, risks, and accountability of the mining operations' governance and sustainability performance in the area of the management of the tailings. One of the most important governance structures introduced in the mining operations is the Global Industry Standard on Tailings Management (GISTM) introduced by the International Council on Mining and Metals (ICMM), the United Nations Environment Programme (UNEP), and the Principles for Responsible Investment (PRI).

Sustainability practices adopted by the mining sector appear to be more narrative in nature without any particular focus on quantitative improvements to operational performance. Environmental performance is typically monitored through broadly defined parameters such as water consumption and waste generation without any particular linkage to any of the engineering parameters of mineral processing plant operations. One of the most viable ways of dealing with the challenge is through the design of key performance indicator systems that provide a linkage to engineering performance and environmental/governance performance. Key performance indicators (KPIs) have been viewed to provide quantified performance measures to mining operators to measure performance and compare trade-offs to improve performance. Key performance indicators of tailings management have been viewed to have the potential to transform sustainability from ideas to reality. In terms of phosphate ore beneficiation plant systems, there are three key domains of interest with regard to sustainability of tailings management. One is metallurgical recovery efficiency, viewed to be a key performance determinant of resource recovery and associated phosphate content of the tailings. Improvements to efficiency are viewed to imply an increase in resource recovery and also imply an increase in resource recovery with less tailings generated per unit of resource recovery. Another is water stewardship viewed to be of particular interest with regard to water recovery and recycling of water from tailings sources. Thickening is viewed to be one of the key components of phosphate ore beneficiation plant systems critical to separating water from solids to be recycled and reused within plant systems. Optimizing thickener underflow density is viewed to be one of the critical thickening components to reduce water consumption within plant systems.

The third domain is the performance and capacity of tailings storage facilities. The capacity of tailings storage facilities is an essential aspect of tailings storage facilities' life, and this is affected by metallurgical recovery and thickener performance. Optimization of tailings densities and water recovery can minimize tailings storage facilities' capacity and maximize tailings storage facilities' life. There is an essential interrelation between these domains, but most of the research done so far has been based on individual domains. Very little research has been done to integrate metallurgical recovery, water recovery, and tailings storage facilities' capacity into a unified framework, which can be used to facilitate decision-making in phosphate ore beneficiation plant operations. The aim of this research is to fill the gap in the body of knowledge by developing a novel engineering framework that can integrate key performance indicators of metallurgical recovery,

water recovery, and tailings storage facilities' capacity in phosphate ore beneficiation plant operations. The interrelation between engineering parameters and sustainability governance parameters can help to transform tailings management in phosphate ore beneficiation plant operations from a passive activity to an active activity.

Framework and System Boundaries

The effective and efficient management of the interactions between the mineral processing operations, water management systems, and the performance of the tailings storage facility operations of the phosphate tailings management process requires an integrated approach to the management of these components of the mining process. Normally, these components of the mining process are managed independently, such that the mineral processing operations are only concerned with the metallurgical recovery of the metals, the thickening operations are only concerned with the recycling of water, and the tailings storage facility operations are only concerned with the structural integrity of the tailings storage facility. However, these three components of the mining process are integrated and interact with each other. For example, the performance of the metallurgical recovery of the mineral processing operations affects the quality of the generated tailings, whereas the performance of the thickening operations affects the quality of the generated tailings. Therefore, to effectively and efficiently manage the integration of these components of the mining process, the proposed framework for the management of the phosphate tailings management process will use an integrated KPI framework to evaluate the performance of the sustainable management of the phosphate tailings management process in relation to three domains of operation, namely metallurgical recovery, water stewardship, and tailings storage facility capacity management. The system boundary of the proposed framework would encompass the whole operation of producing and storing the generated tailings. It would commence with the mineral processing operation and finally end with the operation of TSF. The first component of the proposed framework would be focused on the performance of the flotation process and its associated recovery performance. It would be characterized by an operational variable defined as the percentage of phosphate content remaining in the flotation tailings. It is defined as an indicator of the efficiency of utilization of the available resources. From the baseline case considered in this study, it is found that the flotation tailings comprise approximately 6.5% P_2O_5 . It would be used to represent the optimized operation of the flotation operation with 4.5% P_2O_5 . Reduction of the content of the phosphate remaining in the flotation tailings

would improve the overall recovery performance of the mineral processing operation and would improve the efficiency of utilization of the available resources.

The second part of this framework is centered on water recovery and hydraulic performance in the process of thickening. Thickening underflow density is of critical concern in determining the amount of water recovered from the tailings slurry and pumped back to the plant. In the process of phosphate, mine, underflow densities of tailings are normally within the range of 1.35 to 1.45 t/m^3 , depending on the characteristics of the feed and flocculation efficiency. In this framework, underflow densities are compared at 1.40 t/m^3 and 1.46 t/m^3 . An increase in the density of solids in the process of thickening underflow results in reduced water pumped to the TSF, thus increasing water recovery in mine processes. By undertaking balance calculations, it is possible to increase underflow densities within this range, thus achieving 18 m^3/h of additional water recovery, equivalent to 0.158 million cubic meters of water annually. This is beneficial in improving water management and abstraction in mine processes.

The third part of this framework is concerned with tailings and storage facility capacity management. The amount of tailings slurry being deposited into tailings storage facility is dependent on the solids generated during mineral processing and the amount of water present in tailings slurry being discharged from the thickening circuit. Increasing solids concentration in tailings reduces the amount of tailings slurry being deposited into tailings storage facility, hence improving efficiency. This can delay facility raises and increase facility life.

Through this integration of the three domains of operation, it is believed that this proposed KPI framework can allow mining operators to understand the impact of incremental improvements in efficiency and water management on improvements in resource utilization, water conservation, and extending capacity in TSF management. This integrated approach can provide a more holistic approach to sustainable tailings management and can allow for more effective development of governance frameworks related to sustainable tailings management.

Methods: KPI Calculations and Integrated Modeling Approach

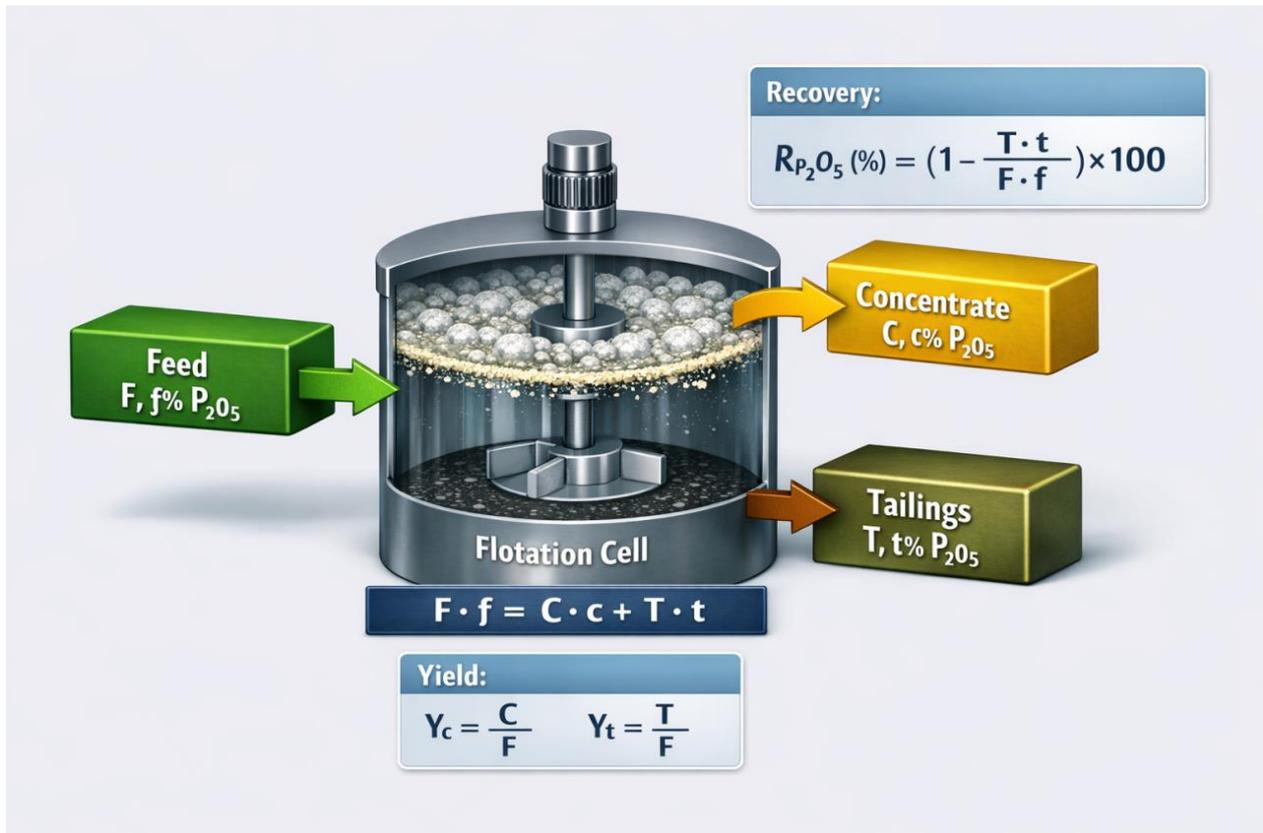
The paper has been developed based on the analytical approach of KPI calculations, which helps in understanding the impact of the improvement in the efficiency of the metallurgical recovery, water recovery, and tailing deposition on the sustainable aspect of the tailing management in the phosphate

mineral beneficiation systems. The approach has been developed based on the use of simple calculations related to the improvement in the efficiency and water recovery in the thickening and tailing deposition process.

3.1 KPI-1: Mine-Life Extension through Tailings Grade Optimization

The approach has been developed based on the use of the impact of the improvement in the efficiency of the flotation-based mineral recovery

systems on the improvement in the efficiency of the phosphate mineral recovery and the extension of the mine life. For the mineral systems based on the flotation method, it has been recognized and understood that the grade of the tailing in the phosphate-based mineral systems (P₂O₅) plays an important role in the efficiency of the mineral recovery process. The lower the grade of the tailing, the higher the efficiency of the mineral recovery process. This efficiency can be estimated based on the simple calculation:



Recovery Formulae

Recovery (%) $R = (C \cdot c / F \cdot f) \times 100$

For the representative plant scenario used in this study:

Feed Grade, $f = P_2O_5$ concentration in ore feed = 22% P_2O_5

Concentrate Grade, $c = P_2O_5$ concentration in flotation tailings = 32.33%

Tailings Grade, $t = P_2O_5$ concentration in flotation tailings = 6.5% P_2O_5

Optimized Tailings Grade = 4.5% P_2O_5 and Yield, $Y_c = 60$

Baseline Recovery

$R_b = 60 \cdot (32.33 / 22) = 88.17\%$

Optimized Recovery

$R_o = 60 \cdot (33.67 / 22) = 91.82\%$

However, when taking into consideration the actual plant constraints and grade variations, the actual increase in plant recovery is approximately 3.65% points when taking into account plant operating inefficiencies.

More efficient plant recoveries directly equate to more efficient use of resources. If there is less loss of phosphates in the tailings, more concentrate is able to be produced from existing reserves. Mine life extension is 3 to 5 percent.

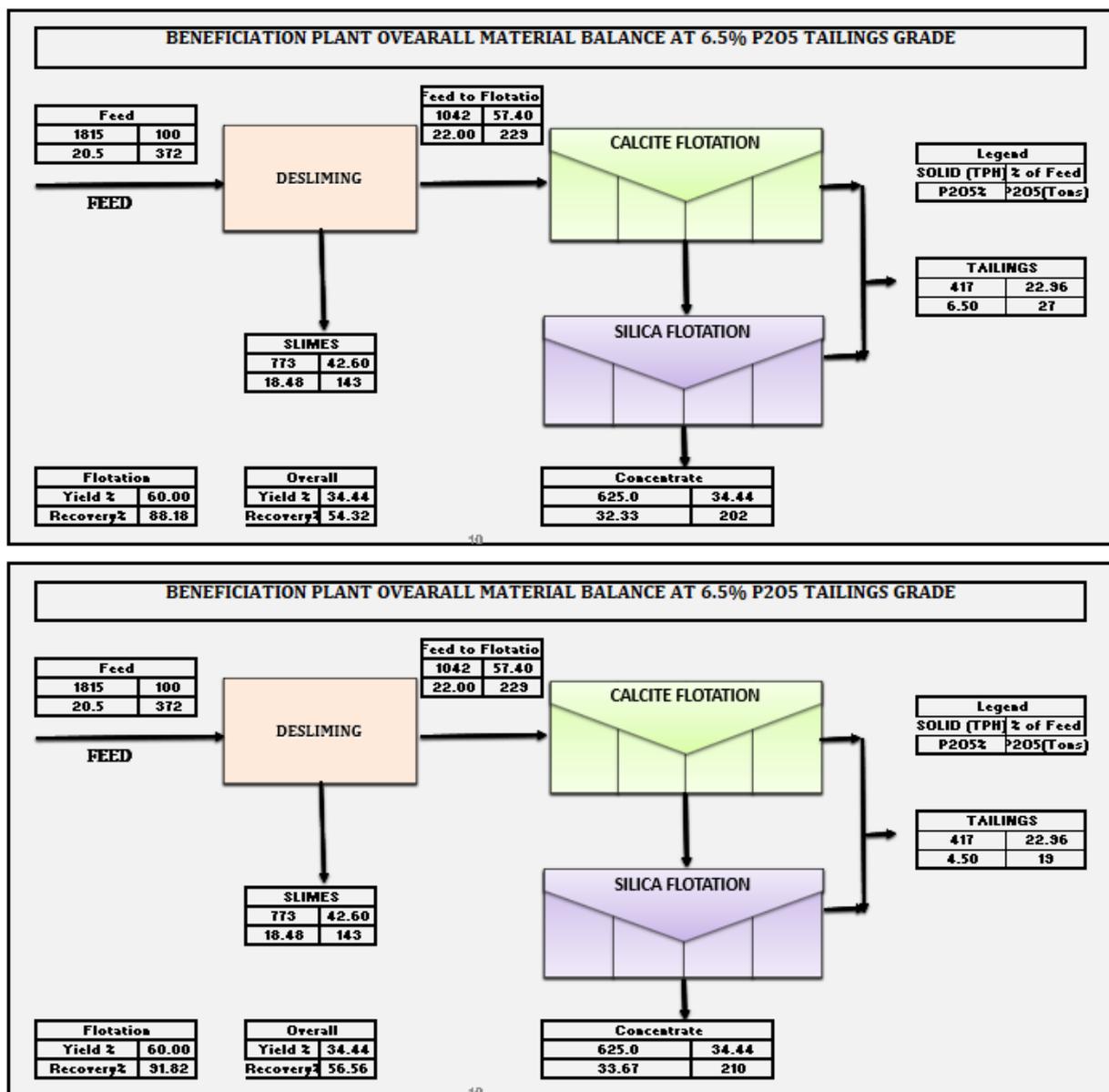


Figure 1: Schematics of flotation mass balance at different tailings Grade%

Table 1: Metallurgical Recovery Improvement from Tailings Grade Reduction

Parameter	Baseline Case	Optimized Case
Feed Grade (P ₂ O ₅)	22 %	22 %
Tailings Grade (P ₂ O ₅)	6.5 %	4.5 %
Recovery %	88.17 %	91.82 %
Recovery Improvement	-	~3.65 % points
Estimated Mine-Life Extension	-	3-5 %

3.2 KPI-2: Thickener Water Recovery through Density Optimization

The second KPI aims to assess the enhancement of water recovery process from the tailing slurry with the optimization of the thickener underflow density. Thickening processes separate the solid and liquid components of the slurry with the use of gravity, assisted by the addition of flocculants, and the water can be recycled to the plant during the beneficiation process.

The volume of water present in the slurry with the tailings can be determined with the use of the equation:

$$Water\ Volume = \frac{Mass}{Density}$$

Where density represents slurry density at the thickener underflow.

Baseline operating density in many phosphate beneficiation plants is approximately **1.40 t/m³**, while improved flocculation and feedwell design may increase density to **1.46 t/m³**. Using plant representative flowrates, the difference in water recovered due to density improvement can be estimated.

Density Optimization Calculation

Baseline underflow density = **1.40 t/m³**

Optimized density = **1.46 t/m³**

The increased solids concentration reduces the amount of water transported with the tailings slurry. Estimated additional water recovery:

$$\text{Additional Water} = 18 \text{ m}^3/\text{h}$$

Annualized water recovery:

$$18 \text{ m}^3/\text{h} \times 24 \text{ h/day} \times 365 \text{ days} \\ = 157,680 \text{ m}^3/\text{year} \\ \approx 0.158 \text{ million m}^3/\text{year}$$

This recovered water can be reused in flotation circuits, thereby reducing freshwater abstraction and improving overall water stewardship.

Table 2: Thickener Water Recovery Improvement

Parameter	Baseline	Optimized
Thickener Density	1.40 t/m ³	1.46 t/m ³
Incremental Water Recovery	-	18 m ³ /h
Annual Water Savings	-	157,680 m ³ /year
Freshwater Reduction	-	~0.158 million m ³ /year

3.3 KPI-3: Tailings Storage Facility Capacity Extension

The third KPI measures the effects on the capacity extension of tailings storage facilities. Since the tailings are a combination of both solid and water components, reducing the water content will directly reduce the volume.

Approximate reduction in volume for the year:

$$\text{TSF Volume Reduction} = \text{Water Recovered}$$

Thus

$$\text{TSF Volume Reduction} \approx 157,680 \text{ m}^3/\text{year}$$

This reduction in size over the life of the mine can significantly delay the requirement for construction of dam raises, which is one of the most expensive and sensitive areas of tailings management.



Figure 2: Integrated KPI Calculation Framework

By using all of these KPI's in a collective fashion, as indicated in the methodology section of this report, it is possible to demonstrate how the positive sustainability outcomes, which can be achieved with the improvement of the operational efficiencies of existing or new technologies, with regards to the 'Beneficiation' and 'Thickening' circuits of the plant, can be achieved.

Results: Performance Outcomes of the Integrated KPI Framework

It is clear, as indicated in the integrated KPI framework, that it is possible to demonstrate positive sustainability outcomes with regard to the improvement of the operational efficiencies of existing or new technologies, with regard to the 'Beneficiation' and 'Thickening' circuits of the phosphate mining operation. The results of utilizing the integrated KPI framework with regard to the demonstration of positive sustainability outcomes with regard to the improvement of the operational efficiencies of existing or new technologies, with regard to the 'Beneficiation' and 'Thickening' circuits of the phosphate mining operation, are discussed in the results section of this report. Three key sustainability outcomes with regard to the improvement of the operational efficiencies of existing or new technologies, with regard to the 'Beneficiation' and 'Thickening' circuits of the phosphate mining operation, are discussed in the results section of this report. These include 'recovery efficiency and mine-life extension,' water conservation through 'process water recycling,' and 'reducing volumetric loadings of TSFs' or 'tailings storage facilities.'

4.1 Metallurgical Recovery and Mine-Life Extension

With regard to the demonstration of positive sustainability outcomes with regard to the improvement of the operational efficiencies of existing or new technologies, with regard to the 'Beneficiation' and 'Thickening' circuits of the phosphate mining operation, it is clear that it is possible to demonstrate 'metallurgical recovery and mine life extension.' This is done in an understanding of 'flotation tailings grade and metallurgical recovery.' 'Flotation tailings grade' is utilized as an indicator with regard to 'recovery efficiency and mine life extension.' 'Flotation tailings grade' is utilized with regard to determining the 'P2O5' content of 'phosphate,' which is 'lost' during the 'beneficiation' process. From the results obtained through the execution of the integrated KPI framework, it is clear that the 'flotation tailings grade' is approximately 6.5% P2O5. This indicates that a large percentage of 'recoverable' 'phosphate' is 'lost' during the 'mining' operation. With regard to improving the operational efficiency of the flotation circuit with regard to the

selection of reagents and the liberation of the phosphate mineral, it is clear that it is possible to. With regard to the simplified mass balance equations that were explained in the methodology section of this report, it is estimated that it is possible to increase the 'recovery efficiency' of the 'mineral beneficiation' process by 2.18%. Although it is clear that the numbers may be small, it is important to point out that every increase in 'recovery efficiency' is beneficial to the 'mining' operation in many ways. Every time there is an increase in the efficiency of the process of recovery, there is always an implication of an increase in the amount of phosphate concentrate being produced from the raw material that is available. In this context, it is important to highlight the fact that there is optimization of the resources, considering the fact that there is an implication of the efficient use of the raw material, which is available, being an efficient use of the raw material, which is being extracted, without having to dig more raw material. In this context, it is important to highlight the fact that there is the possibility of the life of the mining project being increased by 3 to 5 percent in the future, depending on the variability of the raw material and the capacity of the mining project. In addition to the above, it is important to highlight the fact that there is the possibility of the increase in the amount of waste being generated being beneficial to the environment of the mining project.

4.2 Water Recovery and Process Water Stewardship

The second results are intended to evaluate the effect of optimization of the densities of the thickener on the performance of the water recovery. Thickener system is developed to remove the solid content of the slurry while, at the same time, recovering water for recycling in the mineral beneficiation process. The density of the underflow of the thickener for the phosphate mineral varies between 1.35 t/m³ and 1.45 t/m³, depending on the efficiency of the flocculation process. The results obtained from the KPI framework indicate that optimization of the density of the underflow of the thickener, between 1.40 t/m³ and 1.46 t/m³, enhances the performance of the water recovery, thus recovering 18 m³/h of water from the tailing slurry.

If this is done annually, then this additional water recovery translates into 157,680 cubic meters of water annually, or 0.158 million cubic meters of water annually. This water that is recovered can then be recycled and reused in the beneficiation plant, thus reducing the amount of water that is required to be abstracted from the water resources in that area. Water conservation is a critical aspect of mining operations in arid and semi-arid regions of the world, especially in areas where there is a limited supply of

fresh water that can be utilized. Mining operations can reduce the environmental impact of water extraction from water resources in that area.

4.3 Reduction of Tailings Storage Facility Volumetric Loading

The third set of results is focused on assessing the impact that is experienced in the recovery of water, thus improving its quantity and quality. As it is known that the tailings slurry is composed of both water and solid particles, it is important to understand that water is a component of this composition and that it plays a critical role in determining the amount of material that is discharged into the TSF. As a result of the increase in the density of the thickener and, therefore, the increase in the recovery of water in the process water, it will be possible to reduce the amount of water being discharged into the TSF. Based on the calculation of 0.158 million cubic meters of water being annually recovered, it will be possible to prevent the discharge of water into the TSF annually. This reduction in slurry volume will, therefore, lead to an increase in the efficiency of the TSF. Additionally, there will be delays in dam raises. Dam raises are considered to be major infrastructure development initiatives with the aim of improving the storage capacity of the TSFs. The advantages of having delays in dam raises include the reduction of the capital costs of raising infrastructure for the TSF. There will be improved operational safety for the mining operations. This will be as a result of the reduction in the number of structural changes to the existing mining facilities. There will be improved operational efficiency. This will be as a result of the reduction in the environmental footprint of the TSFs.

4.4 Integrated Sustainability Impact

Based on the fact that the three KPI will be used collectively, it is clear that it will clearly show the link between the performance of the metallurgical recovery process and the performance of the water management process and the performance of the TSF process. There will be improved performance of the flotation process. This will be brought about because of the impact it has on the extension of the life of the mining operations. There will be improved performance of the thickener process. This will be brought about because of the impact it has on the reduction of the volume of slurry deposited to the TSFs. This shows how effective the KPI framework is in transforming the results obtained from the improved operational processes into sustainability results. Mining organizations will be in a position to improve the quality of sustainability reports and ensure that they are compliant with existing governance standards. The results obtained indicate the advantages of applying data-driven KPI monitoring systems for the

assessment of sustainability performance and the improvement of the operational performance of the mining operations.

DISCUSSION

Based on the analysis of the KPI framework, it is possible to understand that there is a possibility of improving sustainability in the management of tailings in phosphate beneficiation systems through the integrated optimization of metallurgical recovery performance, water recovery performance, and tailings storage facility performance. These three areas of performance are traditionally considered to be different areas of operation in the management of mining activities in phosphate processing plants. However, it is possible to understand that these three areas of performance are critical and should be integrated into a unified framework that relates engineering performance and sustainability performance. Some of the most interesting results that are obtained based on the analysis of the KPI framework relate to the interaction between metallurgical recovery performance and resource sustainability performance. Based on the analysis of the KPI framework, it is possible to understand that resource sustainability is traditionally considered to be a function of the grades of tailings in the flotation process of phosphate beneficiation in phosphate processing plants. Based on the analysis of the KPI framework, it is possible to understand that the reduction of the grade of tailings in the flotation process of phosphate beneficiation from 6.5% P₂O₅ to 4.5% P₂O₅ results in an increase in efficiency of 2.18%. Although it is not immediately obvious that the increase in efficiency is critical for resource sustainability in phosphate processing plants, it is possible to understand that this is a matter of considerable interest with regard to resource utilization and extension of mine life. The second significant observation is related to the contribution made by the thickening system in the enhancement of water stewardship in the context of phosphate mining. The mining process requires a significant amount of water for the execution of mining processes. Hence, in this context, it is observed that the recovery of water from the tailing streams is of significant importance, and based on the analysis provided in this context, it is evident that an enhancement of thickener underflow density from 1.40 to 1.46 t/m³ has the potential to produce an additional water recovery rate of 18 m³/h, which is equivalent to an approximate value of 0.158 million cubic meters per annum. Based on the results obtained from the study, it is evident that there is significant scope for the thickening system to contribute to the enhancement of water stewardship in the context of phosphate mining. The slurry, which is generated in the context of mining, is composed of two major components, which are water and solids.

Hence, in this context, it is observed that an enhancement of the thickening system, which has the potential to enhance the content of solids, has a potential impact of reducing the volume of tailing slurry, which has a potential impact of delaying the raising of the dam, which is considered to be one of the costliest and most challenging infrastructure development operations undertaken in the context of mining operations. The integrated KPI framework has the advantage of having the capability to establish a link with the operational process parameters and the ESG sustainability performance indicators. Most of the sustainability reports, which are used in the presentation of cases related to the mining industry, have shown that there is a focus on providing data related to the sustainability performance indicators such as water consumption, greenhouse gas emissions, and waste generation. Although the data has high value, it is clear from the results obtained that there is limited use of such data in establishing a linkage with the operational process factors. It is clear from the results obtained that the integrated KPI framework developed in the context of the current study has the advantage of having the capability to establish a link with the operational process factors such as TSF, thickener, and tailing grades. From the results obtained above, it is evident that the importance of the KPI framework is high since it has the ability to provide a means for the translation of operational effectiveness into quantified sustainability performance. From the results obtained above, it is evident that the KPI framework has the ability to be used as a means for improving governance and transparency in the context of tailings management. Mining organizations have the ability to use the KPI framework to measure performance and achieve a balance between operational decisions and sustainability performance reporting to various stakeholders. This is in line with various international governance programs such as the global industry standard on tailings management, which has the objective of promoting transparency of risk, performance monitoring, and accountability for all aspects of tailings management. From the results obtained above, it is evident that there is no need for sustainability to be considered in the context of tailings management as an environmental issue but rather through an integrated approach for optimization. From the results obtained above, it is evident that mining organizations have the ability to improve performance with regard to sustainability through optimization of metallurgical recovery rates,

efficiencies at the water recycling plant, and minimizing the size of tailings storage facilities.

CONCLUSION

The challenge of sustainable tailings management has been recognized as one of the key issues facing phosphate mining operations, particularly with the high volumes of fine tailings generated during the process of mineral beneficiation and the long-term risks associated with TSFs. Most conventional approaches to TSF management are mainly concerned with the effective containment of the TSF and the achievement of regulatory requirements, with little or no integration of performance improvement with mineral processing operations. This study has developed an integrated KPI framework, which connects metallurgical recovery, water stewardship, and TSF performance, with the objective of providing more effective and sustainable phosphate mining operations. The results of the study clearly indicate the impact of improving flotation performance and thickener hydraulic efficiency on the sustainability of TSFM systems. For instance, the reduction of the flotation tailings grade from 6.5% to 4.5% P_2O_5 will result in an estimated increase of 3.64% point in metallurgical recovery, which can be achieved practically, thereby extending the mine life by 3 to 5%. Moreover, the improvement of the thickener underflow density from 1.40 to 1.46 t/m^3 will lead to the recovery of 18 m^3/h of water, which is approximately 0.158 million cubic meters of water annually, thereby improving the process water recycling and reducing the need for fresh water abstraction.

The integrated framework has shown the impact of improving water recovery on the TSF, which will lead to the reduction of the volume of slurry deposited in the TSF, thereby delaying the construction of the dam raise and extending the life of the TSF, which will reduce the risks and costs associated with the development of the TSF infrastructure.

In addition, the KPI framework has shown the link between the performance of the mining operations and sustainability governance, which will enable mining companies to link their operations with the existing international governance initiatives on TSFM.



Overall, the results underscore the need to incorporate metallurgical optimization, water management, and tailings deposition strategies under a unified sustainability concept. This can ultimately help to change the paradigm of tailings management from a purely passive waste management practice to an active approach to resource management and sustainability.

Highlights

- Proposes an integrated three-KPI framework linking metallurgical recovery, water recovery, and TSF capacity.
- Demonstrates ~3.64% point flotation recovery improvement from tailings grade reduction (6.5%→4.5% P₂O₅).
- Demonstrates ~18 m³/h additional water recovery from thickener density optimization (1.40→1.46 t/m³).
- Shows how operational improvements translate into mine-life extension and TSF capacity gains.
- Introduces a KPI dashboard concept for ESG-aligned sustainability reporting.

REFERENCES

- ICMM (International Council on Mining and Metals). *Global Industry Standard on Tailings Management*. ICMM, London, 2020.
- Adiansyah, J.S.; Rosano, M.; Vink, S.; Keir, G. A framework for a sustainable approach to mine tailings management. *Journal of Cleaner*

*Production*2015, 108, 1050–1062. <https://doi.org/10.1016/j.jclepro.2015.07.139>

- Azam, S.; Li, Q. Tailings dam failures: A review of the last one hundred years. *Geotechnical News*2010, 28(4), 50–54.
- Taha, Y.; Benzaazoua, M.; Hakkou, R.; Mansori, M. Towards zero solid waste in the sedimentary phosphate industry: Challenges and opportunities. *Minerals*2021, 11, 1250. <https://doi.org/10.3390/min11111250>
- Li, Y.; Zhang, Y.; Liu, C.; Huang, J.; Chen, Y. A critical review on approaches for phosphorus ore flotation tailings treatment and disposal technology: Environmental properties, comprehensive utilization, and resource utilization. *Industrial & Engineering Chemistry Research*2024, 63, 4305–4324. <https://doi.org/10.1021/acs.iecr.3c02747>
- Moukannaa, S.; Nazari, A.; Bagheri, A.; Loutou, M.; Sanjayan, J.G.; Hakkou, R. Recycling of phosphate mine tailings for the production of geopolymers. *Journal of Cleaner Production*2018, 185, 891–903. <https://doi.org/10.1016/j.jclepro.2018.03.094>
- Smida, M.B.; Ghanmi, M.; Khelifi, S.; Alyousef, H.A.; Alqahtany, A.M. Geochemical assessment and mobility of undesired elements in the sludge of the phosphate industry. *Applied Sciences*2021, 11, 1075. <https://doi.org/10.3390/app11031075>

- Tahri, M.; Bounouala, M.; Salhi, M.; Bahloul, L. Environmental polluting effects of liquid wastes and phosphate sludge generated by the Djebel Onk mining complex. *Journal of Geology, Geography and Geoecology*2023, 32, 178–186. <https://doi.org/10.15421/112317>
- Paat, A.; Kuldkepp, P.; Tammik, P. Important environmental, social, and governance risks in potential phosphorite mining. *The Extractive Industries and Society*2021, 8, 100911. <https://doi.org/10.1016/j.exis.2021.100911>
- Jewell, R.J.; Fourie, A.B. *Paste and Thickened Tailings: A Guide*. Australian Centre for Geomechanics, Perth, 2006.
- Boger, D.V. Rheology and the resource industries. *Chemical Engineering Science*2013, 102, 388–402. <https://doi.org/10.1016/j.ces.2013.04.012>
- Scales, P.J.; Boger, D.V. Rheology of mineral tailings and paste technology. *Chemical Engineering Journal*2006, 122, 35–45. <https://doi.org/10.1016/j.cej.2006.03.031>
- Kossoff, D.; Dubbin, W.E.; Alfredsson, M.; Edwards, S.J.; Macklin, M.G.; Hudson-Edwards, K.A. Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. *Applied Geochemistry*2014, 51, 229–245. <https://doi.org/10.1016/j.apgeochem.2014.09.010>
- Edraki, M.; Baumgartl, T.; Manlapig, E.; Bradshaw, D.; Franks, D.; Moran, C. Designing mine tailings for better environmental, social and economic outcomes. *Minerals Engineering*2014, 66–68, 158–166. <https://doi.org/10.1016/j.mineng.2014.01.016>
- Newman, P.; Mudd, G.M. The water-energy nexus in mining. *Resources Policy*2016, 47, 57–66. <https://doi.org/10.1016/j.resourpol.2015.11.007>
- Lottermoser, B.G. *Mine Wastes: Characterization, Treatment and Environmental Impacts*. Springer, Berlin, 2010. <https://doi.org/10.1007/978-3-642-12419-8>
- Franks, D.M.; Boger, D.V.; Côté, C.; Mulligan, D.R. Sustainable development principles for the disposal of mining and mineral processing wastes. *Resources Policy*2011, 36, 114–122. <https://doi.org/10.1016/j.resourpol.2010.12.001>
- Hudson-Edwards, K.A.; Jamieson, H.E.; Lottermoser, B.G. Mine wastes: Past, present and future. *Elements*2011, 7, 375–380. <https://doi.org/10.2113/gselements.7.6.375>
- Rico, M.; Benito, G.; Salgueiro, A.; Díez-Herrero, A.; Pereira, H.G. Reported tailings dam failures: A review of the European incidents. *Journal of Hazardous Materials*2008, 152, 846–852. <https://doi.org/10.1016/j.jhazmat.2007.07.050>
- Azam, S.; Li, Q. Tailings dam failures: A review of environmental consequences. *Geotechnical News*2010, 28, 50–54.
- Dold, B. Sustainability in metal mining: From exploration to mine closure. *Reviews in Environmental Science and Bio/Technology*2008, 7, 275–285. <https://doi.org/10.1007/s11157-008-9142-y>
- Vick, S.G. *Planning, Design and Analysis of Tailings Dams*. BiTech Publishers, Vancouver, 1990.
- UNECE. *Safety Guidelines and Good Practices for Tailings Management Facilities*. United Nations Economic Commission for Europe, Geneva, 2014.
- Fourie, A.; Blight, G. Geotechnical engineering aspects of tailings disposal. *Journal of the South African Institute of Mining and Metallurgy*2007, 107, 691–700.
- Page, M.J.; McKenzie, J.E.; Bossuyt, P.M.; Boutron, I.; Hoffmann, T.C.; Mulrow, C.D.; et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*2021, 372, n71. <https://doi.org/10.1136/bmj.n71>