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Preliminary Framework for Sustainable Reuse of Iron Ore Tailings in the Philippines

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Abstract— ***Management of iron ore tailings (IOTs) poses significant challenges such as seepage, leachate, and harmful heavy metal (HHM) discharge, as well as high costs for maintenance, monitoring, and rehabilitation, particularly in disaster-prone countries like the Philippines. The potential sustainable reuses of IOTs as a viable alternative to conventional disposal methods was mainly focused in this research. A systematic review of literature revealed that IOTs possess key physical and chemical properties that make them suitable for construction materials including cement, bricks, and ceramics. However, the presence of HHMs requires further risk assessments and pre-treatment processes assuring safe reuse. A preliminary framework for sustainable mine waste management is proposed, grounded in principles like the mine waste hierarchy, circular economy, and the precautionary principle. The framework aims to reduce waste, mitigate environmental risks, and align with global sustainability goals. The successful reuse of IOTs in countries worldwide demonstrates their potential to drive infrastructure development while addressing critical environmental issues. This study also lays a foundation for establishing sediment quality management and environmental standards not only in the Philippines but also in other countries facing similar challenges. By promoting the sustainable reuse of IOTs, this research could contribute to the development of a circular economy, reduces the environmental impact of mining, and supports the achievement of the United Nations' Sustainable Development Goals.***

Index Terms: ***Iron ore tailings, mine waste management, reuse, sustainability, waste reduction.***

I. INTRODUCTION

The increasing prevalence of chronic Between 2012 and 2021, the Philippines mined approximately 4.2×10^6 t^3 of iron ore [1] which is used mainly in steel production and concrete for nuclear facilities [4]. Significant iron ore tailings (IOTs) are generated during extraction process, which pose major mine waste management challenges. Globally, around 1.4×10^9 t^3 of IOTs are produced annually [8], with increasing demand leading to higher reliance on tailings dams. These dams are commonly used but costly and present serious environmental and safety risks, such as the leaching of harmful heavy metals (HHMs) into groundwater system and surrounding ecosystem, and catastrophic failures during extreme weather events.

In the Philippines, approximately 1.2×10^6 t^3 of IOTs were discharged each year, with a 2:1 waste-to-iron production ratio [14]. This volume is concerning due to reliance on tailings dams, which are vulnerable to collapse, considering the country's vulnerability to climatic condition and seismic activity. The country accounts for 3.3% of global tailings dam failures [12] which highlights the serious risks from HHM release.

Potential seepage, leachate, and HHM discharge, as well as high costs for maintenance, monitoring, and rehabilitation, are the main challenges of managing IOTs. These issues entail the need for sustainable solutions. By adopting circular economy principles, reusing of IOTs could mitigate environmental hazards, reduce costs, and support the 2030 UN Sustainable Development Goals. Moreover, only 5% of mine waste is recycled in the Philippines, which indicates significant potential for improvement. This research aims to explore IOT reuse to minimize HHM risks and promote sustainable mine waste management, concentrating on their physical and chemical properties and proposing preliminary framework for sustainable mine waste management.

II. MATERIAL AND METHODS

A. Study Area

Located on the Pacific Ring of Fire, the Philippines is highly seismically active, with over 20 active volcanoes and frequent earthquakes from fault systems like the Philippine Fault Zone [25]. About 20 typhoons visited the country annually, leading to severe flooding and landslides, which pose significant challenges for mining and waste management.

Department of Environment and Natural Resources (DENR) under Memorandum Order No. 32-99 regulates mining by requiring secure tailing dams and rehabilitation of mined areas in the Philippines. However, incidents like the 1996 Marcopper Mining Disaster and the 2012 Philex Mining spill highlight ongoing management issues [47, 49].

The Philippines permits deep-sea tailing placement (DSTP), when onshore disposal is not feasible, to limit the

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spread of contamination. However, DSTP is banned in the United States of America (U.S.A), Canada, and Australia due to environmental concerns, and has confronted global criticism [13]. The London Convention's Scientific Groups reviewed these practices in 2008 which prompting an international effort to improve regulatory standards [46].

B. Evaluation Methods

A systematic review was conducted to gather, synthesize, evaluate, and interpret relevant literature on iron ore tailings. The review aimed to characterize the tailings, assess their physical and chemical compositions for potential reuse, and identify guiding principles to support the development of an initial framework for sustainable mine waste management.

C. Data Collections

This research involved review of literature, including wide to narrow searches, to garner relevant information from sources such as ScienceDirect (11 articles), ResearchGate (7), Multidisciplinary Digital Publishing Institute (MDPI) (6), and other journals (24). The keywords like "iron ore tailings," "mine waste management," "reuse," "sustainability," and "waste reduction" guided the search. Most of the selected articles were published between 2019 and 2024, focusing on Science Citation Index Expanded (SCIE)-referenced sources. Road mapping was utilized to identify and analyze the chemical and physical properties of IOTs, concepts of reuse, and guiding principles like the mine waste hierarchy, United Nations' Sustainable Development Goals (SDG) 12, circular economy, and the precautionary principle, to develop the preliminary framework.

D. Data Analysis

Next step involved systematically synthesizing the collected information by organizing the data using conceptual frameworks to classify important details such as the economic value of iron ore deposits, magnetite processing and beneficiation (origin of IOTs), and defining and classifying IOTs. Key aspects were also identified comprising the environmental impacts (main issue), physical and chemical properties of IOTs from various locations (comparison of chemical constituents and granulomere analysis), and guiding principles like the mine waste hierarchy, SDG 12, dredged material assessment framework, circular economy, and the precautionary principle.

The information, after synthesizing the data, was analysed to assess the variability in iron ore tailings properties across different sources and countries, and to identify which guiding principles could be the pillar for the development of the preliminary framework. The guiding principles were then incorporated into the framework by using input-process-output analysis, which aided to pinpoint key areas and crucial factors necessary for developing the essential components of the framework.

E. Interpretation

The systematic review completed by interpreting data to determine if reusing iron ore tailings (IOTs) is technically feasible. This encompasses comparison of the physical and chemical properties of IOTs with the requirements for specific reuse applications, such as building materials. The potential environmental risks were acknowledged; but not fully explored, with recommendation for treatment if IOTs proved harmful. The selected guiding principles were essential to create a solid foundation for developing the preliminary framework.

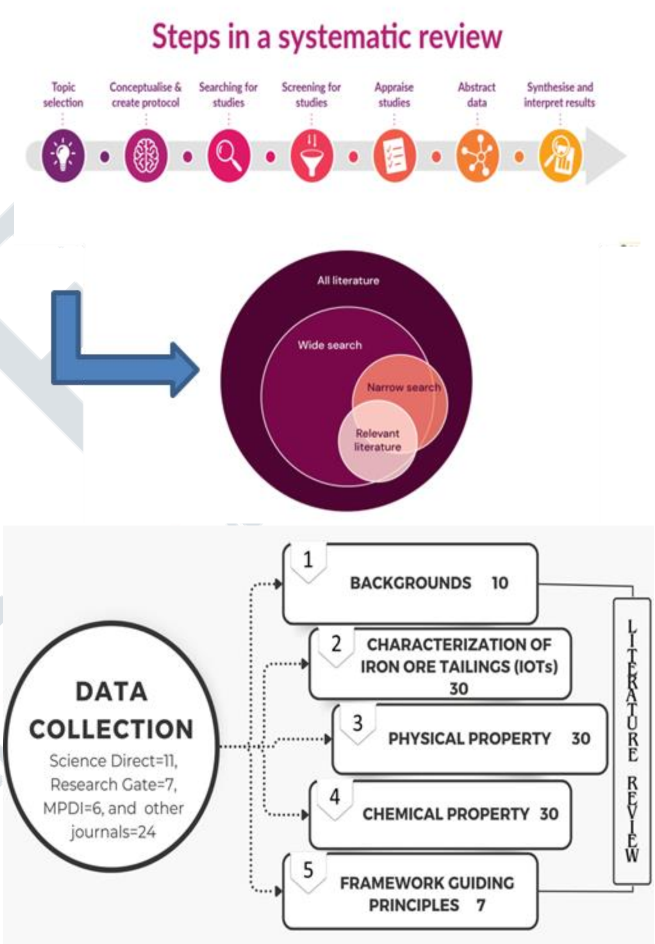

Figure 1. Systematic Review [48] and Data Collection process

III. RESULTS

A. Characterization of IOTs

IOTs are mineral waste products generated during the processing of iron ore. Once the valuable minerals are extracted from the slurry, the remaining materials, often a mix of low-grade ore and non-commercial rock, are referred to as tailings [14]. IOTs are a significant source of mine waste, particularly in the iron and steel industry [12], and are generally classified into two types: coarse sandy and fine

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tailings [8].

B. Chemical Properties

Chemical compositions of IOTs were significantly influenced by the inherent properties of the original iron ore, which entailed variability in concentration. X-ray fluorescence (XRF) is a non-destructive analysis and widely used technique for determining the chemical makeup of IOTs. IOTs typically consist of key components such as ferric oxide (Fe_2O_3), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and other trace elements, according to Carmignano et al. (2021). Among these, Fe_2O_3, SiO_2, and Al_2O_3 are the primary components present in varying weight percentages. Fe_2O_3, SiO_2, and Al_2O_3, dominate the chemical composition which underscore the potential for these tailings to be repurposed in numerous industrial applications, as illustrated in Table I.

Table I: Chemical compositions obtained by XRF of different IOTs [8]

Main Chemical Composition / %						
Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	Other Compounds	Mine Location
8.38	90.4	0.43	0.06	<0.1	0.63	MG, Brazil
11.6	84.2	1.6	-	-	2.6	MG, Brazil
11.31	75.23	2.64	1.47	2.1	7.25	Liaoning, Chia
12.31	34.72	16.22	7.63	8.92	20.2	Nanjing, China
15.1	84.4	0.45	0.07	<0.1	0	MG, Brazil
18.58	36.48	11.67	16.85	5.66	10.76	Jiangsu, China
21.2	45.6	12.1	1.79	-	19.31	China
21.4	65.7	0.8	-	-	12.1	MG, Brazil
21.5	71.4	-	-	-	7.1	MG, Brazil
29.35	49.2	1.46	0.12	-	19.87	MG, Brazil
32.0	46.68	3.89	-	-	17.43	MG, Brazil
35.0	63.0	1.2	-	-	0.8	MG, Brazil
38.8	14	2.01	37.5	0.36	44.83	China
42.4	47.9	5.61	0.13	<0.1	3.86	MG, Brazil
44.52	24.4	10.95	6.2	0.99	12.94	Hubei, China
47.8	30.0	21.2	0.1	0.1	0.8	MG, Brazil
51.37	15.11	3.39	0.23	0.16	29.74	MG, Brazil
55.78	16.58	15.46	1.44	0.13	10.61	Joda-Badbil, Orissa,
69.21	11.42	2.38	0.49	0.11	16.39	India
71.7	20.1	2.3	0.1	-	5.8	Bosnia and Herzegovina
73.3	8.76	1.49	3.88	0.94	11.63	MG, Brazil
						China

Wang et al. (2023) discovered that the IOT's chemical compositions varies significantly depending on the mine type, with higher concentrations of SiO_2, Al_2O_3, and Fe_2O_3 which was observed across different countries, as shown in Table 2.

Table II: Chemical compositions of different IOTs [9]

Main Chemical Composition / %						
Fe_2O_3	SiO_2	Al_2O_3	CaO	MgO	Other Compounds	Mine Location
8.38	90.4	0.43	0.06	<0.1	0.63	MG, Brazil
11.6	84.2	1.6	-	-	2.6	MG, Brazil
11.31	75.23	2.64	1.47	2.1	7.25	Liaoning, Chia
12.31	34.72	16.22	7.63	8.92	20.2	Nanjing, China
15.1	84.4	0.45	0.07	<0.1	0	MG, Brazil
18.58	36.48	11.67	16.85	5.66	10.76	Jiangsu, China
21.2	45.6	12.1	1.79	-	19.31	China
21.4	65.7	0.8	-	-	12.1	MG, Brazil
21.5	71.4	-	-	-	7.1	MG, Brazil
29.35	49.2	1.46	0.12	-	19.87	MG, Brazil
32.0	46.68	3.89	-	-	17.43	MG, Brazil
35.0	63.0	1.2	-	-	0.8	MG, Brazil
38.8	14	2.01	37.5	0.36	44.83	China
42.4	47.9	5.61	0.13	<0.1	3.86	MG, Brazil
44.52	24.4	10.95	6.2	0.99	12.94	Hubei, China
47.8	30.0	21.2	0.1	0.1	0.8	MG, Brazil
51.37	15.11	3.39	0.23	0.16	29.74	MG, Brazil
55.78	16.58	15.46	1.44	0.13	10.61	Joda-Badbil, Orissa,
69.21	11.42	2.38	0.49	0.11	16.39	India
71.7	20.1	2.3	0.1	-	5.8	Bosnia and Herzegovina
73.3	8.76	1.49	3.88	0.94	11.63	MG, Brazil
						China

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In the Philippines, the chemical compositions comprised of 0.62% Iron (II) oxide (Fe^{2+}), 37.3% Titanium oxide (TiO_2), 16.1% SiO_2, 18.2% Al_2O_3, 8.60% MgO, 17.10% CaO, 0.95% Manganese oxide (MnO), along with trace amounts of Phosphorus (P), Sulfur (S), and Vanadium (V) (Fudolig et al., 2018). As shown in Fig. 2, these compositions highlight that the primary components are SiO_2 CaO, and Al_2O_3, which are consistent with the key constituents used in construction products such as cement, bricks, ceramics, glass, and fine aggregates. This similarity in chemical makeup emphasizes the potential for repurposing IOTs in the construction industry.

IOTs may contain harmful heavy metals. Carmignano et al. (2021) identified trace amounts of cadmium (Cd), chromium (Cr), arsenic (As), and mercury (Hg) in IOTs. Similarly, Wang et al. (2023) study disclosed that IOTs contain harmful heavy metals like Cr, zinc (Zn), copper (Cu), nickel (Ni), lead (Pb), Cd, Hg, and As, which can easily migrate and transform in the environment. Moreover, heavy metal leaching was observed in acidic conditions; however, the concentrations were generally below the standard limits set by Chinese National Standard GB 5085.3-2007. In the study of Okewale and Grobler (2023), it was reported that Atomic Absorption Spectroscopy (AAS) revealed Cr levels in IOTs ranging from 118 to 230 mg/kg (exceeding the threshold of 100 mg/kg) and Cu levels from 310 to 480 mg/kg (surpassing the allowable limit of 30 mg/kg). Other heavy metals like As, Zn, Pb, cobalt (Co), zirconium (Zr), and strontium (Sr) remained within acceptable limits which indicate variable concentrations of heavy metals.

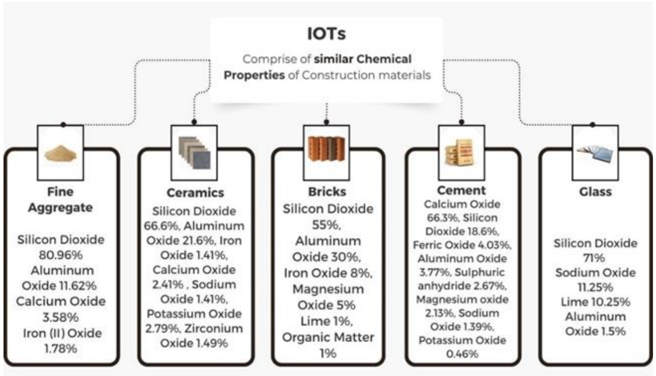

Fig. 2. Possible Reuses of IOTs based on its chemical properties.

Gibaga et al. (2022) employed Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) to analyze heavy metals in IOTs followed by adequate pre-treatments, ensuring accuracy with certified reference materials. According to the study, potentially toxic elements (PTEs) such as As, barium (Ba), Cd, Co, Cr, Cu,manganese (Mn), molybdenum (Mo), Ni, Pb, antimony (Sb), tin (Sn), thallium (Tl), vanadium (V), and Zn were present. Notably, As, Co, Mo, and Ni levels exceeded international environmental standards as shown in Table III. Arsenic concentrations significantly surpassed safety thresholds, which pose severe risks of contamination to soil and water, leading to serious health issues like cancer and skin lesions from exposure. Co levels also approached or exceeded international standards, which can lead to kidney damage and bone degradation from long-term exposure. Similarly, Mo and Ni levels exceeded international thresholds, which pose additional risks of respiratory and cardiovascular problems. Cr, Ba, Sn, and Tl were within safe limits, and Pb and Sb were below hazardous levels, still the presence of these HHMs requires the need for rigorous management and remediation efforts.

Table III: Evaluation of Potentially Toxic Elements (PTEs) concentrations (in ppm) with International Sediment Quality Criteria

Sample Name	As	Ba	Cd	Co	Cr	Cu	Mn	Mo	Ni	Pb	Sb	Sn	Tl	V	Zn	Sc
0727-07	45	54	1.07	26.8	4	148.3	362	62.9	21.1	14.1	0.24	0.79	0.20	43	61	2.4
0727-08	164	26	0.13	95.2	53	840.9	402	86.8	61	22.9	0.82	1.66	0.24	259	62	6.3
0727-09	199	10	0.19	74.9	39	926.2	390	83.8	53.7	14.5	1.1	1.11	0.23	259	43	3.9
0729-13	95	31	0.07	148.2	408	472.9	1,283	22.7	1,894	10.6	0.31	1.5	0.07	243	92	9.4
0729-07	48	12	0.15	82.9	155	378.3	725	27.4	391.8	11.1	0.76	1.82	0.03	771	59	3.7
Average	***110***	***27***	***0.32***	***85.6***	***132***	***53.82***	***632***	***56.7***	***484.4***	***14.6***	***0.65***	***1.38***	***0.15***	***8.85***	***63***	***5.1***
Avg.UCC	***4.8***	***6.28***	***0.09***	***17.3***	***92***	***28***	***775***	***1.1***	***47***	***17***	***0.4***	***2.1***	***0.9***	***97***	***67***	***14***
Canadian Solid Quality Standards	***12***	***750***	***1.4***	***40***	***64***	***63***	-	***5***	***50***	***70***	***20***	***5***	***1***	***130***	***200***	-
Republic of Korea	***20-70***	-	***2.5-10***	-	***80-370***	***65-270***	-	-	***35-52***	***50-220***	-	-	-	-	***200-410***	-
Netherlands	***29***	-	***0.80-4***	-	***100-120***	***36-60***	-	-	***35-45***	***85-110***	-	-	-	-	-	-
USA (Florida)	***7.24-41.6***	-	***0.676-4.21***	-	***52.3-160***	***18.7-108***	-	-	-	***30.2-112***	-	-	-	-	***124-271***	-
Belgium	***20-100***	-	***2.5-7***	-	***60-220***	***20-100***	-	-	***70-280***	***70-350***	-	-	-	-	***160-500***	-

Average values for Upper Continental Crust (UCC) from Rudnick and GAO, 2014 [10]
Canadian soil quality standards for industrial soil from CCME, 2007 [10]
Korean Ministry of Environment. Soil Environmental Conservation Act. [45]
Dutch Ministry of Housing, Spatial Planning and the Environment. Soil Remediation Circular 2009. [45]
Florida Department of Environmental Protection. Soil Cleanup Target Levels (SCTLs). [45]
Flemish Government. Soil Decree. [45]

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C. Physical Properties

Using energy-dispersive X-ray spectroscopy (EDS) combined with scanning electron microscopy (SEM), particle size information for iron ore tailings (IOTs) could be obtained. Carmignano et al. (2021) reported that fine tailings typically consist of particles ranging from 6 to 40 µm, while coarse sandy tailings had an average particle size between 100 and 150 µm, as shown in Fig. 3.

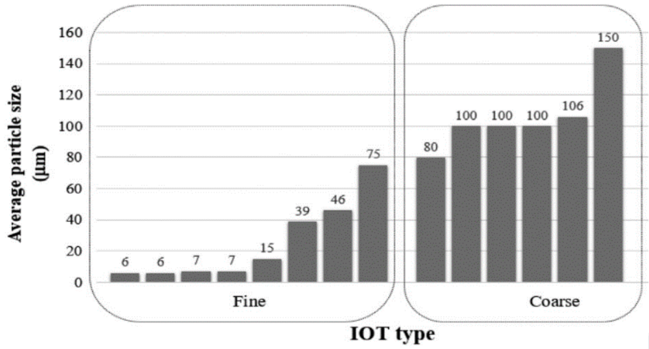

Fig. 3. Average Particle Size of IOTs obtained by light scattering [8]

In the study by Okewale and Grobler (2023), the particle size distribution, also known as grading curves, ranged from 3 to 900 µm. In contrast, iron slags produced in the Philippines show grading curves ranging from 63 to 400 µm, with the majority ranging between 100 and 200 µm, as reported by Fudolig et al. (2018).

As summarized in Table IV, the granulomere analysis indicates that the average particle size of IOTs meets the grading requirements for producing glass, ceramics, cement, and bricks, as well as for use as fine aggregate.

Table IV: Granulomere comparison in microns

AVE PARTICLE SIZE OF IOT	FINE AGGREGATE (PHILIPPINE STANDARD)	CERAMIC PARTICLE SIZE	BRICK PARTICLE SIZE	CEMENT PARTICLE SIZE	GLASS PARTICLE SIZE
FINE TAILINGS <40 µm COARSE TAILINGS 100-150 µm	9,500 µm [9.5mm (3/8in)] 4,750 µm [4.75mm (No.4)] 2,360 µm [2.36mm (No.8)] 1,180 µm [1.18mm (No.16)] 600 µm [0.600mm (No.30)] 300 µm [0.300mm (No.50)] 150 µm [0.150mm (No.100)]	1.8520E+ 11 to 100 µm	>20 µm/ <20 µm/ <2 µm	1-50 µm	75-1,108 µm

D. Development of Preliminary Framework

The proposed preliminary framework for managing IOTs, strategically grounded in well-established principles and aligned with global sustainability goals, offers a sustainable approach to waste reduction and resource optimization by integrating key concepts from the mine waste hierarchy, United Nations' SDG 12, the circular economy, the Dredged Material Assessment Framework (DMAF), and the precautionary principle. These components collectively guide the sustainable reuse of IOTs, transforming them from waste into valuable resources.

1) Mine Waste Hierarchy:

The mine waste hierarchy emphasizes minimizing waste generation and maximizing resource recovery through reuse, recycling, and recovery [36]. The framework ensures that IOTs are managed with a focus on sustainable utilization rather than conventional disposal by embedding this principle. This approach reduces waste volume by converting IOTs into valuable materials, thereby, mitigating environmental impacts and enhancing resource efficiency.

2) United Nations SDG 12:

SDG 12 aims to establish sustainable consumption and production patterns, with Target 12.5 specifically focusing on substantially reducing waste generation through prevention, reduction, recycling, and reuse [40-41]. By integrating this principle, the framework aligns with global sustainability objectives and encourages responsible consumption and production practices. This strengthens the contribution of the framework to international efforts to curtail waste and boost resource efficiency.

3) Circular Economy:

The circular economy advocates the continuous use and reuse of resources to decrease waste and environmental impact. By incorporating this principle, the framework boosts the innovative conversion of IOTs into valuable resources. This approach supports a closed-loop system where materials could be continuously cycled through the economy, reducing reliance on virgin resources and fostering long-term sustainability.

4) Dredged Material Assessment Framework (DMAF):

The DMAF offers a systematic approach to assessing the suitability of dredged materials for reuse before disposal. Benchmarking the DMAF to IOTs allows for a thorough evaluation of their physical, chemical, and environmental characteristics to identify potential beneficial uses.

5) Precautionary Principle:

The precautionary principle advocates for proactive measures in the face of uncertainty to prevent potential harmful effect to the environment or human health [23]. The framework emphasizes the importance of preemptive risk assessments and safety precautions in managing IOT, by incorporating this principle. This ensures that sustainable practices prioritize environmental protection and public safety which aligns with broader sustainability goals.

6) Integration and Application of the Framework

Detailed in Table V and illustrated in Fig. 4, we described

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the essential steps for transforming IOTs into viable construction materials in the preliminary framework. This framework was meticulously structured to outline critical processes including material characterization, identification of beneficial uses, risk assessment, beneficiation process, manufacturing, quality control, and a commitment to continuous development. Table V was translated into the framework. Each step is meticulously crafted to optimize environmental benefits, improve resource efficiency, and ensure safe and effective repurposing of IOTs.

IV. DISCUSSIONS

A. Technical Feasibility

Review results of the literature revealed that IOTs possessed physical and chemical properties compatible for use in construction materials. Key chemical compounds present in IOTs, such as iron oxide, calcium oxide, silicon dioxide, aluminum oxide, and magnesium oxide, were suitable for producing cement, ceramics, bricks, glass, and fine aggregates according to the study. The particle sizes (fine particles under 40 µm and coarser sandy particles averaging 100 µm) were within acceptable ranges for construction applications.

Successful reuse of IOTs in construction applications have been reported. UFMG and mining companies like Samarco and Gerdau have built model houses using IOTs [8]. Moreover, IOTs have been also applied to manufacture bricks and cement in China. Mendes et al. (2019) presented that high-silicon iron ore tailings in red clay ceramics can achieve strengths comparable to 42.5-grade cement. Consoli et al. (2022) reported the potential of using compacted filtered iron ore tailings mixed with Portland cement.

Table V: Input-Process-Output Analysis

PRINCIPLES	Key Areas	INPUT	PROCESS	OUTPUT
Mine Waste Hierarchy SDG 12 Circular Economy	**Characterization:** Characterize the chemical and physical properties of tailings to determine suitability for various reuse options.	Physical Properties	EDS (energy-dispersive X-ray spectroscopy)/SEM (scanning electron microscopies)	Particle distribution size (microns)
		Chemical Properties	X-ray fluorescence (XRF)	Concentration of chemical compounds (weight mass percentage)
	Beneficial Use Assessment: Evaluate the potential uses of tailings	Construction materials	Evaluation of results based on the particle distribution size (microns) and Concentration of chemical compounds (weight mass percentage) of tailings in comparison to the standard for producing construction materials	Cement, Ceramics, Bricks, Glass and Fine aggregates
	Risk Assessment: Conduct risk assessments to ensure safe reuse and prevent environmental contamination	Degree of pollution or contamination of toxic and harmful heavy metals	Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) analysis / Atomic Absorption Spectroscopy (AAS) Sediment Quality Criteria Implementation of remediation strategy	Treated tailings
	Pre-Processing: Pre-process and treat the iron ore tailings to enhance	Treated tailings	Particle size reduction (if necessary) to achieve desired gradation	Desired gradation for fine aggregates., ingredients for

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	their suitability for specific reuse applications			cement, glass, ceramics and bricks
Dredged Material Assessment Framework			Beneficiation or beneficiation processes to remove impurities and enhance material quality	Desired material quality
	Production of Construction Materials	Utilize treated iron ore tailings as raw materials	Manufacturing process	Manufactured construction materials
Precautionary Principle	**Quality Control and Testing**	Manufactured construction materials	Quality Control and Testing process	Quality products in compliance with relevant standards and specifications (material properties and performance characteristics)
	Application and Deployment	Quality manufactured construction materials	Apply and deploy	Infrastructure, building and construction projects
			Monitor and evaluate performance of materials	Feedback, lessons learned
	Continuous Improvement and Optimization	Feedback and lessons learned	Continuous evaluation and optimization of the reuse process	Innovative techniques and applications for further enhancing the value and sustainability of iron ore tailings reuse in construction materials.
	Disposal and Monitoring	Non-Reusable IOTs	Disposal and monitoring	Properly stocked and stable IOTs

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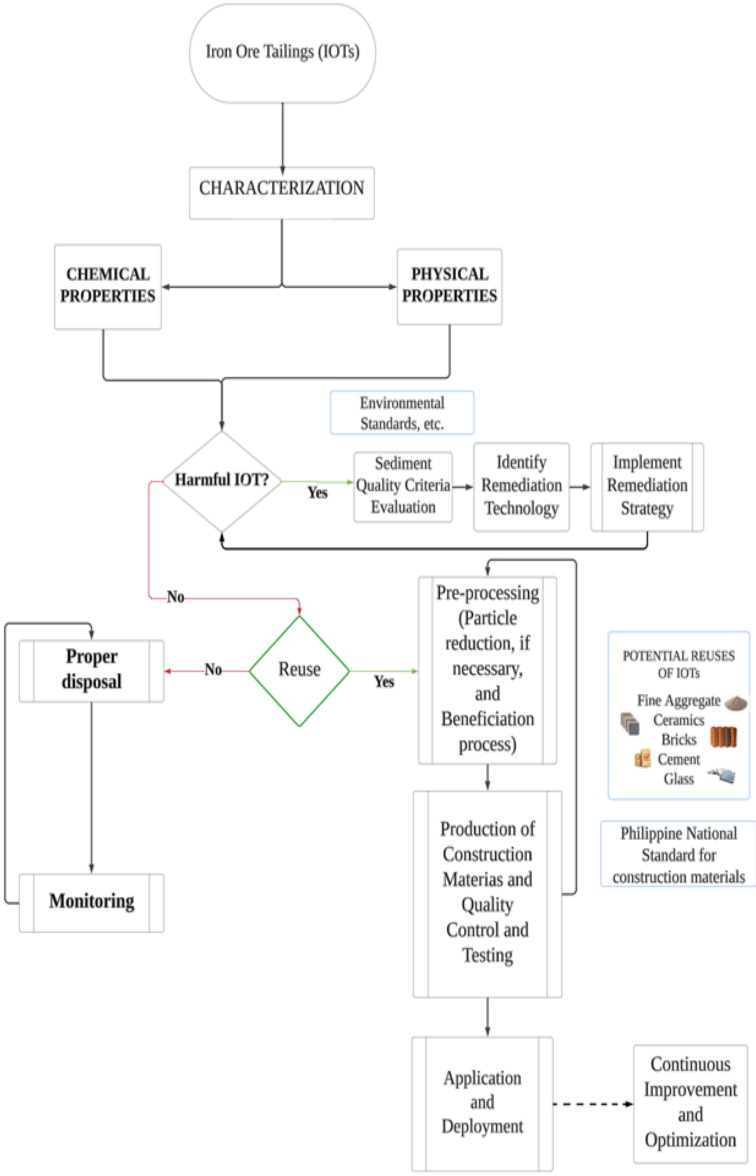

Fig. 4. Preliminary Framework for Sustainable Mine Waste Management

Nevertheless, the presence of harmful heavy metals such as As, Cd, Cr, Cu, Ni, and Zn in IOTs poses environmental and health risks, particularly in the Philippines where concentrations of As, Co, Mo, and Ni were notably high. These harmful heavy metals could potentially contaminate water and soil, disrupt ecosystems, and carry significant health hazards.

This study acknowledges the significance of risk assessments and effective remediation strategies to address HHM contamination; but, it does not delve deeply into these aspects. This will initiate future research to develop appropriate remediation strategies and conduct comprehensive risk evaluations. Nonetheless, this constraint does not weaken the value of the study. This offers a viable solution to address the risks associated with the conventional disposal methods, stressing the requirement for continued investigation. By tackling these research gaps, we can better harness the benefits of IOTs, while assuring public health and environmental safety.

B. Preliminary Framework for Sustainable Mine Waste Management in the Philippines

The proposed framework significantly offers an opportunity to improve mine waste management in the Philippines through the strategic reuse of IOTs. By systematically assessing this potential, we could minimize the volume of IOTs intended for disposal at tailing dams, thereby, mitigating environmental risks such as contamination from seepage, leachate, and harmful heavy metal release. This strategy also decreases the reliance on

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additional disposal sites, addressing impacts on both economic and environment.

In consideration to the Philippines' susceptibility to natural disasters and the inherent risks of tailings dams, alternative method like deep-sea tailing placement (DSTP) confronts strict regulations and environmental concerns globally. Instead, reusing IOTs offers a promising solution by conserving resources, reducing the need for virgin materials, and supporting a circular economy. This approach aligns with sustainable development goals and mitigates the environmental and financial impacts of conventional disposal methods.

The SOAR analysis, as illustrated in Table VI, underscores the benefits of IOT reuse—enhanced resource conservation, environmental protection, and economic viability. The concept of reuse also identifies opportunities for technological advancements and growing market demand, reinforcing the framework's alignment with sustainability goals. Although traditional disposal methods offer containment, they carry long-term risks and economic burdens.

We believe that the preliminary framework epitomizes a promising development in reusing IOTs within the Philippines. Further future research and development of this approach are vital for overcoming the challenges related with mine waste management. Aligning with the conclusions of Long et al. (2024), Das et al. (2023), Carmignano et al. (2021), Lu et al. (2020), and other researchers, we find that integrating IOT reuse can significantly contribute to sustainability and minimization of environmental impacts, and provide substantial economic benefits. This approach proposes a compelling alternative to traditional waste disposal methods, also highlighting its possibility to transform current practices.

C. Limitations

The limitations of the study include limited data on IOTs in the Philippines and challenges related to technological, social, and economic feasibility. In light of these constraints, the preliminary framework offers several potential benefits:

1) Proactive Approach:

By addressing waste reduction early can help manage environmental issues associated with IOTs, potentially avoiding future disposal-related problems.

2) Establishing Environmental Policies:

Research into IOT reuse can establish foundation for environmental policies, such as guidelines for reusing tailings and setting sediment quality standards which the Philippines needs to develop.

3) Long-term Sustainability:

Taking action to minimize waste now can promote long-term environmental sustainability and responsible mining practices.

4) Knowledge Advancement:

Regardless of limited local data, this research can bridge knowledge gaps by leveraging international studies and setting the groundwork for more detailed local research.

5) Global Relevance:

Table VI: SOAR Analysis

SOAR ANALYSIS KEY POINTS	CONCEPT OF REUSE	DISPOSAL METHOD
STRENGTHS	**Resource Conservation: Based** on their chemical and physical properties, reusing iron ore tailings promotes resource conservation by utilizing waste materials as secondary resources, reducing the demand for virgin materials and minimizing the environmental impact of mining activities.	**Containment:** Dam tailings provide a contained and controlled environment to store iron ore tailings, serving as a temporary barrier between waste and environment, decreasing the risk of environmental contamination and human exposure to harmful materials.
	Circular Economy Contribution: Implementing reuse strategies aligns with the principles of a circular economy by promoting the recovery and reuse of valuable materials from waste streams, thereby closing the loop and reducing reliance on finite resources.	
	Circular Economy Potential: Reusing iron ore tailings aligns with the principles of a circular economy, where waste materials are repurposed and recycled to minimize resource depletion and environmental impacts.	

	Environmental Protection: Reuse methods for iron ore tailings reduce the need for additional disposal sites, minimizing habitat disruption, soil erosion, and water pollution associated with dam tailings; thereby, contributes to the protection of ecosystems and biodiversity.	
OPPORTUNITIES	**Innovation and Technology:** Opens up opportunities for technological advancements and process optimization by exploring innovative reuse technologies and methods for iron ore tailings, leading to more efficient resource utilization and waste reduction [8].	**Reclamation and Rehabilitation:** Providing opportunities for post-mining land rehabilitation by reclaiming and rehabilitating for other land uses, such as land reclamation, ecosystem restoration, or recreational purposes.
	Market Demand: There may be increasing market demand for sustainable materials and products, creating opportunities to commercialize reused iron ore tailings in construction, infrastructure, and manufacturing sectors as alternatives to virgin materials [8].	**Technological Advancements:** Advances in tailings management technologies, such as improved dam design, liner systems, and monitoring techniques, present opportunities to enhance the safety, stability, and environmental performance of dam tailings facilities [39].
ASPIRATIONS	**Sustainable Development Goals (SDG) Alignment:** Reuse strategies for iron ore tailings contribute to SDG 12 (Responsible Consumption and Production) by promoting sustainable waste management practices, reducing resource consumption, and minimizing environmental impacts [40-41].	**Environmental Protection:** Minimize environmental impacts, protect water quality, and prevent the release of contaminants into surrounding ecosystems, which is in line with principles of environmental stewardship and sustainability.
	Environmental Conservation: Prioritizing reuse over disposal aligns with the precautionary principle, emphasizing the prevention of environmental harm and the protection of ecosystems and human health from potential risks associated with traditional disposal methods.	
REALITIES	**Economic Viability:** One of the main challenges may be balancing environmental advantages with economic considerations. While reuse methods offer environmental benefits, their economic feasibility depends on factors such as market demand, technological feasibility, regulatory requirements, and cost-effectiveness compared to conventional disposal methods [8].	**Environmental Risks:** One of the main disadvantages of tailing dams is the potential risk of environmental contamination and ecosystem damage in the event of dam failures, leakage, or seepage, which can release contaminants into waterways and soil, leading to ecological harm and human health risks.
	Regulatory Compliance: Meeting regulatory requirements and standards for waste management, environmental protection, and occupational health and safety is essential when implementing reuse strategies for iron ore tailings to ensure compliance and minimize liabilities.	**Long-Term Liabilities:** The long-term management and maintenance of dam tailings facilities present ongoing liabilities and financial burdens for mining companies--monitoring, maintenance, and potential remediation costs, which can extend beyond the operational life of mining operations.
OVERALL	Overall, the highlights of this SOAR analysis	Overall, dam tailings disposal offers certain

ASSESSMENT	are the potential strengths and opportunities of waste reduction through reuse of iron ore tailings, while also addressing aspirations for sustainable development and environmental conservation. However, the analysis also recognizes the realities of economic viability, regulatory compliance, and technological feasibility that need to be considered when implementing reuse strategies.	strengths and opportunities, such as volume reduction and containment; however, it also poses significant environmental risks and long-term liabilities that need for careful management and mitigation to ensure responsible and sustainable tailings management practices.

Exploring IOT waste reduction in the Philippine context will greatly contribute to the global discourse on environmental protection and responsible resource management, highlighting the country's role in advancing these critical issues, financial costs, and support a circular economy by conserving resources and decreasing reliance on virgin materials.

V. CONCLUSIONS

1) Reusing IOTs are more feasible and advantageous alternative to traditional disposal methods. Technical analyses confirmed that IOTs have desirable physical and chemical properties, making them suitable for reuse in construction materials such as cement, bricks, and ceramics.
2) The successful application of IOTs in various countries further validates this strategy for its potential to drive infrastructure development while addressing critical environmental challenges.
3) The proposed framework for repurposing IOTs aims to mitigate the risks associated with conventional disposal methods—tailing dam failures and harmful heavy metal contamination. This will significantly provide countries like Philippines a better option for managing IOTs, where natural disasters exacerbate these environmental risks.
4) Utilizing IOTs may reduce waste volumes, lower of environmental and financial costs, and support a circular economy by conserving resources and decreasing reliance on virgin materials.
5) This framework will not only address current waste management challenges but also align with global sustainable development goals. It will provide a proactive approach to managing mine waste, ensuring long-term sustainability and responsible resource utilization.
6) Acknowledging the limitations (limited data and the need for further risk assessments), the framework presents a solid foundation for advancing sustainable mine waste management practices; therefore, embracing IOT reuse will present an opportunity for both immediate benefits and long-term contributions to global sustainability.

This study also underscores numerous compelling applications for the proposed framework in handling IOTs.

1) Establishes a foundation for crafting sediment quality management and environmental standards, addressing regulatory gaps and promoting sustainable mining practices.
2) Initiates future research pertaining to technological, social, and economic aspects of IOT reuse, providing a roadmap to address challenges and enhance benefits.
3) Advocates for government effort of support to develop policies, open new markets for IOTs, ensure regulatory compliance, and invest in technology and R&D, driving improvements in waste management and economic growth.

The framework not only meets immediate need for sustainable waste management but also fosters the development of environmental standards, encourages continued research, and calls for government support. By integrating these elements, it will establish a foundation for a transformative approach to IOT reuse which offers significant benefits on both national and global scales.

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