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Chemical Processing Development for Radioactive Minerals Processing Facility: A Circular Economy Model

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***Abstract*—The minerals and metals industries are vital in the world's economy, yet their use of resources and waste generation pose considerable issues. The circular economy is a concept that establishes the foundation for economic operations that are carried out to run sustainably and to promote economic welfare, which in turn leads to an improvement in environmental quality. This paper offers a comprehensive literature analysis on the principles and efficacy of circular economy in mineral processing, specifically focusing on radioactive minerals. This research aims to develop a circular economy model that preserves resources, reduces waste production, and complies with regulatory rules on radioactive waste management. The study outlines a clear and structured circular economy model consisting of four modules: sample preparation, decomposition, partial extraction, and total precipitation. Each module integrates energy efficiency, heat recovery, renewable energy, water reuse, and chemical recycling. The validated model provides a roadmap for implementing circular economy principles in processing radioactive materials, contributing to achieving sustainable development goals. The government's agenda in pursuit of the Nationally Determined Contribution (NDC) can be aided by this model. This study suggests that reducing resource use and the volume of material, energy, and waste generated by technological processes can be achieved while still maintaining quality. That concept brings about a change in the mindset of designing a mineral processing installation. Based on the result of this study, further study may be focused on implementing strategies for each module of the studied object.**

***Keywords*— Circular economy; mineral processing; radioactive; efficiency.**

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I. INTRODUCTION

The mining and metals sectors substantially contribute to global economies and clean technology. Demand for minerals and rare earth elements is rising as the global economy becomes more dependent on clean technology such as electric vehicle batteries, wind turbines, and nuclear reactors[1]. Additionally, the mining and metals sectors use a lot of resources. For instance, the process of comminution, which entails the crushing and grinding of solid materials, is one of the major electricity consumers, using 3% of the total amount of electricity produced globally [1].

A comminution process is also used to process the monazite mineral, which can be wet or dry. These processes have advantages and disadvantages but require high energy to operate the milling equipment[2]. The monazite processing routes commonly used commercially in the world consist of acid and alkaline. The main difference between these two methods lies in the initial treatment of monazite, where the acid method uses sulfuric acid for monazite digestion, and the alkaline method uses sodium hydroxide to separate phosphate from monazite. After this initial treatment, purification of the digestion solution, both acid and alkali, is usually carried out and continued with Rare Earth Elements (REE) recovery from the purified solution[3].

In Indonesia, the developed monazite processing technology uses an alkaline method with process stages consisting of comminution, decomposition, partial dissolution, and total dissolution[4][5]. Decomposition is the process of converting monazite from phosphate compounds to hydroxide. Phosphate from monazite will react with sodium hydroxide solution to form a soluble compound[6] [4]. Then, the partial dissolution method is used to dissolve REE from the resulting hydroxide at a certain pH by considering the solubility of radioactive elements so that not much uranium and thorium dissolves with REE [5]. Total dissolution is intended to recover REE from a solution with ammonium hydroxide reagent to obtain a product in the form of REE hydroxide [4]. All stages of the monazite processing process using the alkaline method have been tested on a pilot scale in the Uranium, Thorium, and REE Extraction Pilot Plant facility (PLUTHO), which has a processing capacity of 50 kg monazite/batch. The utilization of excess chemicals in monazite processing is a common practice, which presents an opportunity to enhance efficiency through the recycling of remaining reagents. This approach promotes a more sustainable, energy-efficient, and cost-effective process.

The largest REE resource in Indonesia is monazite mineral, widely distributed in the Bangka-Belitung Islands and obtained as a by-product of tin mining. REE extraction from monazite can be carried out using two process methods, namely the acid method and the alkaline method[3]. The alkaline method has several advantages over the acid method, including a shorter process route, lower energy usage, sodium phosphate by-products that can be obtained, and easier material handling[7]. However, the REE recovery obtained from the primary method was lower than the acid method. The development of REE extraction technology from monazite in Indonesia refers to the alkaline method with process stages, including milling, alkaline digestion, and multistage precipitation.

Milling or reducing grain size increases the contact surface area so the digestion process can occur more efficiently. In the alkaline digestion process, a phosphate bond-breaking reaction occurs so that REE phosphate is converted into hydroxide compounds [8], [9], [10]. The reaction equation is as follows [9]:

$$\mathrm{REPO_4\ (s) + 3\ NaOH\ (aq) \rightarrow RE(OH)_3\ (s) + Na_3PO_4(aq)} \tag{1}$$

REE is dissolved from the REE hydroxide compound using hydrochloric acid at pH 3.5-3.7. In this dissolution process, a small portion of uranium and thorium is also dissolved according to the following reaction equation [4]:

$$\mathrm{RE(OH)_3\ (s) + 3\ HCl\ (aq) \rightarrow RECl_3\ (aq) + 3\ H_2O\ (aq)} \tag{2}$$

$$\mathrm{Th(OH)_4\ (s) + 4\ HCl\ (aq) \rightarrow ThCl_4\ (aq) + 4\ H_2O\ (aq)} \tag{3}$$

$$\mathrm{UO_2(OH)_2(s) + 2\ HCl\ (aq) \rightarrow UO_2Cl_2(aq) + 2\ H_2O\ (aq)} \tag{4}$$

Uranium and thorium, also dissolved in the chloride solution, are precipitated with ammonium hydroxide at pH 6.0-6.5. REE recovery from the chloride solution was carried out in the next precipitation stage at pH 9.0-9.8 with the same reagent, ammonium hydroxide. The resulting product is REE hydroxide concentrate with 80-85% content. Mechanism of the precipitation reaction[4]:

$$\mathrm{UO_2Cl_2(aq) + 2\ NH_4OH\ (aq) \rightarrow UO_2(OH)_2(s) + 2\ NH_4Cl\ (aq)} \tag{5}$$

$$\mathrm{ThCl_4(aq) + 4\ NH_4OH\ (aq) \rightarrow Th(OH)_4(s) + 4\ NH_4Cl\ (aq)} \tag{6}$$

$$\mathrm{RECl_3(aq) + 3\ NH_4OH\ (aq) \rightarrow RE(OH)_3(s) + 3\ NH_4Cl\ (aq)} \tag{7}$$

Many studies discuss the use of an alkaline digestion method for monazite decomposition [11], [12], [5],. Alkaline digestion using sodium hydroxide allows for phosphate recovery as tri-sodium phosphate, which can then be used in fertilizer production. One limitation related to this approach is the substantial quantity of NaOH required, which presents challenges in terms of filtration and costs a significant expense for wastewater treatment [11]. Therefore, this matter brought up the focus of the study to reduce resource use and the volume of material, energy, and waste generated.

In general, the definition of a circular economy is a concept that forms the framework of the economic activities carried out to run sustainably. A system in which raw materials, components, and products lose their value as little as possible, renewable energy sources are used, and thinking over new systems' design or systems' redesign/re-definition is the definition of circular economics (CE).

The goal of a circular economy is to improve economic welfare followed by an improvement in environmental quality and consequently to future generations based on business models and consumption patterns of consumers[13] To achieve the objectives of the circular economy, implement the 5R program on the economic activities carried out, namely Reduce, Reuse, Recycle, Recover, and Revalue[14]. These five principles are guidelines for determining the circular economy framework to be carried out. This, of course, will increase effectiveness and efficiency and will reduce waste generated from economic activity.

In 2015, the United Nations (UN) proposed a new focus to achieve the sustainable development goals (SDGs): the social, environmental, and economic aspects must be balanced. The global community underwent a paradigm shift in developing socio-environmental and economic systems when it recognized the necessity to transition from the conventional economic model of "take, create, throw away" to the principles of sustainable development. One way to achieve this goal is to transition towards a circular economy (CE) based on Reduce, Reuse, Recycle, Recover, and Revalue principles. Traditional linear economic concepts have an open cycle where the principle is "make, use, discard". This will result in inefficient resource use and excess waste[15]. Traditional linear economic models have an open-loop configuration in which the final manufactured product is associated with significant resource costs and anthropogenic pressures; however, the CE model aims to simulate the mechanisms of a closed, self-recovering natural system, reusing and recycling the product at the end its life cycle [16].

This will change the perspective in the traditional linear economy concept because CE has the principle of "reduce the use of resources, reuse what can still be used, recycle what can be reused, repair what is damaged, and provide added value if it cannot be repaired"[15]. Based on this principle, CE will positively impact using the CE approach in the energy aspect and can reduce energy use by 6%-11% to support economic activities worldwide and in the European Union, while in the United Kingdom, the potential energy savings of 5%-8% [17]. Of course, achieving this efficiency requires a particular framework and applied strategy.

CE entails a collection of systemic techniques that allow various economic activities to imitate the biogeochemical cycles that regulate nature, where there is no waste and any products are raw materials or food for other processes or systems[18]. This enables the creation of sustainable and interconnected systems in which natural resources are maintained, and waste is viewed as a resource for other applications rather than a waste. It is important to note that CE has developed components throughout its history beyond enhancing resource flow and waste management techniques, community commitment, design, and innovation. There is no universally accepted definition of CE, and the idea has been covered in at least seven in-depth reviews [18].

Implementing a circular economy will always be related to the waste management of an economic activity. This is because the circular economy is a continuous cycle that applies resource efficiency by carrying out a process on the waste produced to be converted into new resources suitable for use in the following process [19], [20]. Specific strategies must be applied in the waste treatment process until it becomes a new resource ready to be reused in the circular economy cycle. Waste management is the primary key to implementing a circular economy to achieve increased economic value and protection of the environment. That way, the circular economy is a concept that will provide significant added value because it benefits both the economy and the environment [14], [21].

Good waste management is one of the main requirements in radioactive mineral processing facilities. This is because radionuclides dissolve while processing radioactive minerals and then mix with other wastes from the processing process. The waste becomes radioactive because it is contaminated and contains radionuclides. Radionuclides are unstable atoms, so the atom will emit energy in the form of radiation until the atom is stable.

Therefore, special handling is needed related to radioactive waste treatment [22]. This is regulated in Government Regulation No. 61 of 2013 concerning Radioactive Waste Management in Indonesia. The regulation governs the management of radioactive waste originating from the use of nuclear technology must be carried out in an accurate way and method and following the development of science and technology so that potential hazards to the safety, security, and health of workers, the community and the environment can be avoided. Implementing a circular economy in radioactive mineral processing facilities will align with Government Regulation No. 61 of 2013. Applying a circular economy in radioactive mineral processing facilities will reduce the amount of waste produced so that the number of radionuclides in the waste will also decrease. This will protect the environment from excessive contamination levels and radiation exposure from radioactive waste.

This research aims to reduce resource use and the volume of material, energy, and waste generated from technological processes. This action supports the government's agenda to achieve the Nationally Determined Contribution (NDC). The present study aims to develop a circular economic framework for processing radioactive minerals to accomplish this objective.

II. Materials and Methods

A. Method

A literature review methodology was applied to achieve the objective of this study in developing a circular economy model. A literature study approach provides space for researchers to examine the state of knowledge about a specific topic [23]. A literature review can describe a systematic way of collecting and synthesizing previous research as a methodology [24]. The literature review is vital as a foundation for all types of research and gives many functions to engender new ideas and directions for a particular field [24][25]. The study topic is specific: the circular economy for a radioactive minerals processing facility. Case studies have been conducted by the literature on radioactive minerals processing and other minerals processing projects that explain the elements of the circular economy. Then, the results of this literature review are more specific for a radioactive minerals processing facility with experts' opinions. The expert in this study has the requisite work experience of at least seven (7) years in mineral processing. Archive analysis was conducted on literature collected from existing journals, scientific articles, and related publications on efficiency in minerals processing to gather benchmarking data. Fig. 1 illustrates the workflow of the research.

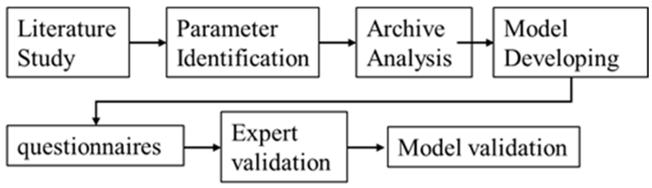

Fig. 1 Research Workflow

B. Materials

The first module is sample preparation. Sample preparation in radioactive mineral processing focuses on comminution. This module's energy efficiency is carried out by energy recovery [26]. The milling stage has evolved to reach greater levels of efficiency. Semi-autogenous technology becomes high-pressure grinding (HPGR)) [27]. Renewable energy use with photovoltaic electricity generation system. This system uses the battery for energy storage[28]. Material or raw material efficiency at this stage involves material embrittlement and dry separation of particles with similar physicochemical properties so that the material or raw material can be used in the following process [29].

The second module is decomposition. Material efficiency is achieved by reusing water from internal processes for the following process [30]. In addition, it recycles chemicals from waste from the decomposition process—reuse of unused NaOH in the reaction [31], [32]. The following module is partial extraction. In this module, the implementation of a circular economy is carried out by reusing internal process water. This step means reducing freshwater use [33], [34]. In addition, material and material efficiency is achieved by recycling reagents [31], [32]. The last module is total precipitation. Energy efficiency is achieved by replacing electric or steam ovens with ovens whose heat source is solar heat [35]. Raw material efficiency can be applied to PLUTHO in 2 (two) ways: reusing reagents and processing water[34]. The waste is used to reuse filtrate resulting from total deposition and sludge wash water in the following process after treatment has been carried out on both types of waste [36]. Table 1 summarizes the literature study on circular economy factors in the radioactive minerals processing facility.

Those values retention and activities variables are used to develop the model. The action required from the previous study is suitable for a radioactive minerals processing facility. Expert opinions were conducted to validate the model.

III. Results and Discussion

A. *The Initial Model*

Pluto's circular economy is more about reducing, reuse, and recycling. This can be seen from the value of the retention option the series of processes provides. The circular economy model is generally created from modules, activities, and actions, as shown in Table 1. The action determines the activities. The results of the literature study are used as the initial model in Fig. 2.

TABLE I
Research Variables

Modul	Value retention [37]	Activities	Action	Ref.
Sample preparation	Reduce (R1)	Energy efficiency	Heat catcher trap	[26]
			Semi-Auto generous tech.	[27]
			High Pressure Grinding tech (HPGR)	[27]
			battery for energy storage	[28]
		Material efficiency	physical or chemical sorting	[29]
			Grinding and crushing	[38]
			embrittlement with electro-fragmentation	[29]
Decomposition	Reduce (R1)	Water efficiency	process water	[30]
	Reuse (R2)			
	Recycling (R7)	Material efficiency	Reagent	[31], [32]
Partial Extraction	Reuse (R2)	Water efficiency	Process water	[33][34]
	Recycling (R7)	Material efficiency	Reagent	[31][32]
Total precipitation	Reduce (R1)	Energy efficiency	Heat catcher trap	[35]
	Reuse (R2)	Material efficiency	Reagent	[34]
			Process water	[34]
	Recycling (R7)	waste reduction	Process water	[36]

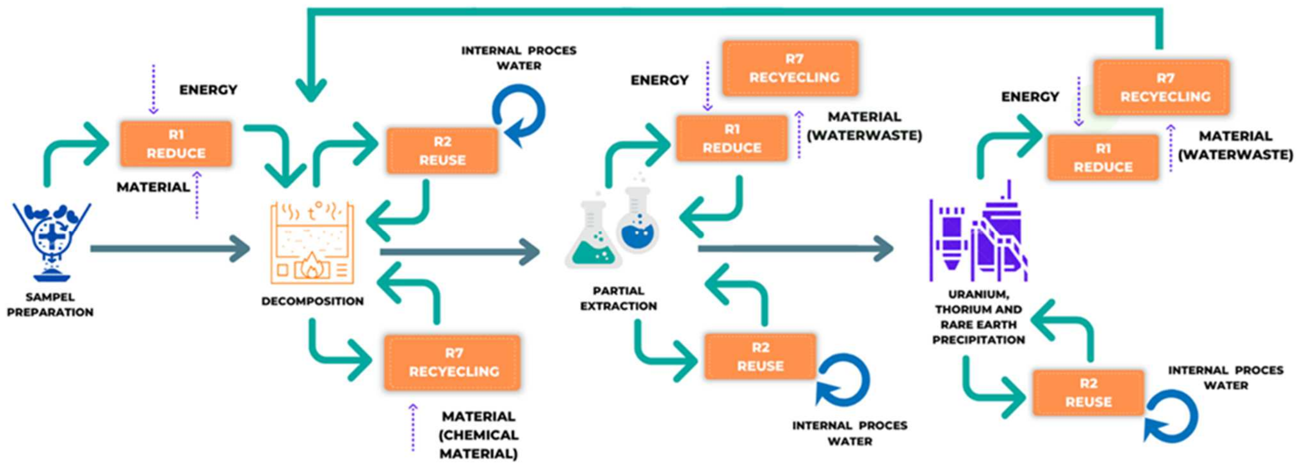

Fig. 2 The Initial Model

A. *The Validated Model*

The questionnaire to experts was conducted to validate the initial model of the circular economy. There are 10 (ten) experts with undergraduate to doctoral education backgrounds. The work experience of experts in mineral processing ranges from 8 (eight) to 40 years: positions or expert positions as lecturers, managers, and researchers in government institutions. The demographic distribution of experts is presented in Fig. 3.

According to experts, the questionnaire intends to obtain actions from Table 1 that are appropriate. These actions can be applied according to the characteristics of PLUTHO. Experts provide an assessment based on their expertise in mineral processing. Energy efficiency through energy recovery by capturing heat that should be released: the majority of experts agree that this can be applied to PLUTHO facilities. The experts also approved using semi-autogenous (SAG) technology as an energy-saving strategy. High-pressure grinding technology (HPGR) and the use of a photovoltaic system with battery energy storage (PV-BESS) are the choices of the majority of experts to be applied to PLUTHO's energy efficiency. Milling stages in previous studies focused on material embrittlement methods (embrittlement by electro-fragmentation or microwave pre-attenuation), dry separation, and crushing and grinding processes. Most experts assess that this strategy can be applied to the PLUTHO facility. Most experts agree that reusing internal process water aims for efficiency in the decomposition module. This action strategy can be applied to PLUTHO facilities. Recycling NaOH remaining in the decomposition residue provides opportunities for efficiency.

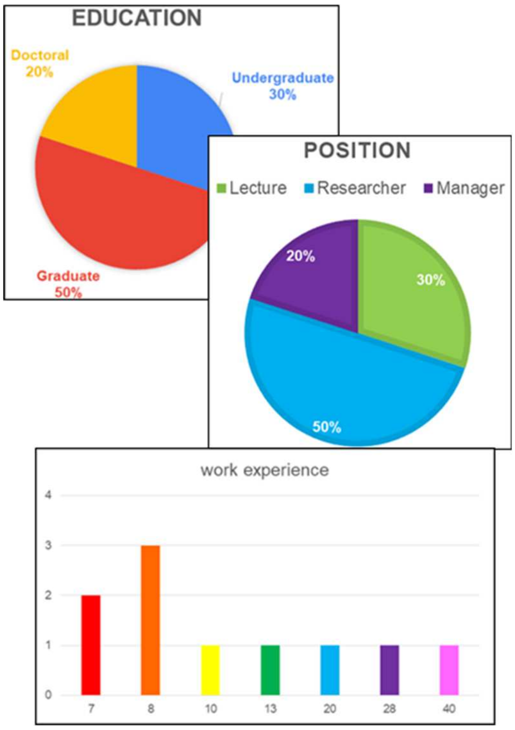

Fig. 3 The demographic distribution of expert

TABLE II
SUMMARY OF EXPERTS' OPINION

Action	Modul			
	Sample prep.	**Decomposition**	**Partial extraction**	**Total Precipitation**
E1	Heat catcher trap Semi-Auto generous tech. High Pressure Grinding tech. (HPGR) battery for energy storage Physical or chemical sorting Grinding and crushing embrittlement with electro-fragmentation	Process water Reagent	Process water Reagent	Heat catcher trap Process water Reagent wastewater
E2	Semi-auto generous tech. High Pressure Grinding tech. (HPGR) Battery for energy storage Physical or chemical sorting Grinding and crushing Embrittlement with electro-fragmentation	Reagent	Reagents	Heat catcher trap Process water Reagent Wastewater
E3	Semi-auto generous tech. Battery for energy storage Grinding and crushing Embrittlement with electro	Process water Reagent	None	Heat catcher trap Process water Reagent Wastewater
E4	Semi-auto generous tech. High Pressure Grinding tech. (HPGR) Battery for energy storage Physical or chemical sorting Grinding and crushing	Process water Reagent	None	Heat catcher trap Process water Wastewater
E5	Heat catcher trap Semi-auto generous tech. High Pressure Grinding tech. (HPGR) battery for Energy storage Grinding and crushing Embrittlement with electro-fragmentation	Process water Reagent	Process water Reagent	Heat catcher trap Process water Reagent Wastewater
E6	Semi-auto generous tech.	Process water	Process water	Process water

Action	Modul			
	Sample prep.	Decomposition	Partial extraction	Total Precipitation
	physical or Chemical sorting Grinding and crushing Embrittlement with electro-fragmentation	Reagent		Reagent Wastewater
E7	Heat catcher trap Semi-auto generous tech. Battery for energy storage Physical or chemical sorting Grinding and crushing Embrittlement with electro-fragmentation	Process water	None	Heat catcher trap Process water Wastewater
E8	Semi-auto generous tech High Pressure Grinding tech. (HPGR) Battery for energy storage Physical or chemical sorting Grinding and crushing Embrittlement with electro-fragmentation	Process water	Process water	Process water Reagent wastewater
E9	Heat catcher trap Semi-auto generous tech. High Pressure Grinding tech. (HPGR) Battery for energy storage Physical or chemical sorting Grinding and crushing Embrittlement with electro-fragmentation	Process water Reagent	none	Process water wastewater
E10	Heat catcher trap Semi-auto generous tech. Battery for energy storage	Process water	Process water Reagent	Heat catcher trap Process water Reagent wastewater
	Physical or chemical sorting Grinding and crushing Embrittlement with electro-fragmentation			

Most experts agree that recycling chemicals is a circular economy strategy at PLUTHO. The partial extraction of water and raw material efficiency by reusing internal process water have received the same percentage of expert opinion. However, some experts argue that reusing the internal water process is not applicable. Material or Raw Material Efficiency by recycling reagents in the partial extraction module is a savings strategy. Experts believe this strategy cannot be applied to PLUTHO facilities. So, the circular economic model at this stage changes.

The energy efficiency strategy for total precipitation is to replace electric or steam ovens with solar heat as a source. Experts approve of this action. Most experts believe using renewable energy for drying can be applied to PLUTHO facilities. Raw material efficiency at the total precipitation module is in 2 ways: reusing reagents and processing water. According to experts, this strategy can be applied to the PLUTHO facility, considering that the filtrate resulting from the total settling process has a reasonably high reagent content. Utilization of waste resulting from total deposition and sludge washing water is an action that can be implemented. According to experts, both types of waste can be reused after a particular treatment. The results of the questionnaire by experts are summarized in Table 2. This summary table becomes the basis for making a validated model Fig. 4.

Energy and material efficiency are forms of reduction (R1) in the sample preparation stage. The sample preparation used a milling module such as a hammer, blower, and bag house filter. HPGR can translate into a reduction in energy costs of 11–32% compared to SAG. Apart from that, several countries are starting to develop renewable energy, such as sunlight. An example of using renewable energy is evaluating the integration of photovoltaic power generation systems in the comminution process, which uses a photovoltaic system with battery energy storage (PV-BESS). Based on this, energy efficiency can be applied to use battery technology to store energy. The use of batteries has the potential to reduce the total energy costs for a series of milling modules. The practices that can be applied at PLUTHO are material embrittlement and dry separation of particles with similar physicochemical properties so that the material or raw materials can be used in the following process.

The application of circular economic principles at the decomposition stage of mineral processing is reuse and recycling. Reuse (R2) with water efficiency. The decomposition stage in PLUTHO uses water. Water heated to a temperature of 40° is used to dissolve the NaOH. Water from this internal process can be reused for the following decomposition process. This step can reduce the volume of clean water use (freshwater) to be friendly to water conservation programs—recycling (R7) with material or raw material efficiency. Recycling chemicals from decomposition process waste has a positive impact on the environment. Apart from that, this step means budget efficiency for purchasing process chemicals. Chemical recycling can also be done to recover value-added products that are part of the waste. Reuse of NaOH that is not used up in the reaction.

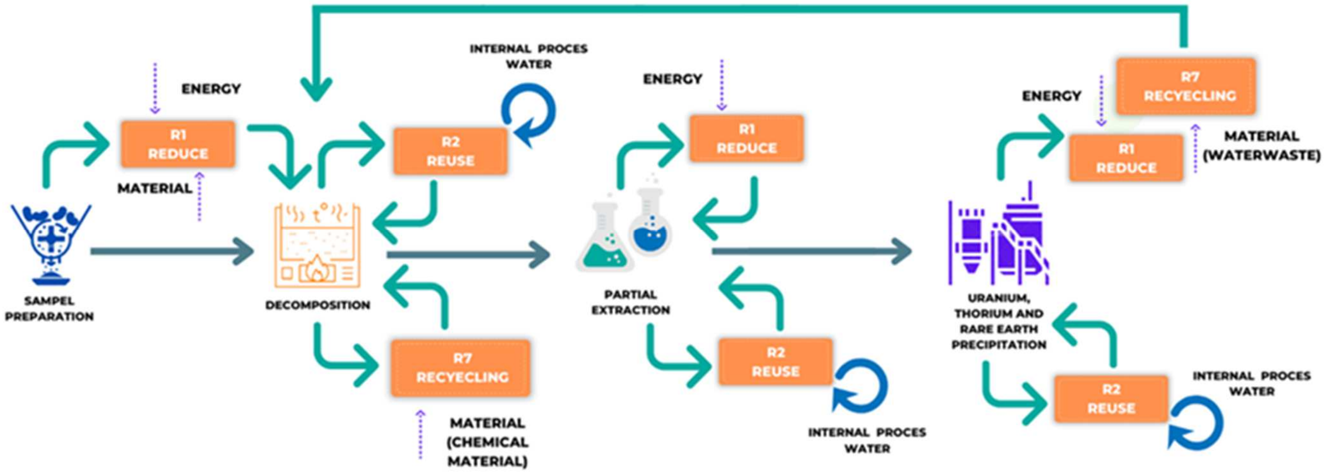

Fig. 4 The Validated Model

One of the short-cycle options significantly reduces the consumption of necessary mineral processing inputs, namely water and energy. Water reuse affects process performance due to the increase in residual reagent content until it reaches the saturation limit. This has proven feasible for concentrate production. The reuse of water in process circuits opens up space for more promising studies and applications on an industrial scale, both from an economic and ecological point of view. This reuse(R2) of water reduces(R1) energy use.

The application of circular economic principles in the total precipitation module of mineral processing is reduction, reuse, and recycling. Reduce (R1) with energy efficiency. The way to apply the concept of energy efficiency is to replace electric or steam ovens with ovens whose heat source is taken from the sun. This can be done and has been applied to mining processing referring to data taken from literature studies, especially in Indonesia, which has a tropical climate with only two seasons, namely the dry and rainy seasons. Reuse (R2) with material efficiency. The Raw material efficiency that can be applied to PLUTHO is in 2 ways: reusing reagents and reusing process water. The total precipitation filtrate obtained from the total precipitation process still has a high reagent content because the deposition in the total precipitation process is not proportional to the amount of reagent contained in the filtrate. This causes the filtrate resulting from having enough reagent content to be reused for the following process—recycling (R7) with waste reduction. The possible use of waste is the reuse of filtrate resulting from total precipitation and sludge wash water in the following process after a particular treatment has been carried out on these two types of waste.

IV. Conclusion

The value retention and activities arrange a circular model that significantly affects the short cycle of mineral processing. The application of a validated model provides an overview of the circular economy at the PLUTHO. The validated circular economy model for radioactive mineral processing explains that reducing resource use and the volume of material, energy, and waste generated from technological processes can be done while maintaining quality. Further research may be needed to implement strategies for each module of the studied object.

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