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International Atomic Energy Agency

IAEA TECDOC SERIES

No. 2086

Recovery of Uranium from Phosphate Ores

RECOVERY OF URANIUM FROM PHOSPHATE ORES

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IAEA-TECDOC-2086

RECOVERY OF URANIUM FROM PHOSPHATE ORES

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2025

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Printed by the IAEA in Austria
April 2025
https://doi.org/10.61092/iaea.2at3-fndo

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Recovery of uranium from phosphate ores / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2025. | Series: IAEA TECDOC series, ISSN 1011-4289 ; no. 2086 | Includes bibliographical references.
Identifiers: IAEAL 25-01744 | ISBN 978-92-0-106325-0 (paperback : alk. paper) | ISBN 978-92-0-106225-3 (pdf)
Subjects: LCSH: Uranium. | Uranium mines and mining. | Uranium industry. | Phosphates.

FOREWORD

The IAEA provides support to its Member States through a variety of mechanisms, including publications and databases related to uranium and thorium resources, production and utilization. Among the unconventional uranium resources, uranium resources associated with phosphate ores are of particular importance because of their large overall quantities. The relatively high concentrations of uranium that can be found in selective phosphate ores resulted in industrial scale recovery of uranium in the past, such that the resource was at one time considered a conventional uranium resource. There continues to be an interest in uranium recovery during phosphate processing, as a large share of radiotoxic uranium transfers to mineral fertilizers and ultimately agricultural soils if it is not recovered during phosphate processing. In 1989, the IAEA issued a first publication on the recovery of uranium from phosphoric acid, an intermediate product in phosphate ore processing to mineral fertilizers. The present publication provides an update on uranium recovery from phosphate ore. The historical commercial uranium recovery from phosphates is discussed, new technical developments since the previous publication are presented, and the potential for uranium recovery from phosphate ores globally as well as six illustrative case studies are showcased.

The IAEA officer responsible for this publication was N. Haneklaus of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

Phosphate ores are minerals that contain elevated concentrations of phosphorus (P), measured by their phosphorus pentoxide (P_2O_5) content. Phosphate ore is among the five most mined materials on earth and P is an essential building block for plants and animals. To feed the world, more than 200 million t of phosphate ore are mined annually [1-2]. More than 90% of the mined phosphate ore is used to make mineral fertilizers. P is currently irreplaceable in the manufacture of fertilizers, and large-scale P recycling is still in its infancy. Thus, there is a clear connection between global food security and phosphate ores, often known as phosphate rock.

Depending on particular market conditions and production costs, phosphate ores can include a variety of valuable companion elements at increased quantities that might justify the commercial recovery of these elements. Notably, it is possible to extract uranium and rare earth elements (REEs) from phosphate ores for commercial use [3-6].

Certain phosphate ores contain uranium at relevant average quantities of 100 mg/kg or higher, that might warrant uranium recovery. In the earth's crust, uranium is a very common element that appears with an average concentration of 2.8 mg/kg. However, seawater that is often regarded as a source of uranium as a result of the tremendous overall quantity of uranium found in it (about 4 billion t), contains uranium in concentrations as low as 0.003 mg/kg, or 3 parts per billion. As shown in Table 1, uranium resources can be classified by concentration into four categories: very high-grade ores, high-grade ores, low-grade ores, and very low-grade ores [7].

TABLE 1. CLASSIFICATION OF CONVENTIONAL URANIUM RESOURCES BY MASS CONCENTRATION.

Classification	Uranium mass concentration	
Very high-grade ore	>200 000 mg/kg	>20 %
High-grade ore	>20 000 mg/kg	>2 %
Low-grade ore	>1 000 mg/kg	>0.1 %
Very low-grade ore	>100 mg/kg	>0.01 %

The different uranium concentrations are further visualized in Fig. 1 to provide an overview about relevant concentrations found in phosphates.

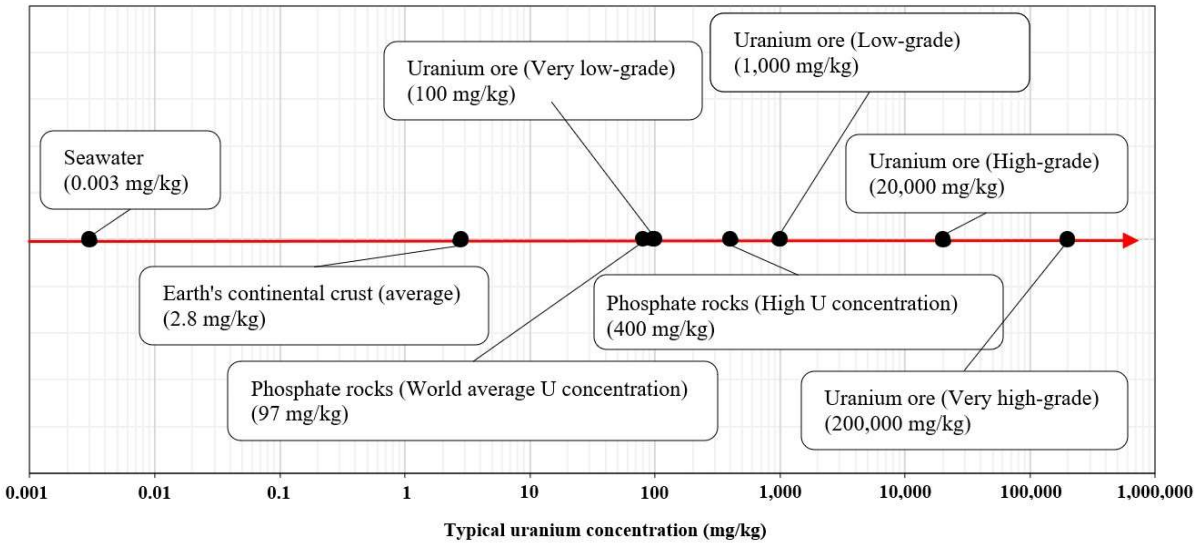

FIG. 1. Uranium concentrations in seawater, phosphates, and various uranium ores, expressed in part per million (ppm).

Average uranium concentrations in phosphate ores in Arad, Israel (150 mg/kg), Araxa, Brazil (182 mg/kg), Cabinda, Angola (260 mg/kg), Catalao, Brazil (220 mg/kg), Central Florida, United States of America (USA) (141 mg/kg), Djebel Kouif, Algeria (100 mg/kg), Hamrawen, Egypt (110 mg/kg), Idaho, USA (107 mg/kg), Khouribga, Morocco (130 mg/kg), Kodjari, Burkina Faso (125 mg/kg), Minjingu, United Republic of Tanzania (390 mg/kg), Safaga, Egypt (120 mg/kg), Tilemsi, Mali (123 mg/kg), West Mahamid, Egypt (100 mg/kg) [8] could thus also be classified as very low-grade uranium ores. Given that more than 70% of the presently known phosphate ore reserves are in Morocco [1], with uranium concentrations exceeding 100 mg/kg, most phosphate ores are thus also very low-grade uranium ores.

Interestingly, several phosphate ore producers mine ores with natural uranium concentrations exceeding those of commercial uranium mines, such as the lower grade uranium deposits found in Namibia Uranium was recovered during phosphate fertilizer production in the 1980s and 1990s before the world uranium prices decreased and made this practice uneconomic [6]. Since it is now deemed unfeasible to mine phosphate ore solely for its uranium content or to recover uranium as a byproduct, uranium extracted from phosphate ore is currently regarded as an unconventional resource. Uranium from phosphates might once again be considered a conventional uranium resource if uranium prices rise or if technological advancements make uranium recovery from phosphate ores more affordable.

1.2. OBJECTIVE

The International Atomic Energy Agency (IAEA) provided an overview of the recovery of uranium from phosphoric acid, an intermediate product in phosphate fertilizer production, in 1989 [9] when solvent extraction technology was used to recover uranium from phosphoric acid (an intermediate product in phosphate fertilizer production) on industrial scale and contributed nearly 20% to the domestic uranium production in the USA. Decreasing uranium prices made uranium recovery from phosphoric acid economically unprofitable and resulted in the end of

commercial uranium recovery from phosphates in the mid 1990s. Expected increasing demand for uranium as well as environmental concerns, and the desire to move from a linear economy model to a circular one kindled new interest in uranium recovery from phosphates. Since the mining, and the ore processing facilities are already in place for phosphate ore processing, it is believed that uranium recovery units can be operated within 2-3 years' time. Given that starting a new uranium mine usually takes between 10-15 years, uranium recovery from phosphates might thus experience a revival. This work provides an update about uranium recovery from phosphate ores.

1.3. SCOPE

This study reports on the lessons learned from past, as well as the current developments on, uranium recovery from phosphates based on contributions from experts in academia, industry and policy making roles. No specific details are provided in this publication to ensure the confidentiality of the information provided by the contributors. The aim of this work is not to provide deep technical insights, but rather to offer an overview on the latest developments, potentials and limitations associated with the recovery of uranium from phosphates that can be accessible to a broad audience. References for further reading are provided.

1.4. STRUCTURE

The publication briefly reviews historical uranium recovery from phosphoric acid in section 2. The commercially proven solvent extraction process is introduced (section 2.1) and the lessons learned from this process, as well as its economics, are presented (section 2.2). Historically, the USA accounted for nearly 90% of all reported commercial capacity for uranium recovery from phosphates and section 2.3 illustrates the regional relevance of this technology.

Section 3 introduces and discusses new technical developments that can promote uranium recovery not only from phosphoric acid, but also directly from the phosphate ores. The global potential of uranium recovery from phosphates at the approximately 400 phosphate fertilizer plants operating worldwide is presented in section 4. Lastly, five case studies from Argentina (section 5.1), Brazil (section 5.2), the Philippines (section 5.3), Saudi Arabia (section 5.4), and the United Republic of Tanzania (section 5.5) are presented to illustrate potential regional opportunities, but also potential regional limitations of introducing uranium recovery from phosphates. Overall conclusions are then presented in section 6.

2. HISTORICAL URANIUM RECOVERY FROM PHOSPHATE ORES

2.1. OVERVIEW

Most phosphate ores are of sedimentary origin, and it is this kind of phosphate ores that can contain elevated concentrations of uranium, typically showing uranium contents ranging between 50-200 mg/kg [10]. Large phosphate fertilizer plants process 500 thousand to 2 million t phosphate ore per year resulting in notable potentials for uranium recovery even if the uranium is only present in trace amounts in the raw phosphate ores processed. Fig. 1 (left) shows sedimentary phosphate ore from Florida (USA) prior to simple concentration using flotation. The concentrated or beneficiated phosphate ore, or phosphate rock concentrate, of the same ore is shown in Fig. 2 (right).

FIG. 2. Sedimentary phosphate ore from Florida (left) and concentrate of this ore after concentration using flotation (right) (courtesy of P. Zhang, Florida Polytechnic University).

Phosphate ore is largely insoluble and cannot directly be used as fertilizer unless the soil is very acidic as is the case in some tropical areas. The phosphate ore is therefore processed to water soluble fertilizers so that the phosphorus can be taken up by plants through their root system. Wet process phosphoric acid (WPA) plants are the most common fertilizer plants in operation today. More than 85% of phosphate fertilizers are produced from WPA using sulfuric acid for the digestion of the phosphate ore. During the WPA process with sulfuric acid that is schematically shown in Fig. 2, approximately 80-90% of the uranium present in the phosphate ore transfers to the liquid WPA from where it was historically recovered using different solvent extraction methods. The remaining 10-20% of the uranium present in the phosphate ore usually transfers to the phosphogypsum, a solid byproduct of the WPA production process. Phosphogypsum can have beneficial uses such as application in soils or use as building material. However, these uses are constrained in some cases by the presence of radioactive isotopes such as ^{226}Ra and other toxic trace elements. To process 1 t of phosphate ore, approximately 0.6 t concentrated sulfuric acid are used. The process then generates approximately 0.4 t merchant grade WPA and 1.2 t phosphogypsum [11]. Historically, uranium was recovered from the merchant grade WPA prior to further concentration.

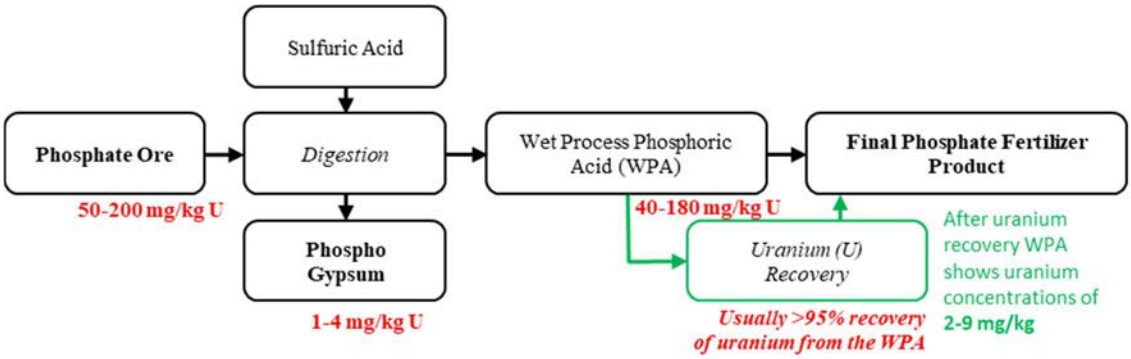

FIG. 3. Simple flow diagram of wet process phosphoric acid (WPA) production with uranium recovery as it was historically done.

At times when uranium prices were relatively high, heavy metal recovery during mineral fertilizer production was monetarily profitable for WPA producing companies. The main

factors that determine the economic profitability are (in no particular order and without considering environmental regulations and strategic considerations) [9]:

- The concentration of uranium in the phosphate ore (higher is better);
- The phosphate ore processing plant's capacity (larger is better);
- The applied uranium recovery process (cheaper is better).

Strategic considerations include increased security of uranium supply (domestic supply) and consequently decreased dependence on uranium imports, savings in foreign currency, acquisition of technology and generation of employment. It is noteworthy that most uranium transfers to the final fertilizer product, and that this uranium can cause contamination of soils and groundwater. There is particular concern that the potential accumulation of uranium can endanger soil fertility and leach into groundwater or even be taken up by crops and can be ingested by members of the public [12-14]. The motivation behind earlier uranium recovery from phosphates was strategic in a first attempt from the 1950s to the 1960s, when countries were exploring different sources of uranium ores, and commercial in a second period between the 1970s to the late 1990s.

Table 2 summarizes past commercial uranium recovery activities in Belgium, Canada, Iraq, Taiwan and the USA. Nearly all plants employed solvent extraction, and the various solvents that were used to recover uranium from the inorganic phase gave their names to the corresponding processes. The most widely used solvent was the DEPA-TOPO method, also known as the ORNL process after Oak Ridge National Laboratory (ORNL) in the USA where the technique was first established. TOPO stands for tri-n-octylphosphine oxide and DEPA for bis(2-ethylhexyl) phosphoric acid.

TABLE. 2. HISTORICAL URANIUM RECOVERY FROM PHOSPHATE ORE BY REGION AND PLANT.

Operating Period	Location	Plant Name	Recovery Process	Capacity (t U/year)
1951-1962	USA, IL	Joliet	Precipitation	31
1952-1956	USA, TX	Texas City	OPPA	20
1954-1959	USA, FL	Nichols	-	-
1955-1961	USA, FL	IMCC Plant, Bonnie	OPPA	31
1957-1961	USA, FL	Tampa	OPPA	62-138
1976-1980	USA, FL	W.R. Grace Plant, Bartow	OPAP	109-127
1978-1981	USA, FL	Farmland, Pierce	DEPA/TOPO	153-173
1978-1999	USA, LA	Uncle Sam, Convent	DEPA/TOPO	265
1979-1982	USA, FL	Riverview Plant, East Tampa	OPPA	138-164
1980-1985	USA, FL	CF Industries, Bartow	DEPA/TOPO	231-243
1980-1992	USA, FL	CF Industries, Plant City	DEPA/TOPO	231-243
1980-1992	USA, FL	IMC, New Wales	DEPA/TOPO	265-288
1980-1998	Belgium, Liège	Engis	DEPA/TOPO	50
1980-1987	Canada, AB	WCFL, Calgary	OPAP DEPA/TOPO	38
1981-1985	Taiwan, Lung Tan	China Phosphate	DEPA/TOPO	10
1981-1998	USA, LA	Sunshine Bridge, Donaldsville	DEPA/TOPO	162
1984-1991	Iraq	Al Qaim	DEPA/TOPO	87

2.2. COMMERCIALLY PROVEN SOLVENT EXTRACTION PROCESS

Solvent extraction processes were the uranium recovery methods successfully deployed to extract uranium from liquid WPA commercially on industrial scale. Beltrami et al. [15], Bunus [10] and Singh et al. [16] provide scientific literature reviews on the used processes. Fig. 3 provides a brief overview of the 2-cycle solvent extraction process (DEPA/TOPO in Table 2) that proved to be the most successful in the past.

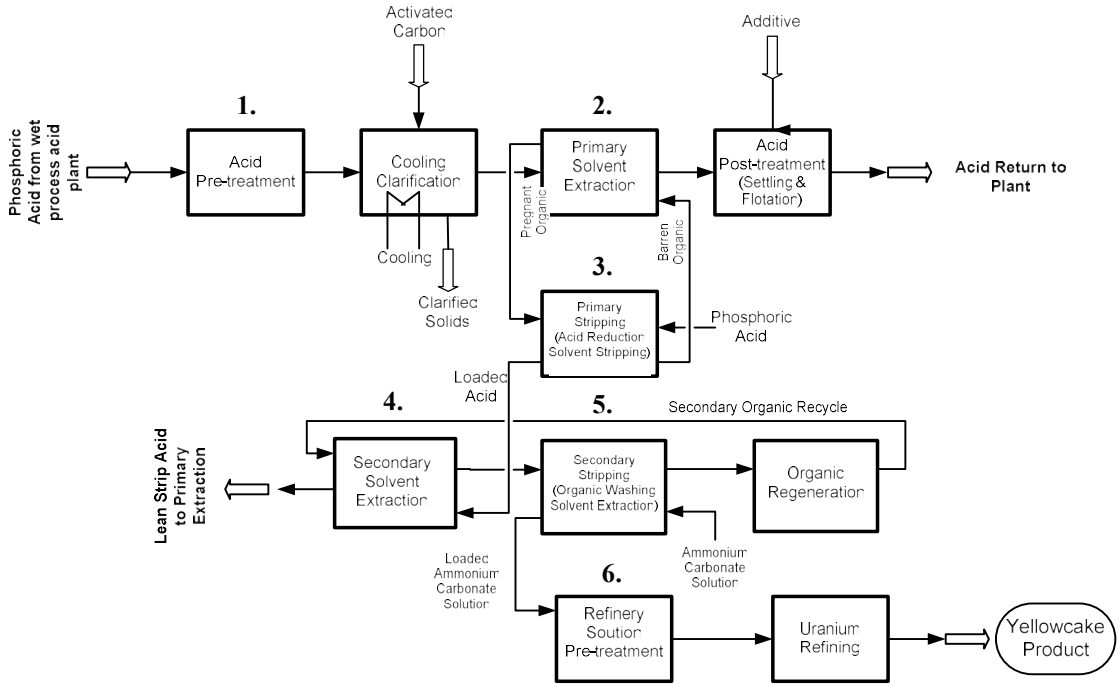

FIG. 4. 2-cycle solvent extraction process used for commercial uranium recovery from wet process phosphoric acid (WPA) in the past (courtesy of V. Astley, Dr. Phosphate Inc).

The fundamentals of the DEPA/TOPO process shown in Fig. 4 are the following:

1. Acid pre-treatment: After being cooled and occasionally having the organics removed (which results in a decolorization), the phosphoric acid from the filter (at 25–30% P_2O_5) is cleared by the removal of solids.
2. Primary solvent extraction: Clarified acid is introduced into a counter-current mixer/settler system containing DEPA/TOPO solvent dissolved in kerosene. Uranium is transferred into the solvent phase, or 'pregnant organic' phase. Raffinate, sometimes referred to as 'lean' or 'barren' phosphoric acid, is delivered to the phosphoric acid plant.
3. Primary stripping: Acid containing a reducing agent is brought into contact with the pregnant organic solution to promote the change of the uranium from the U(VI) state to the U(IV) state. Then, in a second mixer/settler system, the uranium comes into contact with highly concentrated phosphoric acid. In this instance, the uranium is removed from the comparatively large amount of organic solvent and transferred to the smaller volume of a strip acid (the "loaded" main strip acid). This process results in a significant increase in the uranium concentration compared to the previous stage. Concentration factors of up to 20 are usually observed here.

4. Secondary solvent extraction: Uranium is oxidized in the loaded main strip acid to return it to the U(VI) form. The concentrated uranium is transferred to the solvent phase and further concentrated to generate ‘pregnant secondary organic’ when the strip acid comes into contact with DEPA/TOPO solvent in a mixer/settler system.
5. Secondary stripping: In a mixer/settler system, an alkaline solution comes in contact with the uranium-containing pregnant secondary organic solution. In this process, the uranium is liberated from the organic solvent and transported in a concentrated form to the alkaline solution. An acidic uranium solution is created by treating the secondary strip solution to remove the alkali and neutralize it. At this point, the uranium content is around 20 g/l.
6. Refining: The acid-uranium solution is then further processed to generate uranyl peroxide (UO_4nH_2O), ammonium diuranate (ADU), or ammonium uranyl tricarbonate (AUT), which is thickened, washed, dried, and calcined to yield U_3O_8 or yellowcake.

Fig. 5 shows the International Minerals and Chemical Corporation (IMC) Phosphates (now Mosaic Fertilizer Company), New Wales phosphoric acid plant with the first and second cycle extraction facilities operated in Florida in the USA between 1980-1992.

FIG. 5. Uranium recovery facility at the IMC New Wales phosphate fertilizer plant in Florida in the USA (courtesy of V. Astley, Dr. Phosphate Inc).

2.3. LESSONS LEARNED AND COST ESTIMATES OF HISTORICAL URANIUM RECOVERY

The success of solvent extraction in the 1980s and 1990s was driven by commercial interests. Excellent uranium recovery rates exceeding 92-95%, as well as the low impact on the core fertilizer business allowed for uranium recovery on industrial scale. When in the late 1990s uranium recovery eventually ceased at the Florida and Louisiana plants, operators did in fact acknowledge that the phosphoric acid quality was slightly reduced. The most successful uranium recovery plants used the same solvent (DEPA/TOPO), and each operated on phosphoric acid produced by the dihydrate process. The acid typically contained uranium at some 0.5 kg/t. Some of the more significant differences in plant design are summarized in Table3.

TABLE. 3. DIFFERENCES IN PAST COMMERCIAL DEPA/TOPO SOLVENT EXTRACTION PLANTS.

Plant / Design	Freeport	Gardinier	IMC	Uranium Recovery Corp.	Westinghouse
Pretreatment cooling	No cooling	2-stage flash cooling - 32°C	Spiral coolers cool - 49°C	No cooling	Flash cool - 38°C
Solids Removal	Flocculant added before clarification	Filtered using pressure leaf filters	Clay/flocculant added before clarification	Flocculant added before clarification	Flocculant added before clarification
Further pretreatment	None	None	Colour removal -activated C	None	None
Oxidation state change	Oxidised with oxygen	Reduced with scrap Fe	Oxidised with H_2O_2. Later O_2	Reduced using ferro silicon	Oxidised using nitric acid
First cycle solvent	DEPA/TOPO	OPPA	DEPA/TOPO	OPPA	DEPA/TOPO
Mixer settler design	Low profile rectangular pumper-mixer settlers	Rectangular pumper-mixer settlers	Circular mixer settlers	Deep cone bottom settlers	Low profile rectangular pumper-mixer settlers
First cycle strip solution	31% P_2O_5 acid plus iron	15% HF precipitated U as green salt	31% P_2O_5 acid plus sulphuric acid and iron	40% P_2O_5 acid plus hydrogen peroxide	27% P_2O_5 acid plus iron
Second cycle oxidation state change	Oxidised with oxygen	Dissolved in nitric acid	Oxidised with H_2O_2. Later used oxygen	No oxidation change required	Oxidised using nitric acid
Second cycle solvent	DEPA/TOPO	TBP	DEPA/TOPO	DEPA/TOPO	DEPA/TOPO
Uranium precipitate form	Ammonium diuranate	Ammonium diuranate	Uranyl peroxide	Ammonium uranyl tricarbonate	Ammonium uranyl tricarbonate

Despite these differences, the plants with the highest volumes of production managed very high levels of operating efficiency and uranium recovery. The underlying financials for the most efficient plants were broadly similar. Table 4 gives some of the operating and cost data ranges for the same plants. The costing assumption in the table is based on an acid uranium content of approximately 0.5kg/t.

TABLE. 4. ECONOMICS OF HISTORICAL URANIUM RECOVERY FROM PHOSPHORIC ACID FACILITIES (1979 US $)*

Plant	Solvent	On-stream	Recovery	Capital intensity (US $/lb/a)	OPEX (US $/lb)	Number of years in operation
Westinghouse	DEPA/TOPO	98%	92%	55	11	3
IMC	DEPA/TOPO	92%	96%	100	11	3 – 12
URC	OPAP	60%	80%	90	45	4
Freeport	DEPA/TOPO	92%	95%	65	12	17 – 21
Gardinier	OPPA	NR	90%	60	18	3

* Operating costs exclude royalties, dilution and reheat costs which add US $5 to US $10/lb. All costs are in 1979 US $.

There were other significant differences in performance. For the three plants that used DEPA/TOPO, solvent losses costed from US$2 – 5.50/lb of U_3O_8 were for instance reported. Pretreatment costs ranged from US$0.20 to more than US$4.00/lb of U_3O_8. Solvent loss and pretreatment costs combined ranged from US$2.50 to more than US$8.00/lb of U_3O_8. Average solvent losses to the raffinate ranged from 5 to 100 mg/kg. P_2O_5 losses ranged from less than 0.1% to about 1.0%. Effective strip coefficients ranged from 15 to 150 and showed no significant correlation with the P_2O_5 concentration of the strip acid. Solvent losses due to settler cleaning ranged from less than 0.15 to more than 0.5kg/t of P_2O_5 processed. Downstream effects of the uranium recovery process ranged from nil to several million dollars per year, mostly in decreased rubber liner lifetime.

2.4. RELEVANCE OF URANIUM FROM PHOSPHATES IN THE UNITED STATES OF AMERICA

The USA's uranium recovery from phosphates was particularly noteworthy. At its peak, this technique accounted for up to 20% of the country's uranium output in the 1980s, until falling uranium prices rendered the method unfeasible. In the USA, historical and prospective uranium recovery from phosphates is contrasted with historical uranium imports and mining in Fig. 6.

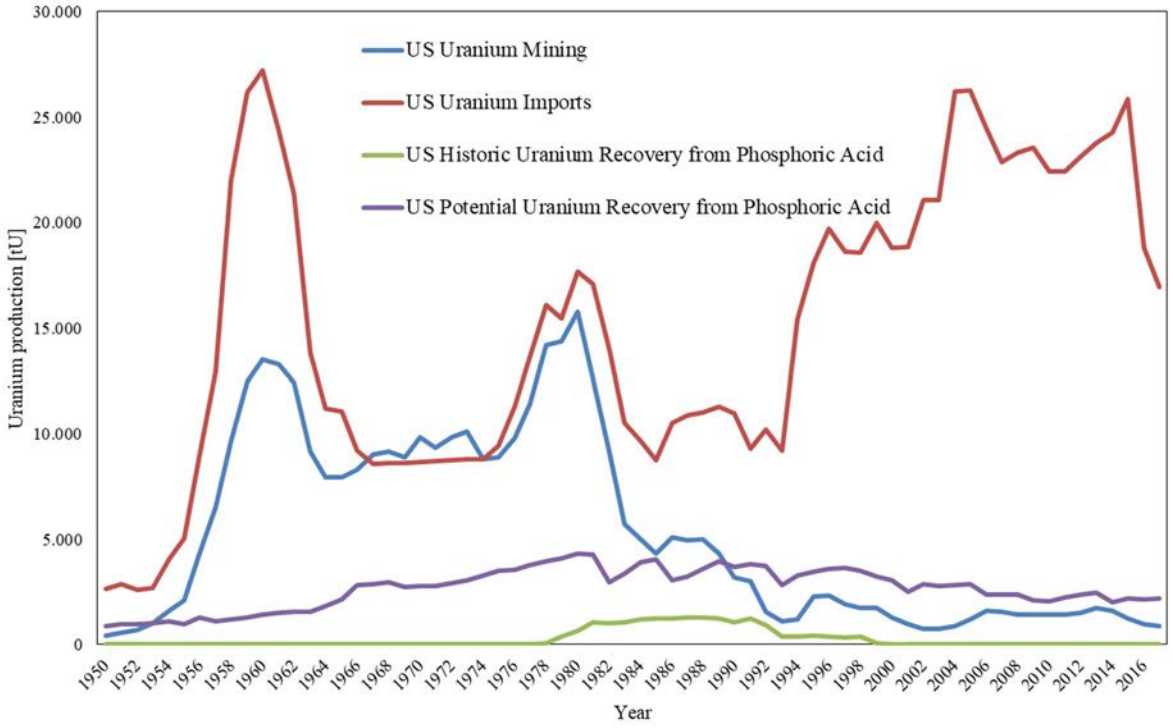

FIG. 6. The USA's historical imports of uranium, mining activities, and prospective and historical uranium recovery from phosphates.

The USA, like many other nations that rely heavily on nuclear power to produce energy, is now importing the majority of the uranium needed from abroad. It is interesting to note that since the 1990s, the quantity of uranium that could be recovered from phosphates as a byproduct in the manufacturing of fertilizer has had the potential to exceed the amount that has been mined domestically. In this regard, as suggested by Steiner et al. [17], current concerns over the nation's uranium supply security might actually “make uranium recovery from phosphates great again”.

3. TECHNICAL DEVELOPMENTS TO PROMOTE URANIUM RECOVERY FROM PHOSPHATE ORES

Since the first IAEA publication on the recovery of uranium from phosphoric acid in 1989 [1] increasing research on uranium recovery from phosphates can be reported. Fig. 7 shows the number of scientific peer-reviewed publications on uranium recovery from phosphates by year that are listed in the Scopus database. The figure was compiled to indicate the global interest in uranium from phosphates. The listed works focus largely on the recovery of uranium from phosphoric acid, but also economic and environmental studies were listed. Notably, a special issue consisting of six contributions was dedicated to research needs and progress on uranium and REE recovery in 2016 [18].

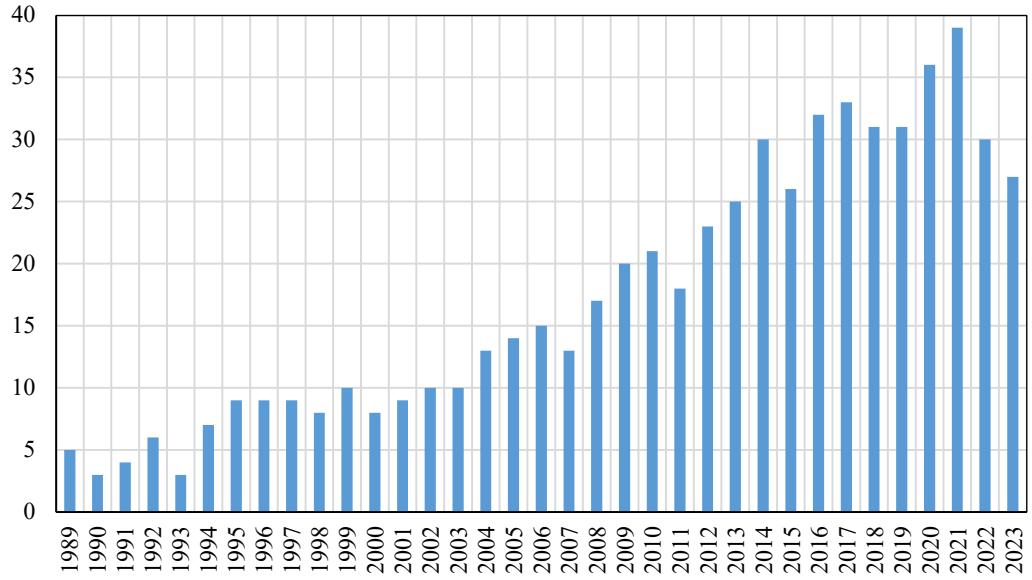

FIG. 7. Amount of scientific peer-reviewed publications on uranium recovery from phosphates per year.

Regarding the scientific work on the recovery of uranium from phosphates, it is noticeable that most scientific studies do not present improvements in relation to proven solvent extraction methods, but often consider ion exchange as an alternative method. The majority of these studies consider inexpensive adsorbents, often waste materials, for the recovery or extraction of uranium from phosphoric acid on laboratory scale. Although solvent extraction processes for uranium recovery from WPA are industrially proven and there are notable developments in making these processes even more efficient [19-21], novel ion exchange processes might also play a role if uranium recovery from WPA would be commercially pursuit again.

A successful example of a recent pilot plant operation for uranium recovery from WPA is the work of PhosEnergy in the USA (see Fig. 8). Specifically, Cameco and Uranium Equities aimed to set up a demonstration plant in Florida (USA) using a refined process based on ion exchange. A prefeasibility study of the PhosEnergy process was completed in early 2015 and its potential as a low-cost process, at about US$ 21/lb U_3O_8 could be confirmed [22]. The capital costs of the process did, however, not convince the stakeholders to move to full scale industrial operation yet and further developments are presently on hold.

FIG. 8. PhosEnergy pilot plant that uses an ion exchange process for uranium recovery from phosphoric acid erected in the USA (courtesy of PhosEnergy).

The ion exchange process tested by PhosEnergy is an improvement to the existing solvent extraction methods. Developments started in 2009 with the aim of developing a process that can recover uranium from WPA produced by large phosphoric acid plants in Florida for US$ 25 to US$ 30 per lb of U_3O_8 that would roughly be half of the costs achieved by commercial solvent extraction plants in the past. The demonstration plant depicted in Fig. 7 was constructed in Adelaide, South Australia, and moved to the USA in 2012. The tests included four trials on two different WPA feed sources and resulted in uranium recovery rates of over 92% slightly below the targeted operating cost of US$ 20 to US$ 25 per lb U_3O_8.

In March 2013, a comprehensive assessment of the project's operations along with an engineering study was released, and estimates for a base case of 400 t/yr U_3O_8 plant operating at projected costs of US$ 18 per lb U_3O_8 and capital costs of US$ 156 million were reported.

The pre-treatment step of the PhosEnergy process involves loading the 27% phosphoric acid into the ion exchanger, which is where the uranium ions are adsorbed. The phosphoric acid passes through the ion exchange column and added back to the main flow of the process. Aqueous ammonium carbonate is used to elute the uranium. Ammonium uranyl carbonate from the main elution is concentrated and purified in a secondary ion exchange operation before being eluted with a bicarbonate solution.

For a US$ 120 million bolt-on plant cost, the method is supposed to recover 95% of the uranium present in the WPA while producing no radioactive waste. It also improves acid quality for the primary fertilizer plant. A 0.44 Mt/yr phosphate plant that could produce 155 tU/yr would reportedly run at costs of US$ 21/lb U_3O_8, according to the 2015 pre-feasibility study, although the construction cost would be much higher in comparison to traditional uranium producing facilities, particularly in situ leach (ISL) plants.

In total, the PhosEnergy demonstration plant operated continuously for ten weeks on site at the location of an active WPA production facility, consistently recovering over 92% of the uranium present in the merchant grade WPA stream. The product was sent to a Wyoming uranium mill with a license for further processing and was processed here to a usable yellowcake.

4. POTENTIAL URANIUM RECOVERY FROM PHOSPHATE ORES GLOBALLY

The global potential for uranium recovery from phosphate ores can be estimated using production data and phosphate ore reserve data as it is for instance reported annually by the United States Geological Survey [2] as well as average concentrations of uranium in the considered phosphate ores. Table 5 provides estimated amounts of uranium associated with phosphate ores globally using 2021 production data of the United States Geological Survey. The average uranium concentrations in phosphate ore by country were estimated using data provided by Van Kauwenbergh [3].

The quantitative assessment featured in table 5 is a straightforward and simple analysis that gives insight into the amount of uranium linked to phosphate ore production and reserves. According to this simple assessment, nearly 14,000 t of uranium are mined with phosphate ore every year worldwide. Out of these 14,000 t, approximately 9,000 t have been observed as being connected to phosphate ores with more elevated uranium concentrations of 90 mg/kg. Such phosphate ores, or a cut-off grade of 90 mg/kg has been introduced in earlier analysis [4] and it was proclaimed that such phosphate ores might allow for commercial uranium recovery, while others with lower uranium contents will probably not. The estimate in table 5 provides a brief overview of the potential that uranium recovery from phosphate ores could have on a global scale. In this context, it is noteworthy that the uranium production in 2021 was approximately 47,731 t [23].

If uranium is recovered during phosphate ore production using the historically proven solvent extraction processes that were introduced earlier in this publication, approximately 95% of the uranium present in the WPA could be recovered. In addition, it can be estimated that 90% of the uranium transfers from the phosphate ore to the WPA. The amount of uranium that could theoretically be recovered from phosphate ore production in 2021 would thus be approximately 7,700 t or roughly 16% of the worldwide uranium production that year considering phosphate ores with a uranium content of at least 90 mg/kg and equations 1-3 that are provided below.

Uranium content in phosphate rock: $$U_{phosphate\,rock} = (C_i \times P_i) \quad (1)$$

Uranium content in WPA: $$U_{WPA} = 0.90\ (C_i \times P_i) \quad (2)$$

Recoverable uranium content from WPA: $$U_{recoverable} = 0.95\ U_{WPA} \quad (3)$$

Where C_i (mg/kg) is the country specific uranium concentration in phosphate ore and P_i (t) is the corresponding quantity of imported phosphate ore (see table 5). U_{WPA} is the concentration of uranium in the WPA and $U_{recoverable}$ is the quantity of uranium that can be recovered from the WPA using best available technology (BAT), such as industrially proven solvent extraction that was introduced earlier.

It is seen as very unlikely that large scale recovery of uranium at the more than 400 mineral fertilizer plants that are operated worldwide will be introduced. The very brief calculation provided here does, however, indicate the large potential that this technology has for the recovery of uranium.

TABLE. 5. ESTIMATED AMOUNT OF URANIUM ASSOCIATED WITH GLOBAL PHOSPHATE PRODUCTION AND RESERVES IN 2021.

Country	Phosphate ore production in 2021 (million t)	Phosphate ore reserves (million t)	Uranium content (mg/kg)	Uranium associated with phosphate production in 2021 (t)	Uranium associated with phosphate reserves (t)
Algeria	1.4	2,200	63	88	138,600
Australia	2.5	1,100	84	210	92,400
Brazil	6.0	1,600	201	1,206	321,600
China	90.0	1,900	27	2,430	51,300
Egypt	5.0	2,800	90	450	252,000
Finland	0.1	1,000	37	37	37,000
India	1.4	46	23	32	1,058
Israel	2.4	60	120	292	7,200
Jordan	10.0	1,000	84	840	84,000
Kazakhstan	1.5	260	100	150	26,000
Mexico	0.5	30	100	49	3,000
Morocco	38.1	50,000	97	3,696	4,850,000
Peru	4.2	210	72	302	15,120
Russian Federation	14.0	600	28	392	16,800
Saudi Arabia	9.2	1,400	100	920	140,000
Senegal	2.1	50	67	141	3,350
South Africa	2.1	1.600	23	49	36,800
Togo	1.0	3,000	94	94	2,820
Türkiye	0.6	50	47	28	2,350
Tunisia	3.7	2,500	44	164	110,000
USA	21.6	1,000	99	2,138	99,000
Uzbekistan	0.9	100	42	38	4,200
Viet Nam	4.5	30	30	135	900
Other Countries	2.0	2,600	-	-	-
World Total	226.0	72.0	-	13,881	6,295,498
	Total uranium with 90 mg/kg cut-off grade			8,995	5,701,620

Moreover, what is equally worthy of note are the overall quantities of uranium connected with phosphate reserves which theoretically stand at nearly 6.3 million t and are thus very similar in quantity to the identified commercially recoverable uranium resources that are reported to be as high as 6.1 million t [5]. Although these uranium resources might be similar in quantity, they are obviously not similar in quality in a way that the identified recoverable uranium resources

can be commercially mined for economic profit while this is presently not the case with the uranium associated with phosphates that was identified here. Nevertheless, the amounts clearly set phosphates apart from other potential unconventional uranium resources that show uranium in similar concentrations but much smaller overall global quantities.

Furthermore, it clearly sets phosphates apart from seawater that shows tremendous overall quantities of uranium at rather low concentrations of 3.3 parts per billion or 0.0033 mg/kg. With presumably decreasing phosphate ore grades, the number of heavy metals, uranium and other, will slightly increase in the long term [24], making uranium recovery slightly more attractive in the future.

5. CASE STUDIES

Nowadays, uranium recovery during phosphate ore processing is not economic, which is why fertilizer companies are not implementing this practice. Phosphate ores vary much with different locations, and so do the economics of uranium recovery from phosphates. In the following, five case studies from Argentina (section 5.1), Brazil (section 5.2), the Philippines (section 5.3), Saudi Arabia (section 5.4) and the United Republic of Tanzania (section 5.4) are introduced to highlight specific aspects of uranium recovery from phosphates.

Argentina is an interesting case study since the country has a relevant fleet of operating nuclear power plants (NPPs) and the public opinion is generally in favor of nuclear electricity generation [25-27]. Argentina also has relevant uranium resources but forbids mining them. Argentina has a strong agricultural industry and requires relevant amounts of mineral fertilizers that are presently imported. Given the public awareness about heavy metal pollution, uranium (and other heavy metal) recovery from phosphates during fertilizer production might favor. In this way, the uranium distribution with fertilizers on agricultural soils could be dramatically decreased. The case study further shows that Argentina currently pays higher prices for uranium than world spot market prices would suggest. This special economic situation might promote the recovery of uranium from phosphates in Argentina.

Brazil is a relevant case study since the ore of the Itataia deposit shows relevant concentrations of phosphorus and uranium, so that it can be characterized as phosphate uranium ore. The ore is not mined yet, but a mining operation to extract both phosphates and uranium is foreseen to commence in the very near future. The case study presented provides new information about this very specific ore and the planned way to process it.

The Philippines constitute a relevant case study as the country has a fertilizer industry that supports large parts of Southeast Asia but no relevant traditional uranium deposits as a result of the young geology of the archipelago country. It is foreseen to build NPPs and domestic uranium supply is a strategic goal of the Philippines. This uranium could come from imported phosphate ores that are processed to mineral fertilizers as discussed in this case study.

Saudi Arabia constitutes an interesting case study since the potential uranium recovery from phosphates can directly be compared with the potential uranium recovery from seawater. Saudi Arabia is the country with the largest seawater desalination plants, and also has a relevant phosphate processing industry. The case study directly compares the potential of recovering uranium from phosphates and seawater during phosphoric acid production, and seewater desalination.

The United Republic of Tanzania is home to the Minjingu phosphate ore deposit that shows average uranium concentrations of nearly 400 mg/kg. The ore is processed using dry beneficiation without producing phosphoric acid as an intermediate product. The case study sheds light on the unique situation in the United Republic of Tanzania and discusses possibilities for comprehensive use of Minjingu phosphate ore.

5.1. ARGENTINA

Despite general acceptance from Argentinians regarding nuclear power generation, public opinion does not favor domestic uranium mining [25-27] as a result of potential health and environmental risks associated with heavy metal mining. Uranium imports result in significant costs for Argentina due to currency conversion to US$, so that costs for uranium exceed international market prices for both short- and long-term contracts. Argentina also relies on imported phosphate ore, as well as imported mineral fertilizers containing elevated levels of uranium that is lost when dissipated over agricultural soils and could cause harms similar to those perceived by uranium mining [14, 28]. This work quantifies the amounts of uranium that are associated with phosphate ore processing in Argentina and compares them to the country's uranium demand.

Nuclear power generates about 7% of Argentina's electricity [29], with plans to build additional reactors in the future [30]. These growth projections indicate that by the year 2030, Argentina will need twice as much uranium as it currently uses [29]. Despite having mined uranium domestically in the past, all current uranium need is imported. In fact, in response to low global prices for uranium, the importation initiative began as early as 1992. Argentina initially purchased uranium concentrates from South Africa and later went ahead to cease local production altogether culminating into a shutdown and closure of all facilities by 1997. Uzbekistan, the Czech Republic, Kazakhstan, and Canada developed to be the main suppliers of uranium for Argentina's nuclear power fleet.

Argentina possesses considerable amounts of domestic uranium deposits, categorized as intrusive, granite-related, volcanic-related, sandstone, surficial and phosphates [31]. In the year 2017 alone, an estimated quantity of approximately 19,000 t of identified resources were reported by Argentina's National Atomic Energy Commission (CNEA) for production costing less than US$ 130/kg uranium. Other public mining companies such as U3O8 Corporation (Coffey Mining Pty Limited), Blue Sky Corporation and UrAmerica Limited also contributed significantly to this figure with a total certified resource estimate expectedly resulting in about 18,000 t uranium. These six major projects are further detailed in table 6 which provides an estimation that Argentina might possess considerable uranium resources.

TABLE. 6. URANIUM RESOURCES IN ARGENTINA.

Deposit (ownership)	Type	Reasonably assured resources, RAR (tU ≤ US$ 130 kg/U)[a]	Inferred resources, IR(tU ≤ US$ 130/kgU)[b]
Amarillo Grande (Blue Sky Uranium Corp)	Sandstone/surficial	-	7,360
Cerro Solo (CNEA)	Sandstone	4,421	3,760 (4,810)*
Don Otto (CNEA)	Sandstone	180	250
Laguna Colorada (CNEA)	Volcanic related	100	60
Laguna Salada (U_3O_8 Corp)	Surficial	2,420	1,460
Meseta Central (UrAmericaLtd)	Sandstone	-	7,350
Sierra Pintada (CNEA)	Volcanic related	3,900	6,110
Sub Total		11,020	26,350 (27,400)*
Total		37,370 (38,420)*	

*tU for production cost category of <260 US$/kgU; [a]UNFC Commercial and Potentially Commercial Projects (E1F1G1,2) and (E2F2G1,2); [b]UNFC Potentially Commercial Projects (E2F2G3).

The Mining Code in Argentina has been effective since 1997 and classifies uranium and thorium as nuclear minerals, with their corresponding resources under the ownership of Provincial States according to the National Constitution [32]. Out of all Argentine provinces, eight have laws that limit metal mining operations. Identified uranium deposits are mostly concentrated within Chubut and Mendoza Provinces, however, restrictions on uranium production exist within both provinces. In particular for Chubut Province where open-pit mining is banned altogether, project developments have to abide by territorial zoning regulations specified under Law 5001/2003 federals terms along with an appropriate legal framework governing its jurisdiction [33].

Argentina's uranium resources are not limited to the conventional ones. The country also has unconventional uranium resources including those associated with phosphate ores that are utilized for fertilizer production. Argentina has a large agricultural industry and heavily depends on phosphate ore and WPA imports that are further processed at a facility located within the Buenos Aires Province.

The estimated costs of recovering uranium from phosphate ores in Argentina might vary due to the significant difference between regional and global uranium prices. The free on board (FOB) prices paid by Argentina for yellowcake over recent years have been considerably higher than reported spot or long-term prices. In 2015, Argentina paid an average FOB price of US$66 per pound U_3O_8 while the spot market price was US$ 37 per pound U_3O_8 and long term average prices were at US$ 46 per pound U_3O_8.

Figure 9 shows the average FOB prices paid by Argentina in comparison to international spot prices and long term prices for uranium reported by UxC, LLC.

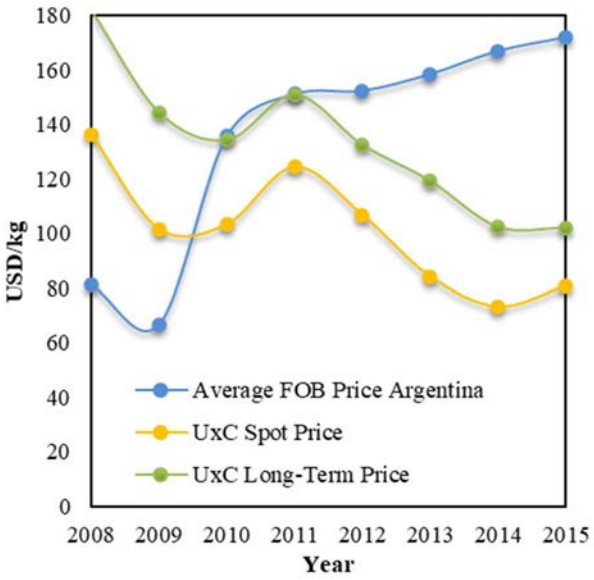

FIG. 9. Price for free on board (FOB) according to UxC, LLC, Argentina paid for uranium between 2008 and 2015, as well as at current long-term and spot pricing (courtesy of L. López, CNEA).

According to López [34], the surge in prices is attributable to escalated transportation fees, insurance premiums and taxes. This has led to higher rates of uranium in Argentina, where a thriving agricultural sector requires substantial quantities of phosphate fertilizer while strict restrictions on uranium mining might encourage extraction of uranium during phosphate fertilizer production.

Argentina's fertilizer industry relies entirely on imported phosphates for its operations. These phosphates are sourced in two ways: imported phosphate ores, which constitute approximately 25% of the total requirements and are processed to phosphoric acid at the Bunge plant located near Buenos Aires; and mineral fertilizers directly imported which make up roughly three-quarters of the total demand. Data concerning both quantity as well as origin of the imported materials was obtained from the United Nations Comtrade database while estimates regarding uranium concentrations in the imported products was taken from Bech et al. [35] that confirmed previous work by Van Kauwenbergh [3].

In Argentina, three pressurized heavy water reactors (PHWRs) are currently in operation. Atucha 1 utilizes slightly enriched uranium (0.85% ^{235}U) with a gross electrical power of 362 Mwe, while Embalse and Atucha 2 use natural uranium fuel and have capacities of 648 MWe and 745 Mwe, respectively [25]. As part of the ongoing nuclear development in Argentina, the country is collaborating with China for instalment of a fourth nuclear reactor, a Canada deuterium uranium (CANDU) PHWR, as well as an additional fifth reactor, a Hualong One pressurized water reactor (PWR) [29].

Additionally, construction of the CAREM prototype small modular reactor (27 MWe net; 32 MWe gross) is currently underway at the Atucha site and is expected to be operational in the coming years. There are plans to expand its capacity up to a possible 120 MWe. Table 7 outlines current and projected large commercial nuclear power plants in Argentina with consideration for two new reactors by the year 2030.

TABLE. 7. COMMERCIAL NUCLEAR POWER PLANTS IN ARGENTINA, BOTH CURRENT AND PLANNED.

Reactor	Startup	Location	Model	Gross Mwe
Attucha 1	1974	Lima, Buenos Aires	PHWR (Siemens)	362
Embalse	1983	Embalse, Cordoba	PHWR (CANDU-6)	683
Attucha 2	2014	Lima, Buenos Aires	PHWR (Siemens)	745
Attucha 3	proposed	Lima, Buenos Aires	PHWR (CANDU-6)	750
Attucha 4	proposed	Lima, Buenos Aires	PWR (Huolong-1)	1150

Due to Embalse undergoing a lifetime extension program, Argentina's natural uranium needin 2017 was 195 t compared to the usual range of 220-250 t per year. The research given here predicts that by 2030, there will be a generating capacity of around 3.470 GWe for the low case and nearly 4.070 GWe for the high case, respectively, based on several nuclear power growth scenarios [29]. To support these projections without revolutionary changes in Argentina’s nuclear fuel cycles, such as using thorium or recycling spent fuel, raw material needs would consist of natural uranium demands of 525-620 t annually. This would translate to at least double current consumption rates generated from the PHWRs utilizing natural uranium (Embalse & Atucha 2) or slightly enriched uranium (SEU) (Atucha 1). Table 8 provides a very brief overview of the current and foreseen uranium need in Argentina.

TABLE. 8. PRESENT AND FORESEEN URANIUM REQUIREMENTS IN ARGENTINA.

Time	Natural uranium requirements
2017-2030	220-250 t
After 2030	525-620 t

All of the phosphate ores used at Argentina's Bunge Fertiliser Plant are imported. 78.4% of the processed phosphate ore that was imported in 2017 came from Peru. Furthermore, Senegal (2.7%) and Morocco (19.0%) supplied higher quantities of this mineral. Argentina's weighted phosphate ore imports from 2007 to 2017 are broken down by nation in Fig. 10.

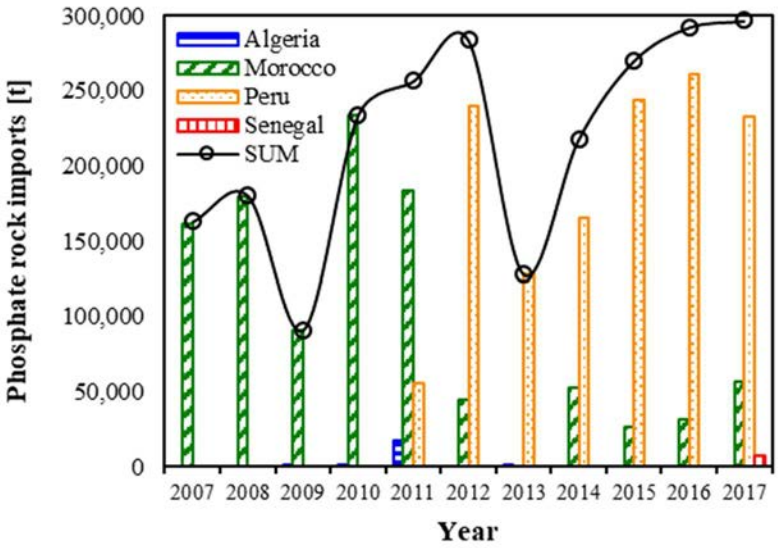

FIG. 10. Argentina's phosphate ore imports by quantity and country from 2007 to 2017 (courtesy of L. López, CNEA).

Over the course of a decade, the quantity of imported phosphate ore experienced a gradual increase, rising from approximately 160,000 metric tons in 2007 to nearly 300,000 metric tons in 2017, with two notable decreases in 2009 and 2013. The first decline in 2009 was a consequence of a significant global price surge of 352% for phosphate rock between 2007 and 2008, which was instigated by market policies in India, the world's largest importer of phosphate fertilizer and phosphate rock [36-37]. Argentina's lack of foreign cash, especially in USD, is the reason for the second decrease in 2013. Fig. 11, which shows the value-added imports of phosphate ore from Argentina between 2007 and 2017, also shows these two dips in 2009 and 2013. Phosphate ore price fluctuations have a significant impact on the value of imported phosphate ore. Although the amount of phosphate ore shipped from Peru rather than Morocco increased, the overall value fell.

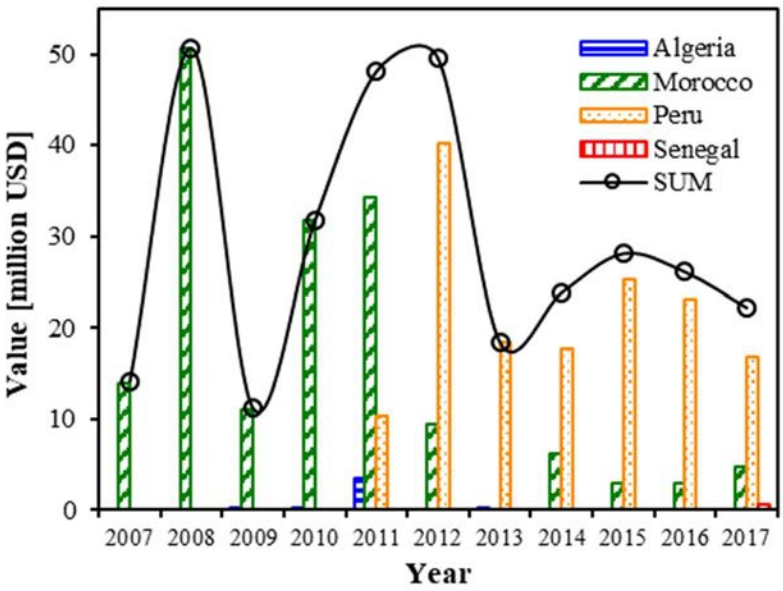

FIG. 11. Argentina's phosphate ore imports by value and country from 2007 to 2017 (courtesy of L. López, CNEA).

Bech et al. [35] provided data on the average uranium concentration in phosphate ore from Morocco (121.5 mg/kg), Peru (70.3 mg/kg), and Senegal (67.9 mg/kg). Using this information, the amount of uranium associated with phosphate ore imports into Argentina can be estimated. Recovery of uranium from these imports can be integrated into existing WPA fertilizer plants without too much difficulty. Some countries, such as India, Pakistan, and the Philippines, import phosphate ore and process it domestically. In 2017, all phosphate ore imports into Argentina showed slightly elevated uranium levels (>60 mg/kg) compared to igneous phosphate ores from the Russian Federation or South Africa. Theoretically, 19.1 t of uranium could have been recovered during domestic phosphate rock production in Argentina, covering 7.7-8.7% of current uranium demand or 3.1-3.7% of expected demand after 2030.

TABLE. 9. URANIUM ASSOCIATED WITH PHOSPHATE ORE IMPORTS INTO ARGENTINA IN 2017.

Phosphate ore exporting country	Phosphate ore imported into Argentina (t)	Average uranium content of the phosphate ore (mg/kg)	Estimated amount of uranium imported with phosphate ore (t)	Estimated recoverable amount of uranium (t)
Morocco	56,280	121.5	6.8	5.5
Peru	232,571	70.3	16.3	13.2
Senegal	7,874	67.9	0.5	0.4
Total				19.1

Morocco owns approximately 75% of the world's phosphate ore reserves, making it a likely source for future exports. This could result in Argentina importing significantly more phosphate ore from Morocco than is presently the case, which is relevant to this study due to the higher uranium concentrations found in Moroccan phosphate ore compared to phosphate ores from Peru that presently constitute the largest phosphate ore source of Argentina. If all phosphate ore purchased in 2017 had come from Morocco, it could have potentially yielded 29.2 t of uranium, equivalent to 11.7-13.3% of Argentina's current, and 4.7-5.6% of Argentina's future, domestic uranium demand, assuming an average uranium content of 121.5 mg/kg.

In addition to phosphate ore, India and other nations import significant quantities of WPA, that usually still contains recoverable uranium since this is presently not extracted by the exporting country. Argentina, for instance, imported 14-25 t of WPA in 2017, suggesting the possibility of further uranium recovery from imported sources.

Argentina's annual demand for phosphate fertilizer is approximately 1.2 million t, with only 25% being produced domestically by the phosphate ore processing plant in Buenos Aires Province [38]. Since 1990, the country's fertilizer demand has been increasing at a rate of over 4% [39]. Therefore, the construction of more domestic phosphate fertilizer plants to reduce foreign dependencies, lower fertilizer costs, and ultimately decrease costs for foodstuff could be considered.

If all of Argentina's needed phosphate fertilizer was produced domestically with 19.0% coming from Morocco, 78.4% from Peru, and 2.7% from Senegal (similar to the shares of current imports) Argentina could recover between 85.3 and 101.5 t uranium per year. Together with

the already imported phosphate ores, this would mean that 45-51% of the current uranium demands and 18-21% of the future uranium demands of Argentina could be supplied by the phosphate industry.

5.2. BRAZIL

Brazil hosts a phosphate ore deposit or more precisely a multielement ore deposit that contains exceptionally high concentrations of uranium. The Itataia deposit stands as Brazil's largest known uranium reserve. Approximately 142,200 t of uranium are intermixed with phosphates [40]. The deposit holds exploitable reserves of 79.5 million t of ore, with concentrations of 11% P_2O_5 that would make it a lower-grade phosphate deposit and 998 mg/kg U_3O_8 that makes this a low-grade uranium deposit. In total about 8.9 million t of P_2O_5 and 79.3 thousand t of U_3O_8 are thus present at the deposit. The current plan is to process the ore like a phosphate ore using industrially proven solvent extraction for uranium recovery. Figure 12 provides the proposed flowsheet for developing the Itataia phosphate uranium ore in Northeastern Brazil.

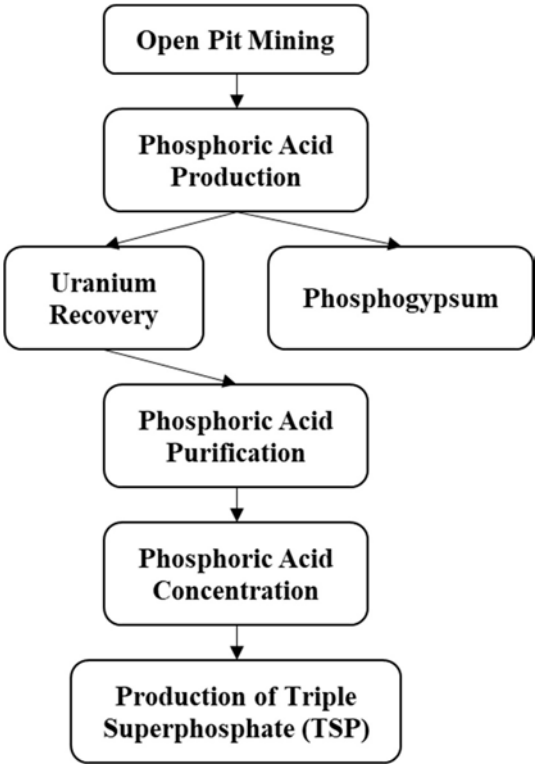

FIG. 12. Proposed flowsheet for developing the Itataia phosphate uranium ore in Northeastern Brazil (courtesy of L.M. da Silva, INB).

It is planned that, when in full operation, a mine and processing plant at the Itataia deposit will contribute a total of 1 020 000 t phosphate fertilizer per year, 220 000 t dicalcium phosphate per year, and 2 300 t U_3O_8 per year. Figure 13 indicates the current plan to start uranium processing at the Itataia deposit in 2026 with the intention of reaching full capacity in 2029. Brazil is presently mining uranium for its two NPPs at the Engenho open pit mine near Caetité in Brazil's Bahia state [41].

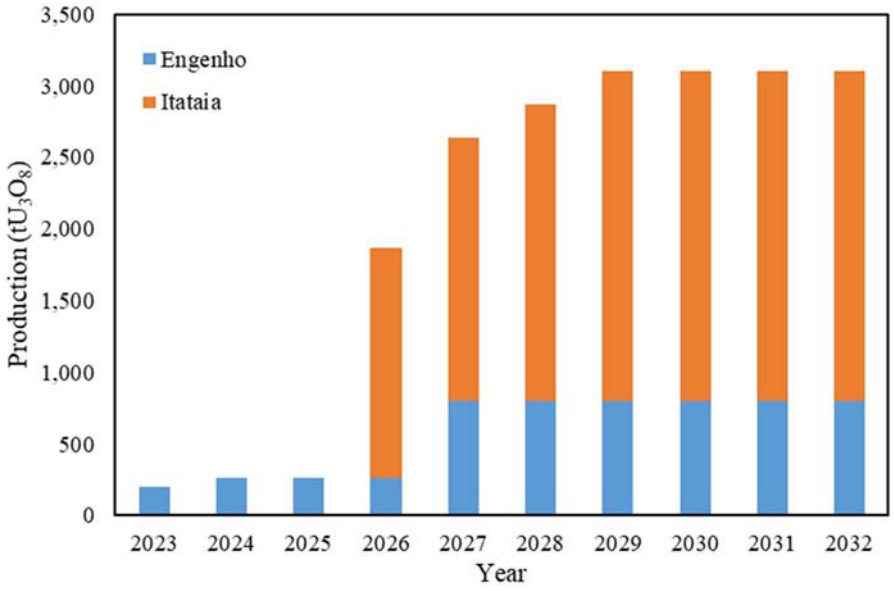

FIG. 13. Planned uranium production of the Engenho mine and at the Itataia deposit in Brazil (courtesy of L.M. da Silva, INB).

If developed as planned the phosphate uranium deposit could significantly contribute to domestic fertilizer and uranium production.

5.3. PHILIPPINES

As a result of its geologically young origin, the Philippines do not possess significant commercial uranium ores. The Philippines are, however, a large regional fertilizer producing country and uranium could theoretically be recovered during fertilizer production from imported phosphate ores and ultimately be used to fuel a fleet of domestic NPPs.

In 2022 the Philippine government has made a historic decision to endorse a national nuclear energy programme. This move is motivated by several key factors, primarily (1.) the potential cost-effectiveness of electricity generated through nuclear power, (2.) the aim to close the national energy supply demand gap, and (3.) the desire to reduce greenhouse gas emissions [42]. In 2021, the cost of household electricity per kWh in the Philippines (US$ 0.163) was marginally higher than in the USA (US$ 0.162) [43], despite the fact that the average income of a Filipino is only $1/19^{th}$ of that of an average American [44]. In that same year, coal accounted for a substantial 48% of the 102 TWh of electricity produced in the Philippines [45]. Despite the nation's commitment to the Paris Agreement, which calls for a 75% reduction in projected greenhouse gas emissions by 2030, this percentage has been rising annually since 2017. The hunt for alternate electricity generating techniques has been prompted by the introduction of a ban on new coal-fired power plant projects in 2020, as well as significant unhappiness by civil society groups in the Philippines.

Nuclear energy, which has a longstanding history in the Philippines, presents a promising alternative to coal-based power generation, offering significant reductions in carbon emissions. The country responded to the 1973 oil crisis, which led to a threefold increase in global oil prices and placed a considerable burden on the Philippine economy, by constructing the first NPP in Southeast Asia. In an effort to meet and enhance energy demands while decreasing

reliance on foreign oil imports, the Philippine government, under then-President Ferdinand Marcos, enacted Republic Act No. 6395 in 1973 to authorize the construction of an NPP [46]. The Bataan Nuclear Power Plant (BNPP), situated in Morong, Bataan, was built between 1976 and 1983 at a total cost of USD 2.2 billion. It is equipped with a Westinghouse pressurized water reactor (PWR) boasting a nameplate thermal capacity of 1,876 MW and an electric capacity of 620 MWe. Due to concerns stemming from the Chornobyl nuclear accident in April 1986, along with apprehensions about potential construction flaws, the proximity of the BNPP to major fault lines, and other risks associated with earthquakes and volcanic activity, the BNPP was never put into operation. For a comprehensive chronology of BNPP-related events, refer to Mendoza et al. [46].

Concurrently with the construction of the BNPP, the Philippine government engaged in an extensive uranium exploration initiative aimed at locating deposits suitable for powering envisaged NPPs. However, it became evident that the geologically young terrain of the Philippines is not conducive to significant uranium mineralization. Despite examining roughly 70% of the country, only minor occurrences of uranium were uncovered [47]. One potential source of uranium identified was the Larap Cu-Au-Mo deposit in Jose Panganiban, Camarines Norte. Within this deposit, uranium is found in the form of dispersed uraninite grains, with an estimated potential recovery of 170 t from 500,000 t of ore, exhibiting a uranium grade of approximately 34 mg/kg [48]. However, the deposit's relatively low uranium concentration and its relatively small size render this operation economically unviable.

A number of initiatives have been launched with the aim of reviving the nuclear programme in the Philippines. The Nuclear Energy Programme Inter-Agency Committee (NEP-IAC) was established in 2020 by Executive Order No. 116, which was issued by then-President Rodrigo Duterte to investigate the integration of nuclear energy into the Philippine energy portfolio [49]. The Philippines also entered into a memorandum of understanding with ROSATOM from the Russian Federation in 2020, with the objective of assessing the feasibility of deploying floating NPPs in the archipelago. Prior to his departure in 2022, former President Duterte additionally endorsed Executive Order No. 164, which formalizes a national stance on a nuclear energy programme in the Philippines [42]. The revival of the Bataan Nuclear Power Plant (BNPP) has emerged as the foremost priority within this programme, widely regarded as one of the most viable means to curtail carbon emissions in the Philippines. Alongside the BNPP, there is a fervent examination of the potential implementation of Small Modular Reactors (SMRs) in the country.

The prospect of deploying NPPs in the Philippines has also spurred a surge in interest regarding domestic uranium resources. While it is acknowledged that natural uranium has to undergo a series of steps, from mining to milling, conversion, enrichment, and finally fuel fabrication, securing the primary material for nuclear fuel production within the Philippines is of paramount importance. The Philippines possess minimal conventional uranium ores, but there are various non-traditional sources of uranium such as uranium associated with phosphate imports and seawater.

Globally, typical uranium levels in phosphates range from 50-200 mg/kg, with some local concentrations surpassing 400 mg/kg [15]. In stark contrast, seawater registers a significantly lower average of merely 0.0033 mg/kg. Phosphate ore stands as one of the fifth most extensively mined materials worldwide, primarily serving as a crucial component in phosphate fertilizer production. The Philippines emerges as a major player in mineral fertilizer production

within Southeast Asia. As the country lacks a domestic source of phosphate rock, it relies on imports from various global suppliers for fertilizer production [50].

The imported phosphate ore is then processed using the WPA process with sulfuric acid. In the process up to 90% of the naturally occurring uranium in the phosphate ore transfers to the WPA [51]. Typically, 0.6 t of sulfuric acid are added to one t of phosphate ore to produce 1.2 t of phosphogypsum and 0.4 t of WPA [6]. In the Philippines, phosphogypsum generally has uranium concentrations between 1-4 mg/kg, whereas 90% of the uranium from the phosphate ore passes to the WPA [52].

It is important to remember that WPA is an intermediate product used in the creation of fertilizer, and that the final fertilizer product's uranium concentrations can fluctuate greatly based on the fluctuating quantities of phosphorus and other nutrients. Palattao et al.'s [53] observations of uranium contents varying from 26 to 228 mg/kg in five popular compound fertilizers in the Philippines provide strong evidence of this variability. It is often possible to recover more than 95% of the uranium that is recovered from the WPA, which reduces the uranium concentration to about 2–9 mg/kg. As a result, there is usually a reduction of more than 95% in the uranium content in the final phosphate fertilizer products.

The Philippines lack significant conventional uranium reserves but could potentially benefit from unconventional uranium extraction from imported phosphate rocks. The Philippine Nuclear Research Institute (PNRI) is currently conducting initial lab-scale experiments on uranium recovery from WPA, as detailed by Palattao et al. [53]. Additionally, there are plans for a pilot plant aimed at uranium recovery from phosphates. This study seeks to offer an estimate of the potential uranium recovery from imported phosphate rocks in the Philippines, thereby assessing the significance of this technology for a potential Philippine nuclear power programme.

In the case of the Philippines, a comparison with the uranium consumption of the Slovenian Krško NPP (KNPP) as a reasonably accurate estimate for the annual natural uranium requirement of BNPP. With a 76 MWe difference in power generating capacity, the KNPP, a 696 MWe NPP using a Westinghouse PWR, was designed, and built concurrently with the BNPP. Both projects had a similar structural architecture. To produce 5.4 TWh of energy in 2021, the KNPP used a total of 127 metric t of naturally occurring uranium equivalent that had been enriched to 5% ^{235}U. With the little difference in power generating capacity between the two NPPs taken into consideration, a reasonable estimate of the yearly natural uranium equivalent need of the BNPP would be 120 t based on the available data.

The historical trends in phosphate rock imports to the Philippines from various exporting countries are illustrated in Fig. 14. From 2002 to 2004, the Philippines primarily sourced phosphate ore from China. However, the subsequent years witnessed a diversification in import sources, with Algeria, Egypt, and Nauru becoming prominent suppliers. Notably, in 2007 and 2008, the imports of phosphate rock experienced a sharp decline due to significant spikes in phosphate prices. Following the devastation caused by Typhoon Haiyan to the main fertilizer plant in Leyte in November 2013, both phosphate ore imports and processing came to a complete standstill. Operations were partially resumed in 2020, albeit at reduced capacity. Over the past three years, the Philippines has predominantly imported phosphate ore from Algeria, Egypt, Morocco, Nauru, and Togo. Currently, phosphate ore imports have rebounded to

approximately 75% of their pre-Typhoon Haiyan levels. This resurgence signifies a positive recovery in the phosphate ore supply chain for the Philippines.

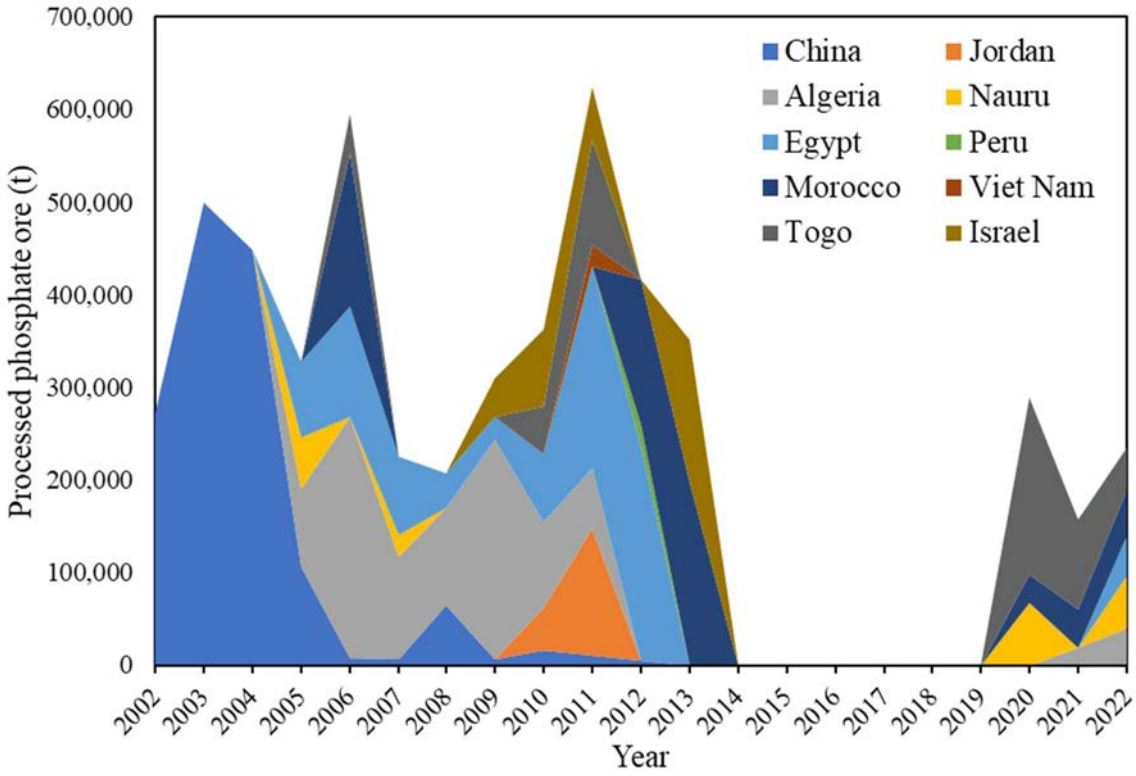

FIG. 14. Historical phosphate ore imports into the Philippines by exporting country (courtesy of J.D. Ramirez, PNRI).

Table 10 provides an estimation of the potential natural uranium yield from imported phosphate ores in the Philippines for the years 2020, 2021, and 2022. Notably, among the various phosphate ore sources, material sourced from Togo boasts the highest inferred uranium concentration at 114 mg/kg. This concentration is based on the comprehensive analysis conducted by Gnandi and Tobschall [54], who examined over 15 samples from Togo and reported an average uranium concentration of 114 mg/kg. It's worth mentioning that Van Kauwenbergh's study [3], which relies on two data points, suggests a slightly lower average uranium concentration of 94 mg/kg, and Vogel et al. [55] observed a uranium concentration of 65 mg/kg in a sample from Togo.

Over the three years under consideration, Togo supplied nearly half of the processed phosphate ore in the Philippines. Therefore, any variation in the assumed uranium concentration for Togo would naturally affect the potential recoverable uranium during phosphate ore processing.

Morocco emerges as the second largest supplier, contributing roughly 18% of the phosphate rock during the specified timeframe. Likewise, there are differing reports on uranium concentrations in Moroccan phosphate rock within the literature. Vogel et al. [55] note uranium concentrations of 169 mg/kg and 132 mg/kg for two distinct samples, while Qamouche et al. [56] state that uranium concentrations in Morocco typically range between 120 and 160 mg/kg. Sun et al.'s extensive study [57], considering 25 samples from this North African nation, also supports higher uranium concentrations in Moroccan phosphate rocks. This research gives

credence to the more conservative estimate presented by Van Kauwenbergh [3]. Morocco's significance is further underscored by the fact that over 70% of the presently known phosphate rock reserves are located in this country [58]. This suggests that, in the (longer-term) future, the Philippines might increasingly rely on Moroccan imports to fulfil their phosphate rock needs.

TABLE. 10. THE AMOUNT OF PRECIPITATE ROCKS THAT ARE IMPORTED, THE ESTIMATED CONCENTRATION OF URANIUM (U) IN PRECIPITATE ROCKS, AND THE ESTIMATED RECOVERABLE URANIUM (U) FROM WET PRECIPITIC ACID (WPA) IN THE PHILIPPINES FOR THE YEARS 2020, 2021, AND 2022.

Uranium	PR imported (t)			Average U concentration in important PR (mg kg^{-1})	U in imported PR (t)			Recoverable U in WPA (t)		
	2020	2021	2022		2020	2021	2022	2020	2021	2022
Algeria	0	18,138	37,057	63	0	1.1	2.3	0.0	1.0	2.0
Egypt	0	0	44,000	90	0	0	4.0	0.0	0.0	3.4
Morocco	29,700	47,250	51,400	97	2.9	4.6	5.0	2.5	3.9	4.3
Nauru	69,498	0	54,450	64	4.4	0	3.5	3.8	0.0	3.0
Togo	198,000	97,500	50,000	114	22.6	11.1	5.7	19.3	9.5	4.9
Total	297,198	162,888	236,907		29.9	16.8	20.5	25.6	14.4	17.5

Based on these considerations, it is projected that between 14.4 to 25.6 t of uranium could have potentially been extracted annually from phosphate ores imported by the Philippines in the years 2020, 2021, and 2022. This quantity of uranium, once recovered, corresponds to roughly 12 to 21% of the BNPP's anticipated annual natural uranium equivalent demand. Following earlier suggestions to adopt a cut-off grade of <90 mg/kg, it is plausible that about 12 to 18% of the envisaged natural uranium equivalent requirement of the BNPP could have been potentially met by the importation of phosphate ores from Egypt, Morocco, and Togo to the Philippines during the specified years.

The amount of unconventional uranium that could theoretically be recovered during phosphate fertilizer production in the Philippines is indeed significant and holds the potential to substantially contribute to securing uranium for the Philippines' forthcoming nuclear power initiative. It is worth emphasizing that Philippine imports of phosphate ores have yet to return to pre-Typhoon Haiyan levels. When the industry rebounds, it is plausible that 15 to 27% of the BNPP's uranium requirements could feasibly be met. The process of uranium recovery from imported phosphate ores in the Philippines can be accomplished relatively swiftly, potentially within a span of 2-3 years. This could facilitate the establishment of a uranium inventory, thereby alleviating concerns about natural uranium supply. To optimize the uranium content in imported phosphate ores, an increase in imports from Morocco and Togo would be advantageous. Additionally, it was found that a thorough investigation into the feasibility of establishing a larger pilot plant for near term, industrially scaled uranium recovery at the phosphate fertilizer facility in Leyte would help promote later industrial scale uranium recovery during phosphate fertilizer production in the Philippines and elsewhere.

5.4. SAUDI ARABIA

According to the World Bank, the Kingdom of Saudi Arabia has one of the highest per capita electricity consumptions (9,444 kWh) in the world, and according to the International Energy Agency, nearly 34% of this electricity is produced by consuming domestic oil resources. Residential electricity consumption accounts for 49.4%, with a 2% annual growth rate [59]. The continued rise in electricity demand might have serious environmental implications because of the large CO_2 emissions, and oil used domestically reduces potential incomes from exports leading to potential negative economic implications as well. It is therefore important for Saudi Arabia to investigate the use of alternative energy resources to address power shortages, revenue generation, and environmental pollution.

Nuclear and renewable energy are both viable low-carbon energy options that can reduce the domestic oil consumption in the Kingdom of Saudi Arabia. Under the Vision 2030 initiative, specifically the Saudi Green Initiative, the Kingdom of Saudi Arabia plans to achieve net zero emission by 2060, reduce carbon emissions by more than 278 million t per year and transform 50% its electricity production to renewable energy sources using non-fossil fuels [60]. To meet these initiatives, the construction of 15 nuclear reactors with a total capacity of 17.6 GW has been proposed by K.A.CARE (King Abdullah City for Atomic and Renewable Energy) that is tasked with the energy transition in the Kingdom of Saudi Arabia. The nuclear power programme initiative is planned to be completed by 2040 [61]. The projected 15 large nuclear power reactors will each require approximately 25 t of enriched uranium or approximately 250 t of natural uranium per year for continuous operation [62]. In addition, some 1,000 t of natural uranium equivalent will be needed for every “fresh” or new reactor core.

In this case study the amount of natural uranium that is required to sustain the future nuclear reactor fleet of the Kingdom of Saudi Arabia is estimated and it was further analyzed how much of these future uranium needs could theoretically be supplied domestically from unconventional uranium resources associated with phosphoric acid production and seawater desalination. All data used for the analysis are openly accessible and have been referenced. It was assumed that during phosphate rock processing, the WPA process is used during which roughly 90% of the uranium transfers from the phosphate rock to the WPA. From the WPA approximately 90% of the uranium can be recovered using best available technologies (BAT) that have already been employed on an industrial scale in Belgium, Iraq, Taiwan and the USA in the 1980s and 1990s, before decreasing uranium prices made this practice uneconomic. In case of seawater desalination, it is assumed that 90% of the uranium present in seawater can be recovered during seawater desalination.

The IAEA estimates that some 187 100 t uranium are associated with phosphate rocks in Saudi Arabia [63] and Al-Eshaikh et al. [64] suggest the consideration of phosphates and desalination concentrates as potential domestic sources of uranium for the Kingdom of Saudi Arabia. Since 2011, Saudi Arabia is a major phosphate ore producer (see Fig. 15) and the United States Geological Survey (USGS) estimated that the country produced 9.2 million t phosphate rocks in 2021 and 8.0 million t in 2020 respectively [2]. The average concentration of uranium in phosphate rocks in Saudi Arabia is probably in the order of 60-80 mg/kg with maximum local concentrations of 100-150 mg/kg [65-66], so that in 2021 some 447-596 t uranium could have theoretically been recovered during phosphate ore processing in Saudi Arabia if 90% of the uranium in the phosphate rock transfers to the WPA from where recovery usually takes place, and this recovery happens at an overall efficiency of 90%. It is noteworthy that previous studies

[4] have set the cut-off grade for (potentially economic) uranium recovery from phosphate ore at 90 mg/kg so that it needs to be investigated if uranium recovery from phosphates might at all make sense, for instance in case of locally higher concentrations, for the Kingdom of Saudi Arabia. The historical potential uranium recovery from phosphates for the Kingdom of Saudi Arabia is depicted in Fig. 15 using USGS phosphate rock production data.

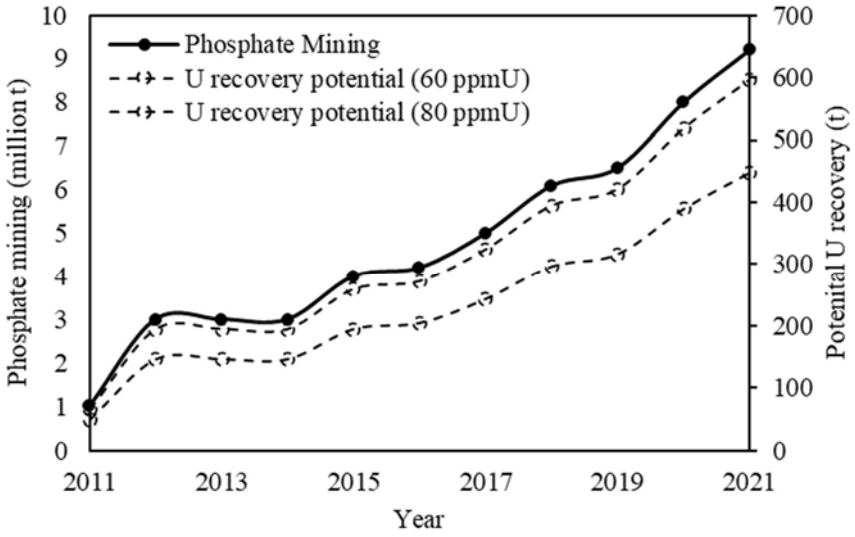

FIG. 15. Historical uranium recovery potential from phosphate mining in Saudi Arabia.

Uranium is also naturally present in seawater in concentrations as low as 3.3 parts per billion or 0.0033 mg/kg. As a result of the very large potential quantities of uranium in seawater that are estimated to be in the order of 4.5 billion metric t or 500 times of all identified terrestrial reserves, uranium recovery from seawater is actively researched. The uranium concentration in desalination concentrates or brine from desalination plants, basically a concentrate seawater, can be approximately two times higher than the uranium concentration in seawater and can show far fewer impurities than seawater [67-69]. There have been several different techniques of uranium recovery discovered during the past four decades. These includes, adsorption, ion-exchange, coagulation and coprecipitation, solvent extraction, membrane filtration, biological separation, and foam separation. Among these methods, adsorption is often considered to be the most convenient, efficient, and low-cost technique [70].

The Kingdom of Saudi Arabia has depended on desalinated water since the 1950s and has since then come to be the major desalinated water producer in the world. As of 2023, 60% of the country's water comes from desalination, with groundwater accounting for less than 40%. As of 2023, the Kingdom of Saudi Arabia had a total of 33 desalination plants in seventeen locations run by the Saline Water Conversion Corporation (SWCC), responsible for approximately 69% of desalination in the Kingdom and 20%of the worldwide desalination capacity [71]. Data on the water desalination per year in Saudi Arabia was sourced from the SWCC [72]. In 2021 a total of 2,154 t of seawater was desalinated in the Kingdom of Saudi Arabia. Assuming a recovery rate of 90%, approximately 5.8 t uranium could have been recovered during seawater desalination that year. Figure 16 provides an overview of the historical uranium recovery potential during water desalination in the Kingdom of Saudi Arabia.

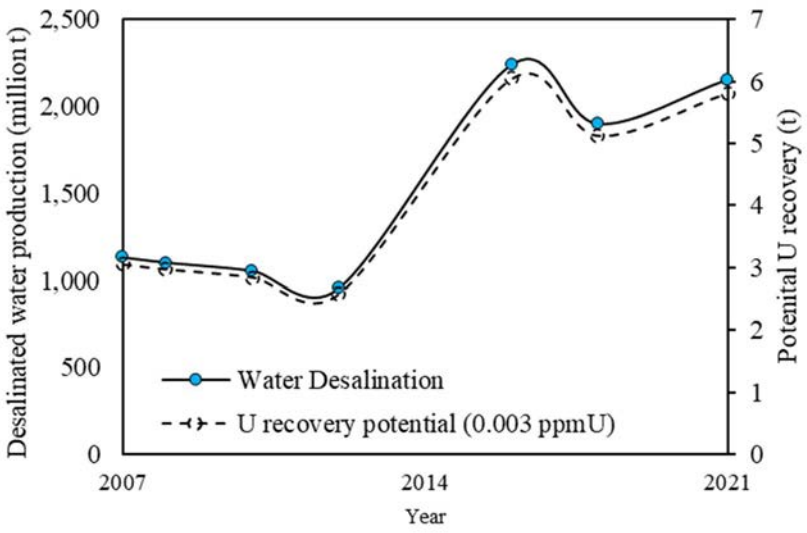

FIG. 16. Historical uranium recovery potential from seawater in Saudi Arabia.

The brief analysis presented here estimates that the Kingdom of Saudi Arabia will after the construction of 15 large commercial NPPS in 2040 have annual natural uranium needs of approximately 3,750 t per year. In addition, another 1,000 t per newly installed reactor unit will be required for the fresh core. This uranium is often provided by the vendor or developer of the NPP. The brief calculation presented here shows that unconventional uranium from phosphate ore production in the Kingdom of Saudi Arabia could have provided between 447-596 t (12-16%) of the projected future natural uranium requirements of the Kingdom. An additional 5.8 t (0.2%) are associated with desalination concentrate in the country. Both phosphate ore production and water desalination are expected to increase in the Kingdom of Saudi Arabia so that the amount of unconventional uranium that can theoretically be recovered with technologies being available today will also increase. Recovering uranium from phosphates and desalination concentrate reduces the environmental risks associated with this radiotoxic heavy metal. Therefore, both phosphate rock and desalination concentrate could be considered as potential uranium resources in the Kingdom of Saudi Arabia, while also reducing environmental risks if the radiotoxic uranium is not recovered and used.

5.5. UNITED REPUBLIC OF TANZANIA

The Minjingu phsphate ore found in the northern part of the United Republic of Tanzania that shows uranium concentrations of approximately 400 mg/kg makes for another relevant case study. This phosphate ore is presently processed using a unique dry process so that if uranium should be recovered, new processes would have to be specifically designed to the needs of the Minjingu processing plant.

Phosphate ores that are used to produce mineral fertilizers can show elevated concentrations of heavy metals of which particularly cadmium has been identified as a potential health risk [73].

Phosphate ores can be of magmatic (or igneous) and sedimentary origin and these ores tend to show very different concentrations of accompanying trace elements. In case of igneous phosphate ores REEs can reach concentrations of 0.2 wt% while the concentrations are usually lower in sedimentary phosphate ores. Globally a REE concentration of approximately 0.05 wt% for phosphate ore is realistic [74] since there are much more sedimentary than igneous

phosphate ore reserves. Uranium can show concentrations of 0.01 to 0.02% in Moroccan phosphate ores [57] that present more than 70% of the currently known reserves [58] while uranium concentrations are usually below 0.005% in phosphate ores of magmatic origin.

Although the concentrations of uranium in phosphate ore can be considered moderate at best, the overall quantities of both REEs and uranium that could theoretically be recovered are relevant given that approximately 220 million t/year, phosphate ore is mined globally. Phosphate ore is among the 5th most mined materials on earth and Hakkar et al. [75] estimated that REEs recovered from phosphate ore mining in Morocco alone could cover 7-15% of global demand. Zhang [76] further shows that the USA could cover its whole demand of REEs if these elements would be recovered during phosphates processing in Florida.

The Minjingu phosphate ore deposit is known for its relatively high concentration of naturally occurring uranium. It was in fact the increased radiation that led to the discovery of the deposit at the edge of Lake Manyara, now a national park and protected area in the northern part of the United Republic of Tanzania, by a South African mining company in 1956 [77].

Minjingu phosphate ore shows natural uranium levels that would also qualify the deposit as a very low-grade uranium ore under the definition of the World Nuclear Association (WNA), and recent reviews on this subject [78, 79] concluded that the uranium concentration in Minjingu can indeed be higher than at commercial uranium mines in Namibia on the other side of the African continent. Since fertilizer is more important for the United Republic of Tanzania's economy than uranium, the ore is mined for its elevated P_2O_5 content (20-25% on average) and not its elevated uranium content (0.03-0.04% on average).

Previously, some 10-15 years ago, Minjingu phosphate ore was after simple beneficiation that included sorting, sieving and rapid drying at 700-800 ˚C applied directly as fine fertilizer powder on agricultural soils in East Africa. The fertilizer produced this way proved to be effective on the acidic soils found in East Africa and the material was considerably less expensive than imported fertilizers from abroad so that it was historically not only used in the United Republic of Tanzania, but also in Kenya, Uganda, Burundi, Zambia, and South Africa. In all these regions similarly, acidic soils can be found.

Fifteen years ago, all fertilizer powders started to be further processed to granules which constituted a tremendous improvement since the fertilizer produced this way can be distributed much better by hand on agricultural soils. Some 10 years ago, the granules were further blended with urea, a source of nitrogen, to produce different kinds of compound fertilizers that show a similar agronomic response than commonly used mineral fertilizers [80].

Nowadays, the fertilizer plant at the Minjingu mine produces some 50 000 t fertilizer per year that are distributed with agro-dealers in Tanzania. The Minjingu Mine and Fertilizer Ltd. intends to double production with a new rotary dryer for mechanical drying of the mined phosphate ore, as well as a larger granulation and blending plant (currently under construction) in the next 1-2 years. Even after the Minjingu fertilizer plant extension, the combined output of 100 000 t fertilizer per year will be far from covering the fertilizer needs of Tanzania that easily exceed 400 000 t per year and might double over the next 5-10 years given the still relatively low crop yields in the country.

Locally produced, Minjingu products are currently heavily subsidized in the United Republic of Tanzania, so that they are largely used in the United Republic of Tanzania with only small quantities leaving the country. In this context, it is noteworthy that agriculture contributes to more than 25% of the GDP of the United Republic of Tanzania and employs around 75% of the labor force in the country. A large ammonia and urea fertilizer plant is currently being constructed in the port town Mtwara in southern Tanzania with the goal to provide more affordable fertilizers to local farmers in East Africa. In addition, there are numerous promising studies on the use of organic fertilizers such as goat manure.

Due to the relatively high uranium concentrations at the Minjingu deposit (0.03-0.04% on average) that is similar to the concentrations found at commercial uranium mining projects, such as the Manyoni Uranium Project (0.011-0.013% uranium) [81] and the Mkuju River Project (0.026% uranium) in the United Republic of Tanzania, an economic case (pull-factor) can also be made for uranium recovery in Minjingu despite the relatively small phosphate ore processing operation of approximately 100 000 t per year. Large WPA units process 2-3 million t phosphate ore per year, and often multiple units make up a whole phosphate fertilizer plant as is for instance the case in Jorf Lasfar (Morocco), the largest WPA complex in the world. Given the average uranium concentration of 0.03-0.04% or 300-400 ppm (parts per million), theoretically 30-40 t uranium could be recovered per year at the Minjingu fertilizer plant, assuming no losses. Given a uranium price of USD 50 per lb U_3O_8, USD 3.9-5.2 million revenue could thus theoretically be generated annually from selling co-recovered uranium during Minjingu fertilizer production.

The amount of co-produced uranium is low in comparison to commercial uranium mines, such as the Mkuju River project in southern Tanzania, that if started as planned, is expected to produce some 1 600 t uranium annually [82]. It is noteworthy though that a potential uranium recovery at the Minjingu fertilizer plant, will ideally result in a cleaner fertilizer product, and does not come with the potential environmental pollution that is presently discussed for in-situ leach (ISL) and open pit uranium mining in Tanzania. It is further noteworthy that due to the ongoing uranium exploration and mining operations, Tanzania already has a regulatory framework for uranium production in place that could ease the way for byproduct uranium recovery at the Minjingu deposit.

The key questions (that are literally worth one million-dollar) is, what are realistic average uranium concentrations? What are realistic uranium recovery rates, do the final fertilizer products still work as effectively as they do now, and are there other valuable minerals, such as REEs present in sufficient concentrations so that they could also be co-extracted and sold as well?

The objective of this case study is to provide an overview of what is presently known about the REEs and uranium concentrations at the Minjingu deposit and discuss current as well as potential alternative processing pathways to answer as many of the previously raised questions as possible.

Radiation measurements can be conducted with relatively simple measurement equipment while the determination of REEs and other trace elements in phosphate ores is more challenging and requires more sophisticated machines (usually inductively coupled plasma mass spectrometry (ICP-MS) is used). It is believed that this, and the fact that REEs are less relevant for the economy of the United Republic of Tanzania, that is largely based on agricultural

products, are the reason that there is a relevant number of studies reporting uranium content and radiation measurements of Minjingu ore, while there are no studies that systematically analyzed the REE content of the ore. There are further considerable differences of the reported uranium content. Interviews with researchers from the Tanzania Atomic Energy Commission (TAEC) that are monitoring the Minjingu mine for more than 20 years and mining engineers of the Minjingu Mining and Fertilizer Ltd. suggest that there is a large difference in the radiation of the Minjingu ore depending on the location and depths at which ore samples were drawn, so that all measurements reported in this literature review, though different, seem indeed to be correct, but simply report on samples taken from different locations of the Minjingu deposit.

Bianconi [83] for instance reported a maximum uranium content of 680 ppm or 0.068% in Minjingu ore when the material was still transferred to the Tanga WPA fertilizer plant for processing. The relatively high uranium concentration (if compared to other phosphate ore deposits) was later confirmed by Meza et al. [84] who analyzed a total of 45 Minjingu phosphate ore samples from different locations and identified a peak uranium concentration of 650 ppm. It is noteworthy that apart from the one sample showing this peak uranium concentration, all other samples were below half that value. To provide wider perspective, it is pertinent to note in this context that the German Commission for the Protection of Soils advocated setting the limit for uranium in fertilizers at 50 mg per kg P_2O_5 in Germany [85] or 167 ppm for fertilizers with a 30% P_2O_5 concentration, despite the fact that there is currently no legal restriction in Germany. In addition to Bianconi's initial evaluation, Mustonen and Annanmaki [86] found a similarly high value for the highest phosphate ore layer of 767 ppm eU (uranium equivalent), whereas lower radiation was observed for the lower phosphate ore layer. Before operations at the Tanga fertilizer factory at the coast halted in the early 1990s, Makweba and Holm [87] examined ground phosphate ore, triple superphosphate and single superphosphate fertilizers, and phosphogypsum produced there. For ground phosphate ore, the authors observed gamma-ray spectrometry values of 408 and 481 ppm eU and alpha-spectrometry concentrations of 337 and 377 ppm eU. These investigations were supplemented by Banzi et al.'s [88] measurements of the activity of phosphate ore, mine tailings, leaf vegetation, cow meat, poultry feed, surface water, and ambient radiation background near the Minjingu mine. The assessment for mine tailings was 4,250 Bq/kg ^{226}Ra and 5,760 Bq/kg ^{226}Ra for phosphate ore. The study looked on local population hazards and exposure mechanisms. After the paper was published, Minjingu's phosphate ore production was briefly stopped, but it soon became obvious that not having access to low-cost local fertilizer cannot be a sustainable solution either.

Another relevant study is the work by Semu and Singh [89] that investigated the long-term accumulation of heavy metals (Cd, Zn, Mn, Cu, Ni, and Pb) in soils and plants after use of Minjingu phosphate rock. The authors did not consider uranium but found that the relatively low levels of cadmium in Minjingu phosphate rock are an advantage compared to other fertilizers that can show higher cadmium concentrations.

More recently, Mwalongo et al. [78] analyzed phosphate ores from Burundi, Kenya, the United Republic of Tanzania, and Uganda, as well as fertilizer products sold in these countries as well as Rwanda. Minjingu phosphate ore was reported to have a uranium content of 446 ppm, and fertilizers produced from Minjingu phosphate ore generally showed the highest concentrations of uranium. Mwalongo et al. [90] then investigated the influence of compound fertilizers with varying uranium content on the radioactivity of tobacco plants in Kenya, the United Republic of Tanzania, and Uganda (all countries are major tobacco producers in East Africa). Uranium concentrations in Minjingu phosphate ore were not reported, but it was reported that Minjingu

phosphate ore products (fertilizers produced with Minjingu phosphate ore) contain relatively high uranium concentrations if compared to other fertilizers, and the tobacco plants grown with these fertilizers also showed slightly higher levels of radioactivity (still within allowed limits) then tobacco plants grown with fertilizers that show lower levels of uranium.

The fact that there is no recent systematic analysis of the present uranium and REEs content in Minjingu ore and related products led to this study that aims to shed light on the unique composition of the Minjingu ore as well as its products and discuss potential cleaner production pathways.

Figure 17 shows a direct comparison between the dry beneficiation process currently used to develop Minjingu phosphate ore (Fig. 17a) and the very different WPA process that is usually deployed to process phosphate ore (Fig. 17b). Globally less than 0.5% of mined phosphate ore is used directly on agricultural soil after simple beneficiation. Both processes are simplified here, and the intention is to indicate how different they are and what the challenges of integrating uranium recovery in a dry phosphate ore beneficiation process might be.

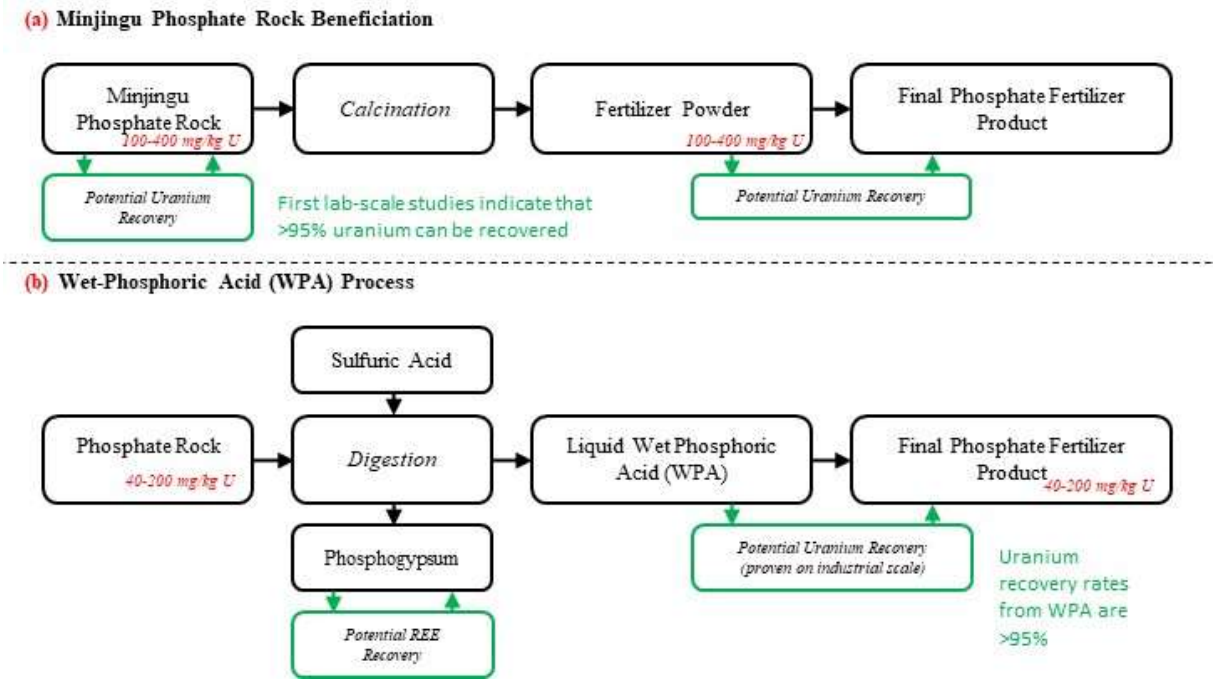

FIG. 17. Comparison of (a) the present Minjingu phosphate rock beneficiation process and (b) the wet phosphoric acid process with sulfuric acid that is commonly used in fertilizer production.

It is unlikely that Minjingu phosphate ore will be processed using the WPA process or another wet-chemical process. The WPA- and by extension other chemical processes require significant amounts of water in addition to sulfuric- or other acids. The Minjingu mine and processing plant is located in a semi-arid region some 550 km away from the closest seaport making the supply of large amounts of water challenging. In addition, using the WPA process results in considerable amounts of fine-powdery phosphogypsum. If phosphate ore with low radiation- and heavy metal concentrations is used to produce fertilizers, the resulting phosphogypsum can be utilized as a secondary raw material in construction or in agriculture. Since the Minjingu ore contains considerable amounts of uranium, this would not be the case so that the overall environmental footprint of any wet-chemical process (even with uranium recovery) will most

likely be significantly larger than that of the current dry beneficiation process (without uranium recovery).

During the WPA process with sulfuric acid (Fig. 17b), uranium can be recovered from the liquid WPA using solvent extraction. This process has been used on industrial scale in the past and has been well-documented.

Minjingu phosphate ore might benefit from alternative dry processing such as electrostatic separation as described by Bittner et al. [91] as well as Sobhy and Tao [92], the improved hard process (IHP) presently under development in Florida or other innovative dry concentration processes that have recently been reviewed by Sajid et al. [93]. It is noteworthy that the present process, though simple in its design, works extremely well. Calcination is energy intensive, so that reducing energy inputs, by introducing solar thermal calcination might be a long term proposition for the Minjingu plant that is located in an area that offers the required high levels of solar radiation.

More importantly, uranium recovery during the processing of Minjingu phosphate ore could make recovery economically profitable. Comparable high concentrations of REEs and other valuable elements could not be confirmed in this work. It is noteworthy, that although the concentrations of the uranium can be considered elevated in the Minjingu ore, the resulting compound fertilizers do not show significantly higher uranium concentrations. Since traditionally uranium is recovered from the liquid WPA during wet chemical processing, new innovative solutions for uranium recovery during Minjingu phosphate ore beneficiation would need to be investigated. Theoretically the uranium could be directly leached from the phosphate ore after primary sieving and sorting before calcination or from the fertilizer powder [94] after calcination.

Abilash et al. [95] and Mäkinen et al. [96] proposed for instance bioleaching of a lower-grade uranium apatite ore in India and Finland. Al-Khaledi et al. [97] and Roshdy et al. [98] propose direct leaching of REEs and uranium from Egyptian phosphate ore and Guzmán et al. [99] were probably the first to propose such an approach for phosphate ores from Mexico with the explicit aim of reducing dissipation of radiotoxic uranium. Gabriel et al. [100] rightfully point out that direct leaching of uranium from phosphates is presently not economically profitable, and this will most likely also be the case at the Minjingu fertilizer plant, given the relatively small size of the operation, as well as still fairly low uranium prices worldwide.

6. SUMMARY AND CONCLUSIONS

Phosphates contain uranium in significant amounts and concentrations; in fact, uranium derived from phosphates is likely the most significant non-mined unconventional uranium resource. Byproduct uranium recovery from these ores is not economical today, despite the fact that the phosphate sector already pays for the majority of the expenditures associated with excavation, infrastructure building, mining, and processing of phosphate ore. The economics of recovering uranium from phosphates depend on a number of circumstances, and as long as uranium prices are relatively low, it is doubtful that this process can be profitable.

Global uranium prices might further increase as a result of geopolitical uncertainties and increased use of NPPs that cannot be supported by the present uranium mining activity alone. It was found that in 2021 commercial uranium mining covered 79% of the world reactor needs with the remainder coming from secondary resources [63]. Presently idle, unprofitable commercial uranium mines might fill this uranium supply gap on a global level. Uranium from phosphates could also play a role supplying additional uranium to the global market or as highlighted in the different case studies to local, national markets. In this case, it is worth noting that the time period of 2-3 years needed to add uranium recovery units to existing WPA fertilizer plants is considerably shorter than the 10-20 years that are usually needed to develop a new mine site.

Uranium supply security and environmental concerns are additional drivers that might lead to uranium recovery from phosphates at selected locations. The case studies and contributions have shown that there is tremendous interest for NPP operating countries as well as embarking countries to own as much of the nuclear fuel cycle as possible. This includes uranium mining as well as processing and could be a driving force for the development of uranium recovery from phosphates in regions that do not have uranium ores. In addition, this work showed that the uranium concentrations in phosphate ores can vary significantly. Since this uranium largely ends up in the final fertilizer products, upcoming regulations on heavy metal limits in fertilizers might create further incentives leading to increased interest in uranium recovery from phosphates.

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LIST OF ABBREVIATIONS

AB	Alberta
ADU	Ammonium diuranate
AUT	Ammonium uranyl tricarbonate
BNPP	Bataan Nuclear Power Plant
CANDU	Canada deuterium uranium
DEPA/TOPO	Bis(2-ethylhexyl) phosphoric acid Tri-n-octylphosphine oxide
EU	European Union
FL	Florida
FOB	Free on board
IAEA	International Atomic Energy Agency
ICP-MS	Inductively coupled plasma mass spectrometry
IL	Illinois
K.A.CARE	King Abdullah City for Atomic and Renewable Energy
KNPP	Krško Nuclear Power Plant
LA	Louisiana
NEP-IAC	Nuclear Energy Program Inter-Agency Committee
NPP	Nuclear power plant
OPAP	Octylphenyl acid phosphate
OPEX	Operational expenditures
OPPA	Dioctylpyrophosphoric acid
ORNL	Oak Ridge National Laboratory
P	phosphorus
P_2O_5	Phosphorus pentoxide
PHWR	Pressurized heavy water reactor
PNRI	Philippine Nuclear Research Institute
PPB	part per billion
PPM	part per million
PWR	Pressurized water reactor
REE	Rare earth element
SEU	Slightly enriched uranium
SWCC	Saline Water Conversion Corporation

t	metric tonne
TAEC	Tanzania Atomic Energy Commission
TBP	Tri-n-butyl-phosphate
TX	Texas
U	uranium
USA	United States of America
USD	United States of America dollar
WPA	Wet process phosphoric acid

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Consultancy Meeting

Vienna, Austria: 4–28 May 2021

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