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# Overview of naturally occurring radioactive materials (NORM) in mineral processing industries and consideration of ionising radiation in life cycle assessment (LCA) – PART II. NORM impact assessment

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## Abstract

This work provides an overview of issues related to naturally occurring radioactive materials (NORM) in mineral processing industries across European countries, including the production of phosphoric acid and phosphate fertilisers, titanium dioxide (TiO<sub>2</sub>), zircon and zirconium, and cement production industries. The study examines the impact of NORM from these industries on radiation exposure to workers, the public, and the environment. Relevant exposure scenarios are analysed, and effective radiation doses are evaluated. Potential treatments and final destinations of NORM residues are considered, with special attention to their possible valorisation and reuse. The aim of this work is to enhance overall knowledge of radiation protection in mineral processing industries, support the management of NORM-containing residues and waste, and assist regulatory decision-making. This is particularly important within the framework of Life Cycle Assessment (LCA) and the circular economy, which emphasizes optimal resource use, reduction of raw material extraction, waste minimization, and product life cycle extension. Current residues may be valorised as raw materials for future industrial applications. In such an economic strategy, the environmental impact of NORM and potential risks to the public can be significantly reduced—or even eliminated—at certain stages of the product life cycle. However, potential radiation exposure must always be considered. Therefore, further development of the LCA approach for NORM is important and requires substantial effort. An initial evaluation of the case of phosphoric acid production in the context of LCA is presented in this paper as an example of the broader development work needed in this area.

**Keywords** Natural radionuclides · NORM · Mineral processing industries · Radiological impact assessment · LCA · Impact category ionising radiation

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## Introduction

Naturally occurring radioactive material (NORM) contains no radionuclides other than those already present in nature from the Earth's origin, such as primordial radionuclides  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and their radioactive decay products, and  $^{40}\text{K}$ , which are usually referred to as naturally occurring radionuclides (NOR). Materials in which the activity concentrations of NOR can be altered as a result of technological processes or other human activities are also included under the term NORM (IAEA 2022; ICRP 2019).

Many industries, including mineral processing industries, which are the subjects of this study, process raw materials containing NOR in a wide range of activity concentrations. This results in various NORM matrices in the form of products, by-products, residues, wastes, liquid effluents, and atmospheric discharges. The presence of NORM may increase exposure to ionising radiation, and therefore, pose potential health risks to workers, the public and the environment.

Within the context of a zero-waste economy, interest is increasing in analysing the recovery of by-products or residues from industries involving NORM. This expands the scope of applying Life-Cycle Assessment (LCA) to NORM. Information collected on waste management routes can serve both as an early warning of risks associated with the use of secondary raw materials or, on the contrary, increase confidence in NORM residue use, with respect to industry operators, regulators, and the public alike. The “*New Circular Economy Action Plan*” (EC 2020) emphasises that, in order to increase confidence in the use of secondary raw materials, important aspects are (a) “*to develop methodologies to minimise the presence of substances that pose problems to health or the environment in recycled materials and articles made thereof*”, and, (b) “*to co-operate with industry to progressively develop harmonised systems to track and manage information on substances identified as being of very high concern and other relevant substances...*”. In the context of NORM involving industries, such initiatives are most pertinent to the stages involving the use of raw materials and the subsequent management of residues and wastes, where potential exposure and environmental risks must be carefully controlled.

The present study investigated the potential impacts of NORM in mineral processing industries. It extends the scope of the previous work, where NORM identification methodology and data collection tools were developed (Michalik et al. 2023; Mrdakovic Popic et al. 2023a) and NORM inventory in mineral processing industries, across different stages of industrial processes (raw materials, main products, residues, wastes), were evaluated and established (Dvorzhak et al. 2025). All activities were conducted within

the framework of the European RadoNorm research project (Kulka et al. 2022).

The main objectives of this study were to:

- assess existing radioactive hazards in relevant exposure scenarios in selected industries - phosphoric acid production, phosphate fertilisers production,  $\text{TiO}_2$  pigment production, zircon and zirconium industry and cement production;
- analyse waste features from mineral processing industries and their possible involvement in a product life cycle;
- present an evaluation of LCA applied to NORM involving industry, using phosphoric acid production as a case study. This example is limited only to consideration of RadoNorm project gathered NORM data, complemented with data relevant for other impact categories, such as trace metals,  $\text{CO}_2$ ,  $\text{SO}_2$  emissions and energy use from peer-reviewed literature sources.

Integrating ionising radiation into LCA is of significance for a successful circular economy. This holistic approach expands on classical radiation protection (RP) by evaluating the cumulative impacts—both radiological and conventional (e.g., climate change, toxicity, resource use)—across a material's entire circular lifecycle. Crucially, its comparative power enables the selection of materials and processes with the minimum overall health and environmental footprint. LCA is foreseen to be essential, particularly in light of the constant introduction of new products and materials including NORM residues, for which the full, long-term lifecycle impacts are not always immediately apparent at the point of market entry (Paulillo et al. 2018). LCA is therefore expected to serve as a valuable decision-making tool in today's rapidly evolving context of novel materials and complex cross-border supply chains. While EU product-safety and RP legislative frameworks (e.g., GPSR (EC, IAEA, 2024) and the EU BSS (EC 2014) provide robust protection, LCA offers additional value by, as above-mentioned, enabling comparison of radiological and non-radiological impacts across entire life cycles. In this way, LCA does not replace RP methodologies, but complements and strengthens them within a broader, sustainable and holistic assessment framework. This perspective is particularly relevant in cases such as the use of NORM by-products in construction, where multi-stage mineral supply chains are involved. Early, system-wide evidence can inform regulators and industry decision-makers at the design stage, supporting safer and more sustainable choices.

In line with the study's objectives, our findings are expected to support countries at different stages of NORM management and RP regulatory control.

## Materials and methods

The data analysed in this study were collected within the RadoNorm project, during the period 2022–2024 using:

- the developed identification methodology for NORM exposure situations (Michalik et al. 2023);
- the tools for harmonized data collection (Mrdakovic Popic et al. 2023a);
- the e-NORM survey conducted in European countries (Mrdakovic Popic et al. 2023b).

The main data for mineral processing industries evaluated in this study were collected from Belgium, Finland, France, Italy, Norway, Poland and Spain, which directly participated in the RadoNorm project. These data were further compared with data from other European countries obtained through the e-NORM survey (Mrdakovic Popic et al. 2023b). An inventory of NORM in selected mineral processing industries is presented in Dvorzhak et al. (2025).

All data sets were collected by systematised tools, as mentioned above; however, to ensure reliability, before any joint data analysis, they underwent a quality control procedure. This included checking different criteria, such as methodological consistency with respect to analytical and dose calculation methodology. For analytical methodology, common criteria were used – methods applied, performance characteristics, uncertainty analysis, etc. For dose assessments – a review of the exposure scenarios and pathways described was done, including an examination of the assumptions and degree of conservatism applied in the national assessments – specifically the parameters considered in particular scenarios and pathways (e.g., radionuclides of concern, their activity concentration in NORM matrices, information about exposure time, dust levels, uncertainty level, and use of occupational, health and safety (OHS) and RP measures). Additionally, the consistency of reported values across industries was evaluated.

**Uncertainties:** The level of available details varied between countries: in some cases, complete methodological descriptions were available, while in others, only partial information was provided. In the latter case, this was noted as a limitation of the dataset and either mentioned in this paper or the affected data were excluded from further analysis.

Because results were nationally reported in different forms (e.g., maximum, minimum, mean values), after validation, the pooled data were presented either as ranges (where possible) or as mean values. Although the authors believe that a good structured framework for data collection, checking and analysis was ensured, we highlight the uncertainty associated with this kind of data presentation, as it

may affect direct country-to-country comparisons or the identification of trends.

## Potential radiation exposure of workers, the public and the environment due to mineral processing industries

Reported national assessments of potential doses to workers, members of the public, and the environment, based on the investigated mineral processing industries and various exposure scenarios, are presented in the following sections.

### Potential exposure of workers to NORM

Workers in the industrial processes involving NORM can be occupationally exposed to radiation. The exposures can generally (though not always) be considered moderate, as proper OHS measures, already implemented within the workplace to safeguard workers from other non-radiological hazards, may offer a degree of protection against radiological hazards as well (IAEA 2006).

In Table 1, the considered exposure scenarios, exposure pathways and total effective doses for workers are presented for the investigated industries.

In the *phosphoric acid production*, using the wet technological process, the effective doses to workers were reported in our data for scenarios (a) processing of rock raw material in milling area, and (b) loading of materials. In both scenarios, exposure to external radiation was considered the main exposure pathway. The effective doses due to external gamma irradiation were calculated to be in the low range of 0.30 to 0.62 mSv/year. The evaluated scenarios included conservative working time estimations and application of standard Personal Protective Equipment (PPE), such as FFP2/FFP3 masks, gloves, and protective clothing.

There was limited quantitative national data available on potential doses due to inhalation and ingestion of airborne dust, or inhalation of radon (Rn) and its progeny. However, based on qualitative information about the proper use of OHS measures in daily activities, it was suggested that eventual effective doses from these exposure pathways would be negligible. Similarly, in the IAEA Safety Report no.78 (IAEA 2013), for the wet process of phosphoric acid production facilities, handling of raw materials is considered one of the most critical exposure scenario, together with cleaning and maintaining the filter systems, where radium (Ra) rich scales are concentrated, while airborne dust inhalation does not appear to be of significant concern. The nationally reported effective doses to workers in this study, below 1 mSv/year, confirmed previous international findings (Attar et al. 2011; Akfas et al. 2024; Bolívar et

**Table 1** Occupational exposure pathways and doses for selected exposure scenarios (mSv/year)

Exposure scenario	Exposure pathways	Comments	Annual effective dose RadoNorm project (mSv/year)	Annual effective dose from published reports (mSv/year)
<b>Phosphoric acid production</b>				
Processing of phosphate rock in the milling area	External gamma exposure	Maximum NOR activity concentration in rock considered	0.01- 0.30	0.1- 0.4 (IAEA,2013)
	Inhalation, ingestion of dust, and Rn and Rn-progeny inhalation not considered	Real-life occupancy factor PPE and ventilation used Background dose not reduced		
Material loading	External gamma exposure	Maximum NOR activity concentration in rock considered Conservative occupancy factor	0.02 -0.62	
	Inhalation, ingestion of dust and Rn and Rn-progeny inhalation not considered	PPE and ventilation applied Background dose not reduced		
<i>Phosphate fertilizers</i>				
Material loading and cleaning of the areas	External gamma exposure	Maximum NOR activity concentration considered Conservative occupancy factor	0.20 - 0.69	0.15 - 0.7 (IAEA, 2013)
	Inhalation, ingestion of dust and Rn and Rn-progeny inhalation not considered	PPE applied Background dose not reduced		
Routine production activities	External gamma exposure	Real-life occupancy factor PPE and ventilation used	Negligible, close to 0	
	Inhalation, ingestion of dust and Rn and Rn-progeny inhalation not considered	RP dosimeters used Background dose not reduced		
Maintenance	External gamma exposure	Maximum NOR activity concentration in relevant NORM considered Real-life occupancy factor	Negligible, close to 0	
	Inhalation, Ingestion of dust, Rn and Rn-progeny inhalation not considered	PPE and ventilation used RP dosimeters used Background dose not reduced.		
Unloading of raw material Transportation	External gamma exposure	Maximum NOR activity concentration Real-life occupancy factor	0-0.01	
	Inhalation of dust and resuspended particles considered Rn and Rn-progeny inhalation not considered	OHS measures applied Background dose not reduced		
RP 122, part II and tailor-made scenarios	Pathways considered: External gamma exposure Inhalation, Ingestion of dust, Rn and Rn-progeny inhalation not considered	Considered parameters provided in RP 122, Part II (EC, 2001)	0.36	
Specific assessment from the operator (tailor-made)	External gamma exposure	Maximum NOR activity concentration	Dose due to External exposure: 0.094 Dose due to Inhalation: 0.244	
	Inhalation of dust and resuspended particles	Conservative occupancy factor	Dose due to Rn and Rn progeny Inhalation: 0.023	
	Inhalation of Rn and Rn-progeny	No OHS applied	Total effective dose: 0.36	
<b>Zircon and zirconium industry</b>				
Routine production activities in refractory industry	External gamma exposure Inhalation of dust and resuspended particles	Real-life exposure scenario with real-life occupancy factor	0.28 - 2.0	0.05-0.2 (IAEA, 2007)

**Table 1** (continued)

Exposure scenario	Exposure pathways	Comments	Annual effective dose RadoNorm project (mSv/year)	Annual effective dose from published reports (mSv/year)
Sanitary ware production	External gamma exposure Inhalation of dust and resuspended particles	No PPE applied,	<0.01	<0.08 (IAEA, 2007)
Tiles and stone-ware production	External gamma exposure Inhalation of dust and resuspended particles	Background dose reduced	0.05 - 1.3	0.01-0.48 (IAEA, 2007)
<i>Cement production</i>				
Routine production activities	External gamma exposure Inhalation of dust and resuspended particles	Real-life occupancy factor OHS and RP applied	Negligible, close to 0	
Cement kilns services	External gamma exposure  Inhalation of Rn and Rn progeny	Maximum NOR concentration  Maximum occupancy factor No OHS and RP measures applied	External gamma dose: 0.044 Rn and Rn progeny inhalation dose: 0.1 Total effective dose: 0.14	
<i>TiO<sub>2</sub> pigment production</i>				
Routine production activities	External gamma exposure  Inhalation of dust and resuspended particles	Maximum NOR activity concentrations Conservative occupancy factor No PPE applied Background not reduced	0.02- 2.0	<0.01–1.35 mSv (IAEA, 2012) (effective dose values higher than 1 mSv/year are evaluated for workers involved in maintenance and decontamination of equipment without respiratory protection; if respiratory protections are worn, effective doses do not exceed 1 mSv/year)
Sandblasting	External gamma exposure Inhalation of dust and resuspended particles	Conservative occupancy factor Respiratory mask applied (calculated efficiency 50 %) Background reduced	0.035	
Transportation	External gamma exposure	Conservative occupancy factor Background reduced	0.03	
Waste treatment	External gamma exposure	Conservative occupancy factor Respiratory mask applied (calculated efficiency 50 %) Background reduced	0.08	
Fixing the load	External gamma exposure	Conservative occupancy factor Respiratory mask applied (calculated efficiency 50 %) Background reduced	0.01	
Processing of raw material	External gamma exposure  Inhalation of dust and resuspended particles	Conservative occupancy factor  Respiratory mask applied (calculated efficiency 50 %) Background reduced	Dose due to external gamma exposure: 0.1 Dose due to Inhalation (excluding <sup>222</sup> Rn): 0.005 Total effective dose: 0.11	
Maintenance: replacement of filters, electro filters	External gamma exposure  Inhalation of dust and resuspended particles	Conservative occupancy factor  Respiratory mask applied (calculated efficiency 50 %) Background reduced	Dose due to external gamma exposure: 0.25 Dose due to Inhalation (excluding <sup>222</sup> Rn): 0.005 Total effective dose: 0.26	
Management of unattached sludge inside the factory	External gamma exposure	Conservative occupancy factor OHS and RP measures applied Background reduced	0.1	

al. 2009; CSN 2011, 2012; Guerrero-Márquez et al. 2017; IAEA 2013).

In the *phosphate fertilisers production industry*, reported worker exposure scenarios included (a) loading and unloading of raw materials, (b) routine operation of processing equipment, (c) maintenance and repair activities including cleaning of facilities and filter systems, (d) handling and transport of NORM-containing feedstocks and NORM residues, (e) handling, storage and disposal of residues, and (f) other site-specific or tailor-made operational tasks. In addition, RP 122, Part II (EC 2001) remains widely applied across many facilities and countries. Workers were reported to be exposed to external gamma radiation in all the above-mentioned exposure scenarios, and to inhalation of dust and particulate matter in some of reported scenarios, while other pathways, such as NORM ingestion and inhalation of Rn and its progeny, were reported as being considered in those countries where scenarios from EU publication RP 122, part II (EC 2001) have still been used, or in certain case studies for particular investigated facilities. In the IAEA Safety Report no. 78 (IAEA 2013), for the production of phosphate fertilisers, dust inhalation is considered as a significant pathway of exposure, since the production process generally generates a large quantity of dust that can easily be inhaled by workers involved in sampling, cleaning and handling materials manually.

The effective doses to workers, supplemented with specific details on diverse exposure scenarios and assumptions used are given in Table 1. The highest reported effective dose was 0.69 mSv/year, due to external gamma exposure only, in a conservative scenario with maximal activity concentrations in raw materials used as parameters and maximal occupancy factor, but also with reported proper use of PPE. Most of the countries included in this investigation reported the use of protection measures against non-radioactive hazards (e.g., ventilation and specific respiratory masks, gloves, glasses, limitation of working time-contact with material), which were generally sufficient to protect against radiation exposure, regarding exposure pathways of inhalation and ingestion of dust,  $^{222}\text{Rn}$  and  $^{222}\text{Rn}$  progeny. Still, when no standard OHS measures are in place, the dose magnitudes per pathway can be different, i.e., the contribution from inhalation and ingestion should not be neglected. For instance, the tailor-made, specific assessment carried out in this investigation with conservatively assuming no PPE application throughout the whole process – reported workers effective doses 0.094 mSv/year, 0.244 mSv/year and 0.023 mSv/year due to external gamma exposure, inhalation of dust, and inhalation of  $^{222}\text{Rn}$  and its progeny, respectively.

Comparable to our findings, both somewhat lower and higher results were reported in the past (Bolívar and

García-Tenorio, 2015; IAEA 2013; Mulas et al. 2016), showing that depending on the real-case scenarios characteristics – different exposure pathways can be relevant, and as such, need to be specifically considered.

In the context of *refractory and ceramic ware manufacturing*, the most relevant exposure scenarios encompass (a) raw materials and residues transport, (b) exposure to heaps, and (c) landfill disposal, as discussed in detail in the RP 122, part II (EC 2001). For *refractories*, reported dose estimates for the production process generally ranged from 0.28 to 2.0 mSv/year. The most relevant identified exposure pathways are external radiation and dust inhalation. The values under consideration are significantly higher than those reported in the IAEA reference document (IAEA 2007), where the contribution relating to the inhalation of furnace dust was the more significant. From the RadoNorm project data, external radiation resulting from operations carried out by workers in close proximity to refractory products, such as cutting and finishing operations, also appears significant. For the *ceramics ware manufacturing*, annual effective doses associated with *tiles and stoneware* production process were in the range from 0.05 to 1.3 mSv/year, with upper range values above the previously reported range of <0.01–0.5 mSv/year (IAEA 2007). In production of *sanitary ware*, very low dose values, <0.01 mSv/year were found, what was in accordance with values reported by Righi et al. 2009 and with the lower end of the range <0.01–0.09 mSv/year, reported in IAEA (2007). Notably, the maximum doses found in this study for *both refractories and ceramic ware* (above 1 mSv/year) were higher than those reported in the literature (IAEA 2007). The known uncertainty in the dose evaluation was related to inhalation exposure, as it was not always specified whether the dose was assessed in the presence of PPE or not.

For the *cement industry*, data collected in the current study as well as published in European literature concerning occupational exposure were scarce; most of the available literature data originated from countries outside Europe. High dust concentration, often present during the various handling processes, including (a) transportation, (b) storage, (c) crushing, and (d) grinding of raw materials in cement-producing factories, were found to be important exposure scenarios in the occupational radiation exposure. Moreover, the high-temperature conditions in kilns can promote the buildup of NORM bearing scales on internal surfaces, while radionuclide  $^{210}\text{Pb}$  can also accumulate in thin films on the refractory linings inside a kiln. During maintenance activities (e.g., cleaning, inspection, reparation), exposure doses can be elevated due to dust inhalation or direct skin contact (although rarely when using PPE). Reported levels of exposure to dust were comparable to 1.0 mg/m<sup>3</sup> of respirable dust and 3.7–5.4 mg/m<sup>3</sup> of total dust. Although

no firm conclusions can be drawn, recent studies reported a dose-response relationship between cement production dust exposure and declining lung function, indicating a causal relationship, and generally underlining the need to control exposure among workers in this industry (Fell and Nordby 2017). From a RP perspective, assuming the above given dust concentration and composition with low NOR activity concentration gathered from the data in the current investigation, the committed dose was negligible, not exceeding a few  $\mu\text{Sv}/\text{year}$ . In cement kiln related activities, exposure pathways - external gamma dose and inhalation of Rn and its progeny - could lead to low total annual effective doses of 0.044 mSv. Our data further showed that radiation exposure due to the use of coal combustion products (CCP) in cement production is commonly limited and of no concern across European countries, although the main source of potential exposure - Rn and Rn-progeny inhalation - should be assessed.

Still, there were internationally reported examples of specific exposure scenarios where the received worker doses were calculated as elevated. For instance, a regular worker in a storage area with CCP (whose NOR activity concentrations were measured as 417, 156 and 454 Bq/kg for  $^{226}\text{Ra}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$ , respectively) could receive a total effective dose greater than 3 mSv/year (Turhan and Jamasali 2024). When reporting this, the authors of the current study emphasized, however, that for the limited available scientific literature on occupational exposure - the performed evaluations did not always meet relevant quality assurance, as no specific characterization of workplaces was used and significant overestimation of real exposure could be assumed, as also reported by Aslam et al. (2012) and Mubarak et al. (2021). Notwithstanding these issues, all reported values (from the given study and previously published literature) were comparable to the worldwide data reported in UNSCEAR publications (UNSCEAR 2000, 2008, 2020/2021).

For the ***TiO<sub>2</sub> pigment production industry***, doses ranging from 0.01 to 2.0 mSv/year were reported, depending on the selected scenario, dose rates, production operation and occupancy period. Regarding specific exposure scenarios, there was available information that the annual effective dose, received by a worker, might exceed 1 mSv during operations related to hydrolysis, when using ilmenite as feedstock. In that case, restrictions on access to the hydrolysis area and control of occupancy periods were necessary to ensure protection, as also recommended by IAEA (2012). Workers responsible for maintenance work, including the removal of scales (that may have elevated NOR activity concentration), commonly use special dosimetric and chemical monitoring and apply proper OHS and RP measures to ensure occupational doses below 1mSv/year. One of such examples from the literature was a sludge park where measured external

dose rates were up to 0.5–0.6  $\mu\text{Sv}/\text{h}$  (García-Tenorio 2012), which, with the occupational factor of less than 200 h/year, resulted in an occupational dose of the order of 0.1 mSv/year. Regardless that even high gamma dose rates noticed in some cases, up to 90  $\mu\text{Sv}/\text{h}$  (McNulty 2008), effective doses received by workers, usually were below 1 mSv/year, considering different technological process (sulphate or chloride) applied and related exposure scenarios, e.g., for workers in charge of handling and management of unattached sludge or scales (García-Tenorio 2012; Gázquez et al. 2021a; McNulty 2008). Another important dose contribution reported, but commonly considered separately, was high  $^{222}\text{Rn}$  concentrations that could be measured in crystallizers with open doors (about 1000 Bq/m<sup>3</sup>). Thus, forced ventilation during the maintenance operations is needed to reduce Rn concentration to the acceptable reference value given by the EU BSS (EC 2014) for working places.

In summary, findings from the current study of mineral processing industries involving NORM showed that the external exposure to gamma radiation and the inhalation of dust containing NOR were the main exposure pathways, with the former being the dominantly reported. Still, the occupational doses were mostly low, up to 0.69 mSv/year for reported and analysed exposure routes. The exception were effective doses reported for workers in the refractories, ceramic ware and in TiO<sub>2</sub> production, which were 2.0, 1.3 and 2.0 mSv/year, respectively, all higher than the general dose criterion of 1 mSv/year for exemption from notification, set in the EU BSS (EC 2014).

### Possible underestimation of effective dose from NORM containing dust

The reported values in this work are mainly related to external exposure. Internal exposure, although also considered an important exposure pathway in this type of industries, was in practice less reported, with missing details concerning the evaluation method. That is why for the investigated mineral processing industries, the simulation of potential committed effective doses was performed (Table 2; Fig. 1).

Although the effective inhalation doses reported in the literature for NORM industries are generally low, it is worth noting that such estimates are often based on typical dust concentrations in the range of 1–2 mg/m<sup>3</sup>, as indicated, for example, in RP 122 report (EC 2001). Nevertheless, the OHS system, which must be implemented irrespective of RP measures in mineral processing industries, establishes Maximum Allowable Concentrations (MAC) that are considerably higher (used in the simulation), as illustrated in Table 2.

The observed discrepancy between dust concentration levels used for dose estimation purposes suggests the

possibility of an underestimation of the potential inhalation risk. In fact, assuming that OHS regulations are followed, the most conservative exposure scenario was defined by relevant MAC, normative working time of 1800 h per year, breathing rate of 1.3 m<sup>3</sup> per hour, and absence of PPE. Then, assuming NOR's most radiotoxic speciation, with all radionuclides in a secular equilibrium state and an activity concentration at the exemption level – 1 kBq/kg (EU BSS, EC 2014), the effective committed doses were calculated. The results are presented in the Fig. 1 for MAC of dust type expected in industries of interest and for the normative grain size of the respirable dust fraction.

In each case, the exemption level expressed in terms of effective dose significantly exceeded 1 mSv/year. For this reason, a graded approach for the assessment of inhalation dose is highly recommended, as follows. Firstly, it is important to note that the conservative phase should be based on MAC values (Table 2), assuming exposure for the full working duration and in the absence of PPE. Should the preliminary assessment indicate estimates in excess of 1 mSv/year, a more in-depth analysis will be required. The second, more realistic phase should account for the actual use of PPE (e.g., a mask with a typical 50% efficiency) and, most importantly, be based on direct, site-specific measurements of dustiness. It is reasonable to assume a conservative mask efficiency of 50%, rather than the theoretical efficiency (which is generally higher than 80%), in order to account for uncertainty regarding proper use or maintenance by the workers. This two-step approach is consistent with the most recent scientific literature. For instance, a study by Hewson et al. (2025) on mineral industries in Western Australia demonstrated that standard sampling protocols can lead to a dose underestimation by a factor of two or more. This highlights the importance of using site-specific and realistic parameters instead of default assumptions (Hewson et al. 2025).

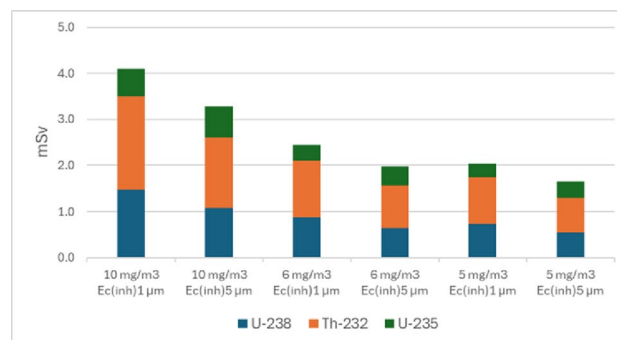
With the real-life data and simulations presented in this section, the authors aimed to emphasize the importance of understanding case- or scenario-specific conditions, as well as the importance of graded approach starting with a conservative screening.

### Potential exposure of public and non-human biota to NORM

Information about possible exposure scenarios and corresponding effective doses for the public related to each mineral processing industry was collected. Different exposure pathways were considered, including external gamma irradiation from deposited radionuclides, external gamma irradiation from immersion in air contaminated by radionuclides, inhalation of NOR contaminated air, and ingestion of soil

**Table 2** Dust type and MAC values considered for discussed industrial sectors (EC 2017)

Dust type	MAC (mg/m <sup>3</sup> )
Apatite and phosphate rocks' dust containing free crystalline silica below 2%	6
Portland and metallurgical cement dusts	6
Gypsum dusts containing less than 2% free crystalline silica and not containing asbestos	10
Titanium dioxide dusts containing free crystalline silica below 2% and not containing asbestos	10
Zirconium and zirconium compounds dusts	5



**Fig. 1** Effective committed dose evaluated for different MAC assuming most conservative exposure scenario

and food products contaminated by NORM. The most common NORM exposure scenarios included (a) people living close to installations involving NORM and being affected by their atmospheric and/or liquid discharges, as well as (b) those living in the vicinity of NORM residues disposed of in landfills. Public exposure caused by (c) the use of NORM containing products is also considered in relation to the final fate of NORM in the context of possible LCA development. In general, the provided dose estimations across European countries showed relatively low effective doses for the public in all considered scenarios.

For the *phosphoric acid and phosphate fertilisers industry*, the reported estimated doses were in the range of 0.04–0.21 mSv/year. For the phosphate industry, the exposure of members of the public, irrespective of the exposure pathway involved, was likely to be low because mining and beneficiation operations are typically conducted at considerable distances from residential areas and involved materials with low activity concentrations, as also noted by IAEA (2013). In many cases, the public impact was associated more with NORM residues and wastes management, such as, for example, phosphogypsum (PG) stacks. In the Spanish case of Huelva, the radiological impact on the members of the public associated with the radioactive pollution of the Huelva estuary and the presence of the PG piles was shown to be limited—lower than 0.02 mSv/year adopting conservative assumptions for this estimation (Matarranz 2013). In

Norway, in case of phosphate fertilisers production, effective doses to public due to NORM atmospheric discharge were found to be in a range 0.02–0.04 mSv/year (for two separate facilities) – with  $^{210}\text{Po}$  being the main radionuclide dose contributor, and the exposures pathway of ingestion of contaminated food stuff (berries) being of the highest importance (DSA, Norway, *personal communication*, 2025).

The data on public dose assessments for the ***zircon and zirconium industries*** were provided for scenarios of radionuclide dispersion in atmospheric and liquid effluents. In general, the assessments showed relatively low doses, of about 0.02 mSv/year, in line with published data (IAEA 2007; UNSCEAR 2008). In some cases, the dose estimates for the population living near refractory facilities were about 0.5 mSv/year, with a contribution of 0.16 mSv/year from external gamma irradiation and 0.34 mSv/year from dust inhalation, excluding  $^{222}\text{Rn}$ .

For the ***refractories industry***, the impact from the release of NOR-containing dust to the atmosphere and from the release of NOR in wastewater was assessed, giving effective doses of about 0.004 mSv/year for both scenarios. For the ***ceramic ware industry***, the reported dose estimation for the population living 500 m from the emission point was approximately 0.02 mSv/year.

For the ***cement industry***, no effective dose data based on the impact of the cement production industry, in terms of impact of emissions from kiln chimney or wastewater, were available in the current study. One of the few studies available in the literature on this subject was that by Kunze et al. (2018). In this study, the authors employed modelling tools based on a generic approach to estimate the annual effective dose due to the emission of airborne effluents containing  $^{210}\text{Pb}$  and  $^{210}\text{Po}$  into the atmosphere by the industrial sectors listed in Annex VI of the EU BSS (EC 2014). It was determined that the most significant exposure pathway was dust settling on agricultural products and the subsequent consumption chain from the mother to infants (age < 1 year). For the cement production industry, the annual effective dose in infants was found to be approximately 0.03 mSv/year. Data concerning public exposure from the use of cement in construction were reported. It was observed that cement itself did not pose a significant radiological hazard when used for building construction, as previously reported by El-Taher et al. (2010).

The doses for members of the public due to ***TiO<sub>2</sub> pigment production*** provided in this study were low, up to 0.1 mSv/year. As an illustration, process of atmospheric emissions of NOR from TiO<sub>2</sub> production facility was reported, analysed and modelled in Norway (DSA, Norway, *personal*

*communication*, 2025). The effective dose to public was found to be low, 0.0014 mSv/year due to gaseous discharge from TiO<sub>2</sub> facility, with external irradiation being the main dose contributor (66% contribution to the dose) followed by the inhalation of contaminated airborne dust (34%). The main radionuclide dose contributor was found to be  $^{226}\text{Ra}$ . This information is in good agreement with data reported by IAEA (2012), which also stated that exposure of members of the public is minimal. Other documents confirmed that the radiological impact on the members of the public caused by activities associated with the production of TiO<sub>2</sub> pigments and by-products, as well as the management of derived waste, was low, even close to zero (CSN 2010). Apart from the negligible radiation hazards, other works highlighted the possible toxic effects of TiO<sub>2</sub> particles (Ayorinde 2023), and the assumption that protective measures for hazardous elements other than radioactive ones (e.g., new-generation high-efficiency filters, methods for liquid discharge cleaning and filtration before discharge, etc.) also ensure radiation safety for the public.

Regarding environmental impacts, only limited RadoNorm information was available on NORM discharges and effluents and possible exposure of non-human biota due to NORM from mineral processing industries across European countries. According to OSPAR (2024), reported discharges from primary steel manufacturing, TiO<sub>2</sub> pigment manufacture, and phosphate industry were low, and none of these sub-sectors made a significant contribution to the overall discharges of total alpha, total beta, or tritium.

In Norway, there are legislative requirements to assess the potential impact of NORM (alongside other hazardous radioactive and non-radioactive elements) on non-human biota and environment *per se*, to consider protective requirements and implement relevant measures where necessary (Pollution Control and Act 2010; and related RP regulations). In the recent study on possible exposure dose rates to non-human biota due to NORM atmospheric discharge from four selected mineral processing industries in Norway (DSA, *personal communication*, 2025), the maximum weighted absorbed dose rates were modelled with site-specific data to values between 1 and 3  $\mu\text{Gy/h}$  for the most highly exposed organisms, lichen and bryophytes. The values were below the ERICA screening benchmark of 10  $\mu\text{Gy/h}$  (Brown et al. 2008) and the UNSCEAR (2000) benchmark dose rate of 40  $\mu\text{Gy/h}$ . Even accounting for uncertainties in dose rate non-human biota calculations, which can be related to both qualitative assumptions and modelling, the maximum dose rates remained far below any level that could conceivably be considered detrimental.

## NORM generated by mineral processing industries and their management

Investigated mineral processing industries generate NORM residues and wastes. In accordance with the principles of the circular economy, it is important to reduce waste and recycle or reuse residues to create new products. Therefore, knowledge about the type of residues and waste generated, their quantity, and NOR content is important for both recovery and for disposal (depending on the case). In this study, these issues were also analysed for the five above-mentioned industries, residues and their management routes, including disposal options (Table 3). The efficient management of residues and waste disposal are essential for any industry affected by NORM. Differences in approaches across Europe regarding the reuse of NORM residues and categorisation, handling and disposal of NORM waste are also noted by García-Talavera et al. (2021) and Gellerman et al. (2023).

In the case of *phosphoric acid* production and the *phosphate fertilisers industry*, a large part of the residues, such as PG, liquid and solid sludges, scales, contaminated water, filters, and others, was reported as commonly stored in PG stacks, waste dams or specific landfills, which was in accordance with observations of Akfas et al. (2024). In terms of final disposal, PG is reported to be managed through stacking, landfilling, or filling voids, in accordance with existing findings of IAEA (2013), Tayibi et al. (2009), and others. In some cases, the destination of washed PG in temporary landfill was reported, as well as its use for soil quality improvement and protection of the waterbodies. The most used method of stacking is the wet method, in which PG is mixed with water for transport to settling ponds. In the case of dry stacking, the PG is transported to the evacuation area without adding water. In general, an important highlight nowadays is to focus on PG valorisation and its use in the circular economy. The exploration of options for PG reuse in European countries was not included in the data collection tools, as primarily was outside of the scope of the current work. However, a simple conducted analysis of the options for PG different application showed that PG in construction is one of the most searched and explored topics on the Web of science, where 1078 research articles about use in cement production, 754 about application for building materials, and 141, 115, and 139 for road construction, plaster, and civil engineering, respectively, were found. However, although technologies for PG recycling and reuse are available and applied in industry, their wide global application remains limited, mainly due to cost-benefit considerations, regulatory requirements, and market acceptance. As a result, of the ~300 million tonnes of PG generated annually, approximately 58% is stacked, 28% discharged into

coastal waters, and only about 14% further processed (Bilal et al. 2023; IFA 2025).

The study results further indicated that most residues in *zircon and zirconium industry* were reused within the industrial facility. However, when reuse was not feasible, residues were either sold as by-products or sent to treatment and recovery plants. Specifically, in the refractory industry in Italy, it was specified that fusion furnace dust containing NORM was recycled within the plant without any treatment, as was the NORM residue obtained from grinding waste. Sludge and other process residues could be reused externally or sent for disposal in conventional or hazardous waste landfills, as widely reported by the investigated countries.

In the *ceramics industry*, disposal in landfills was specified only for hydrated lime, while the other residues were mostly recycled internally.

*The cement industry*, contrary to the other industries discussed in this article, has often been considered an industrial sector capable of using residues from other technological processes rather than generating waste itself. Beyond non-radioactive hazards, most importantly being CO<sub>2</sub> emissions, the main waste stream reported was spent refractories from kiln linings. For commonly used fireclay bricks, NOR concentrations typically were not significantly above background radioactivity values, and such residues were reported to be usually disposed of in common landfills or recycled in refractory production. However, there are other refractories that may be used, such as high-alumina bricks (from bauxite), magnesia bricks, or zircon refractories with significantly bigger content of NOR (Turhan et al. 2014; Radic et al. 2025).

Therefore, the inclusion of the cement industry in Annex VI of the EU BSS (EC 2014) reflects specific situations in which NORM may become relevant. Certain raw materials and additives (e.g., zircon- or phosphate-rich components), as well as refractory materials containing zirconia, can contain elevated radionuclide concentrations. During kiln operation and subsequent maintenance, NORM may accumulate in dusts, scales, or refractory residues, potentially leading to occupational exposure.

Different types of residues, identified as generated in *titanium dioxide pigment production*, including sludge, scale, digester residues, and filter residues, were shown to be mainly stored in on-site disposal facilities. In addition, other residues, such as iron sulphate, Ilmenite mud, and filter press residues are disposed of in dedicated landfills unless used in agriculture or recycled, respectively.

In some cases, information about the reported NORM residue's destination was missing, such as for rubberization, brick lining of tanks, dust filters, surface material of tank lining, metal hydroxide, piping and scale. Some sludges

**Table 3** Summary of residues generated in mineral processing industries involving NORM and their management routes; reported in the current study of the radonorm project

Industrial sector	Residue	Management routes
<i>Phosphoric acid and phosphate fertilisers industry</i>	Phosphogypsum (PG)	Landfilling – majority of cases Recycling - construction materials for buildings, roads – limited Soil quality improvement and protection of waterbodies
	Equipment and pipes material	Reuse or scrapyard
	Hydrated lime	Landfilling
<i>Zircon and zirconium industry</i>	Fusion furnace dust	Recycling
	Grinding scrap	Recycling
	Sludge	Reuse or recycling, landfilling
<i>Cement industry TiO<sub>2</sub> pigment production</i>	Spent refractories	Landfilling or reuse
	Red gypsum	Recycled for construction
	Equipment and pipes	Reuse or scrapyard
	Iron sulphate	Use in agriculture as fertilizer
	Filter cake residues	Recycling
	Sludge	Landfilling
	Scale	Landfilling
	Ilmenite mud	Landfilling or reuse

were commonly subjected to inertisation in the dedicated treatment plant and disposed of in hazardous waste landfills, while other sludges were stored in storage parks. Furthermore, it is reported that liquid effluent (wastewater) from TiO<sub>2</sub> industry was discharged into water bodies, such as rivers and lakes, while recycling of filter residues, red gypsum and iron sulphate was also reported, what was in accordance with Gázquez et al. (2021b). The latter was also shown to be used in agriculture as a fertiliser.

As shown in Table 3, different NORM residues in the investigated mineral processing industries are, according to collected data, reused in the construction sector for landfilling or for the improvement of soil quality in agriculture. However, for the last-mentioned example, based on published literature, the possible radiological impact of ferrous sulphate monohydrate is quite limited, since it contains only high levels of uranium and thorium isotopes, but not their decay products (CSN 2010). The main use of this byproduct, therefore, is as a fertiliser for iron-deficient soils and it presents similar or even lower concentrations of uranium compared to most phosphate fertilisers currently available on the market (CSN 2010).

In line with the circular economy, all listed NORM residues can be seen as a potential resource, even those for which a marketable use has not yet been found. Having in mind that NORM residues commonly contain also non-radioactive hazards (metals, arsenic, acids, and different organic compounds) an integrated approach should be adopted to manage NORM residues properly (IAEA 2021; ICRP 2019). At the same time, a broader holistic perspective is also needed to incorporate additional factors—such as economic feasibility, regulatory drivers, technological options, available infrastructure, and societal acceptance—so that NORM residues can be managed and potentially

valorised in accordance with circular economy principles (IAEA 2024). It is considered useful to conduct an LCA for mineral processing industries to implement this holistic approach. This includes accounting for the impact category of ‘ionising radiation’ in the first attempt.

### **NORM in impact category of ionising radiation in life cycle assessment (LCA)**

Life Cycle Assessment – LCA – is defined by ISO as the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system over the course of its entire life (ISO, 14040: 2006). According to the EU consortium for Life Cycle Impact Assessment (LCIA), the following impact categories should be considered over the entire life cycle of a product or service: climate change, ozone depletion, human toxicity – cancer, human toxicity – non-cancer, particulate matter, **ionising radiation – human health**, photochemical ozone formation – human health, acidification, eutrophication – terrestrial, eutrophication – freshwater, eutrophication – marine, ecotoxicity – freshwater, land use, water use, resource use – minerals and metals, and resource use – energy. A graphical representation of all these categories can be seen in Fig. 2.

The impact category “Ionising radiation” is generally treated as a single overarching category. However, “subcategories” can also be defined, referring to how the impact is modelled and what it ultimately affects. As displayed in Fig. 2, human health, ecosystem health, and natural resources are the three most common areas of protection. The application of LCIA for different impact categories within these protection areas allows the overall interpretation of impact and risks depending on study objectives,

evaluation of limitations, and the formulation of recommendations for proper decision making.

The details about the impact category **ionising radiation – human health** are scarcely mentioned in the literature because it has not yet been well developed in the context of LCA, although some research in this field has been conducted (Frischknecht et al. 2000; Joyce et al. 2017).

The European Commission has identified and prioritized the need to “*Extend the number of radionuclides covered for both human health and ecosystems*” as a relevant task for the further development of the ionising radiation category in LCA, classifying it as a “**high workload**” (EC 2011; Annex 2: Research needs). The present work, therefore, addresses this EC requirement, in addition to other aspects, as data for different NOR –  $^{238}\text{U}$ ,  $^{226}\text{Ra}$ ,  $^{210}\text{Pb}$ ,  $^{232}\text{Th}$ ,  $^{228}\text{Th}$ ,  $^{228}\text{Ra}$  and  $^{40}\text{K}$  - have been collected and analysed. The focus was on the impact category of **ionising radiation related to NORM**.

According to the theory, LCA is based on four main phases: 1) Goal and Scope, 2) Inventory Analysis, 3) Impact Assessment, and 4) Interpretation (Sala et al., 2016). Figure 3 illustrates these steps, adapted for the mineral processing industries associated with the impact category of **ionising radiation related to NORM**.

According to these four phases, the overall NORM activities conducted within the RadoNorm project, and related to mineral processing industries involving NORM can be, to a certain initial extent, considered as LCA stages:

- 1) **Goal and scope:** making an updated overview of NORM involving industries (including mineral processing ones) across European countries was set as a work priority early in the RadoNorm project. This was conducted through (a) development of a NORM identification methodology (Michalik et al. 2023), (b) development of tools and NORM registers for qualitative and quantitative data collection (Mrdakovic Popic et

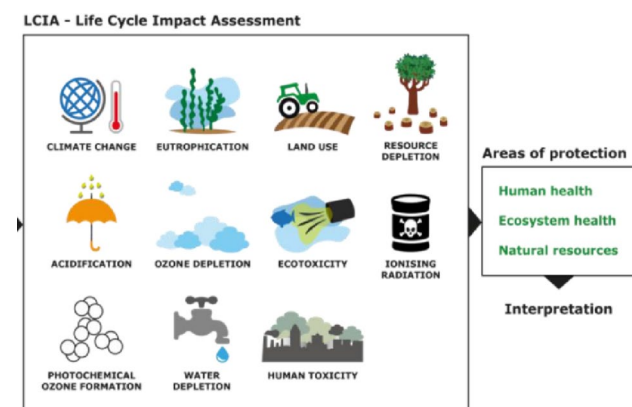
al. 2023a), and finally, (c) thorough analyses of numerous datasets of collected European data for different industries and exposure situations. Within the scope of investigating NORM qualitatively and quantitatively in both industrial activities involving NORM from the EU BSSD and IAEA BSS lists but also wider (Michalik et al. 2023), information on the presence of other non-radioactive hazards, such as metals, organics, asbestos, noise, and physical hazards was also collected (Mrdakovic Popic et al. 2023b) and can be further used for the development and application of a complete LCA to NORM involving process or product.

- 2) **Life Cycle NORM Inventory:** the collected NORM data - inventory in mineral processing industries and their analysis (Dvorzhak et al. 2025) can be reasonably considered as the initial steps toward taking into account the impact category of **ionising radiation related to NORM** for a specific industry or product. For each stage of various consecutive industrial processes (e.g., raw material or natural resources extraction  $\rightarrow$  manufacturing  $\rightarrow$  use  $\rightarrow$  residues and wastes management) relevant NORM-related data were collected and analysed.

The obtained data included:

- Identification of various NORM occurrences in industrial processes/conditions;
- NORM characterisation: type of material, their annual production quantity, NOR activity concentration in raw materials, main products, by-products, residues and wastes, as well as in liquid NORM discharge and gaseous emissions into the environment, and;
- Handling, treatment and destination of the NORM residues and wastes.

Therefore, an **LCNI** for the products of mineral processing industries was provided and is foreseen to have potentially beneficial use in terms of LCA. However, authors would like to highlight the fact that while earlier surveys (e.g. EC and IAEA reports, national case studies) provided valuable NORM data, which made it possible to identify NORM-relevant sectors of possible RP concern, many of these data are now over two decades old. Recent surveys, such as those carried out within the RadoNorm project, have shown that in some countries NORM inventories are still lacking or are incomplete and that in many countries developing the graded approach for NORM control remains an issue. The LCNI presented here aims to complement and update this knowledge, and more importantly, introduces a new perspective by explicitly framing NORM data within the context of LCA. This integration allows ionising radiation from



**Fig. 2** Life Cycle Impact Assessment categories in accordance with the European Platform on LCA (EP LCA)

NORM to be considered as an impact category alongside other environmental impact.

3) **Life Cycle Impact Assessment:** The risk of developing adverse health effects depends on the type of radiation and the magnitude of the dose. The exposure pathways of inhalation, ingestion, and external gamma radiation were considered in the dose assessment in this study. The assessment of impact in category of ionising radiation – human health is proposed to be evaluated through radiation effective dose loads for workers and members of the public, measured in mSv/y as the most appropriate and understandable functional unit. Although the dose does not represent a health effect, it is a term that can be directly connected to health effects (via the Linear No Threshold Model) and is widely used in radiation impact assessment and RP. The dose assessment for workers and the public, presented in the sections above, are thus considered as the first steps to assessing health impacts for LCIA associated with the impact category of ionising radiation related to NORM.

4) **Life Cycle Interpretation:** Interpretation and concluding remarks regarding LCNI and LCIA are provided in the related papers (Dvorzhak et al. 2025; Mrdakovic Popic et al. 2025, *in publication* ) and in the present work.

Finally, it should be emphasized that, while the above given LCA stages for NORM evaluate how updated NORM data from European countries, obtained in the RadoNorm project, can be considered as an impact category within LCA, this still represents only one element of the broad LCA. The sequence 1–4 presented above largely mirrors the conventional RP framework for NORM (e.g. EC 2014; IAEA 2021; ICRP 2019). To achieve a complete LCA, however, existing data must be complemented with information on other environmental impact categories and then subjected to appropriate analyses. Further research and practical developments are required to compile such information for diverse industrial activities and products, and to update existing databases and LCA modelling tools so that they can

support truly holistic decision-making and the transition to more sustainable operations.

**Evaluation of aspects of life cycle assessment (LCA) on case of phosphoric acid production**

Within the broader characterization of NORM in industrial activities, the LCA approach was evaluated for phosphoric acid production as an illustrative example, showing both the complexity of the data required and the process itself, but also the potential benefits of such a broad assessment for human and environmental health.

The scope of this study was limited to phosphoric acid production, while the primary objectives were to:

- present NORM occurrence at different stages of the production chain to clarify where and how NORM should be incorporated into an LCA;
- evaluate other additional relevant parameters for various impacts categories as well as potential holistic assessment outcomes.

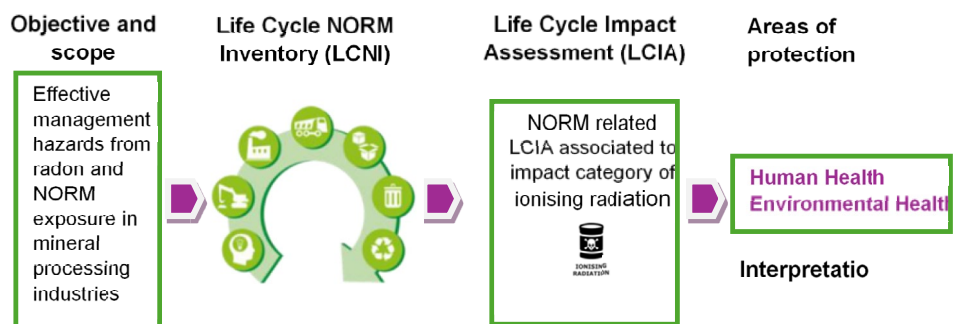
It is important to note that this evaluation did not involve running a full LCA using common software tools and model datasets. Instead, it relied on RadoNorm data, peer-reviewed literature, and selected data from existing LCA datasets. Thus, this section should be considered as an initial and limited conceptual framework illustrating how NORM can be integrated into LCA under the ionizing radiation impact category, alongside other commonly assessed categories.

**Life cycle inventory**

- *Naturally occurring radioactive material (NORM) -.*

In this NORM-focused consideration of LCA, data on NORM partitioning at various industrial stages and in different matrices were required. Radionuclides <sup>238</sup>U, <sup>226</sup>Ra, and <sup>210</sup>Pb have previously been reported at activity concentrations exceeding 1 kBq/kg in raw materials (phosphate rock), merchant-grade 54% P<sub>2</sub>O<sub>5</sub>, phosphogypsum

**Fig. 3** Life Cycle Assessment (LCA) steps in mineral processing industries associated to the impact category of ionising radiation related to NORM



(PG), scales, sludge, and filters from the production process (Sect. 3, Table 1, and Fig. 4). Additionally, as illustrated in Fig. 4, the NORM distribution throughout the phosphoric acid production life cycle shows potential exposure pathways for workers and the public.

In the stage of **raw material acquisition** for phosphoric acid production (phosphate rock mining), the activity concentrations of  $^{238}\text{U}$ ,  $^{226}\text{Ra}$  and  $^{210}\text{Pb}$  in phosphate rock were found within wide ranges, with maximum concentrations up to 1.7 kBq/kg. These values, although still moderate, are higher than the ELs and CLs of 1 kBq/kg, defined by EU BSS (EC 2014) and IAEA BSS (IAEA, 2014), and indicate the need for screening of industrial stages to decide on RP measures, level of graded regulatory control, and proper management practice. For the main product, some reported samples of phosphoric acid had activity concentrations of  $^{238}\text{U}$ , up to 2 kBq/kg, while at the end of production life cycle - residual NORM, solid and liquid discharges showed values of activity concentrations for  $^{238}\text{U}$ ,  $^{226}\text{Ra}$  and  $^{210}\text{Pb}$  above 1 kBq/kg; the maximum value was measured in solid sludge for  $^{226}\text{Ra}$  (4.9 kBq/kg).

- *Other impact categories -*

Examples of other indicators that should be considered in the LCA for phosphoric acid production across various impact categories include:

- Human and environmental toxicity – indicator: trace metals (As, Cr, Cd, Cu, Pb, Ni, Zn);
- Climate change – indicator:  $\text{CO}_2$ -eq;
- Acidification – indicator:  $\text{SO}_2$ -eq;
- Eutrophication – indicator:  $\text{PO}_4$ -eq;
- Electricity – indicator, kWh;
- Process heat – indicator: GJ.

Trace elements that commonly accompany phosphate rock are usually distributed between phosphoric acid and PG, typically showing a higher accumulation rate in PG. They have been investigated in the international literature (Weiksnar et al. 2022; Zou et al. 2023) as they can contribute substantially to human toxicity and freshwater ecotoxicity impact categories. Table 4 summarises measured trace element concentrations in PG for the production of 1 tonne of  $\text{P}_2\text{O}_5$  (functional unit used in LCA). The calculations account for the mass of PG generated (4.5 tonnes per 1 tonne  $\text{P}_2\text{O}_5$ ).

Similarly, LCAs of process of phosphoric acid production includes consideration of the above-mentioned indicators  $\text{CO}_2$ ,  $\text{SO}_2$ ,  $\text{PO}_4^{3-}$ , kWh, GJ (and others, but less present in the literature) usually per unit of 1 tonne of  $\text{P}_2\text{O}_5$  production (Table 5).

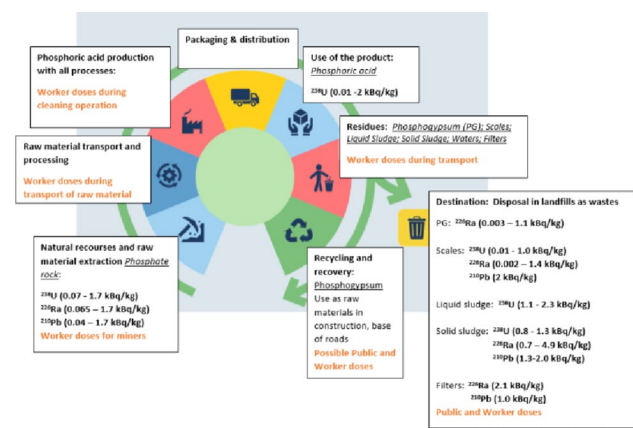
## Life cycle impact Assessment – Phosphoric acid production

Figure 4 clearly identifies stages where occupational or public exposure may occur. Finally, the absorbed dose depends not only on radionuclide activity concentrations but also on other factors, including exposure duration and protective measures. Workers handling feedstock rock, performing area cleaning, and managing transportation represent relevant occupational exposure scenarios in most European contexts, primarily through external gamma radiation. Effective doses range from 0.01 to 0.6 mSv/year. For accumulated NORM residues (e.g. scales), elevated activity concentrations may occur, requiring attention to protective measures and exposure duration during maintenance and cleaning activities. Still, effective doses in European countries have been found to be low, almost negligible due to strict procedures and applied OHS and RP measures. Other exposure scenarios also reported doses below 1 mSv/year, comparable to previous IAEA findings (IAEA 2013). Estimated doses for the public were also low, ranging from 0.04 to 0.21 mSv/year.

Work on the adaptation of existing LCA datasets and tools should be conducted with respect to linking effective doses to possible health and environmental risks. More fundamental research results should therefore be evaluated and appropriately incorporated into LCA.

Moreover, assessment of **other impact categories** should include evaluation of the potential consequences/impacts:

- Climate change (GWP): The representative GWP of approximately 800 kg  $\text{CO}_2$ -eq/tonne  $\text{P}_2\text{O}_5$  is roughly equivalent to the  $\text{CO}_2$  emissions from driving a typical passenger car about 3,000–4,000 km (depending on vehicle fuel efficiency). The main drivers are upstream sulphuric acid production, process heat (often fossil fuel), and electricity consumption (Hasler et al. 2015; Wu et al. 2016). Consequences may include an increase in global mean temperatures, differences in precipitation patterns, including direct and indirect impacts on agriculture, biodiversity, and human health via extreme weather.
- Eutrophication: While the phosphoric acid manufacturing stage contributes modestly to eutrophication (about 0.1 kg  $\text{PO}_4$ -eq per t  $\text{P}_2\text{O}_5$  in the representative values), the major eutrophication impacts associated with fertilizer systems occur at the application stage (runoff, leaching of P and N to water bodies). Eutrophication can lead to harmful algal blooms, hypoxia, and ‘dead zones’ in coastal and freshwater ecosystems, loss of biodiversity, impacts on fisheries, and water quality issues for human use. It should be considered from the perspectives of phosphorus fate and transport in surface freshwaters, in



**Fig. 4** NORM footprint across the life cycle of phosphoric acid production. Reported ranges of activity concentrations for <sup>238</sup>U, <sup>226</sup>Ra, and <sup>210</sup>Pb are shown for raw material extraction, transport, production, in main product, for residue material, which may either be used for recycling or disposed of. Associated exposure pathways for workers and the public are highlighted. Key residues include PG, scales, sludge, filters, and process waters

soil and groundwater, and in marine ecosystems (Morelli et al. 2018; Wu et al. 2016).

- Acidification: Acidification potential arises from SO<sub>x</sub>, NO<sub>x</sub>, and HF emissions during sulfuric-acid production and the wet process. Acid deposition damages freshwater organisms, soils (leading to nutrient leaching and mobilization of toxic metals), and built infrastructure (Belboom et al. 2015).
- Human and Ecotoxicity: Emissions of metals (e.g., cadmium, lead) in PG leachate can increase local human toxicity and ecotoxicity potential. These are highly site-specific and depend on wastewater treatment and PG stack containment conditions (Belboom et al. 2015).
- Energy use and Resource depletion: The phosphoric acid production process consumes both electricity and process heat; improving energy efficiency by changing heat-sources to low-carbon ones would substantially reduce CO<sub>2</sub> emissions. Phosphate rock is a non-renewable mineral resource; depletion contributes to resource scarcity indicators and geopolitical risks (Issaoui et al. 2021; Wu et al. 2016).

**Table 5** Levels of CO<sub>2</sub>, SO<sub>2</sub>, PO<sub>4</sub><sup>3-</sup>, electricity and heat through the cycle of production of 1 tonne P<sub>2</sub>O<sub>5</sub>

Category	Average value	Unit/1 tonne P2O5
Climate change	800	kg CO <sub>2</sub> -eq
Acidification	5	kg SO <sub>2</sub> -eq
Eutrophication	0.1	kg PO <sub>4</sub> -eq
Electricity	200	kWh
Process heat	4	GJ

In summary, in this subsection, we have provided:

- a sequence of points/stages in phosphoric acid production, including visualisation, where particular attention should be paid to NORM activity concentrations in given NORM matrices, potential exposure scenarios, and consequently radiation doses to workers and the public. This is foreseen as helpful not only for RP experts, but LCA experts who need to understand the processes regarding NORM and to further develop LCA to include NORM as subcategory within the category of ionising radiation;
- an overview of other impact categories and indicators, commonly included in LCA, what is information that may be useful for people orientated only on RP aspects, but understand the need for holistic considerations of all impact categories.

Further detailed work is needed to fully integrate NORM hazards into LCA by properly defining input data for NORM and associated contaminants for LCA databases, assessing current methods and assessment parameters, and adapting existing LCA software tools. This would help in conducting such a complex method as LCA with a certain level of automatization, aggregation of results within the system boundary, compare and test alternatives, and results visualisation. Close collaboration of experts in RP field with LCA experts is needed for such complex work. However, ultimately, policymakers and regulators will be able to compare the environmental impact of products involving NORM with non-NORM alternatives, enabling informed decisions. Industry will benefit from improved NORM risk management and possible value creation from NORM materials. Public awareness of natural radioactivity and its implications could also improve NORM acceptance.

**Table 4** Trace elements (mg/kg) measured in PG in process of phosphoric acid production, for production of 1 tonne P<sub>2</sub>O<sub>5</sub> as functional unit used in LCA

Indicator - metal	As	Cd	Zn	Pb	Cr	Cu	Unit
PG	1–24	0.1–28	2–137	0.8–28.1	1.52–70.52	1.56–70.56	mg/kg
P <sub>2</sub> O <sub>5</sub> *	4.5–108	0.45–126	9–617	3.6–126	6.84–315	7–315	g/tonne

\*The common functional unit for presenting P<sub>2</sub>O<sub>5</sub> is 1 tonne – when producing 1 tonne of P<sub>2</sub>O<sub>5</sub>, 4.5 tonnes of PG is made; therefore, calculations were made (mg/kg x4500) to obtain content of metal (mg) in amount of PG when produced 1 tonne P<sub>2</sub>O<sub>5</sub>.

## Conclusions

This research, conducted within the framework of the RadoNorm project, focuses on mineral processing industries involving NORM. It aims to improve knowledge and understanding of NOR-related hazards in various exposure scenarios to ensure effective radiation protection. Additionally, the study contributes to the integration of NORM into the ionising radiation impact category within LCA, and outlines paths for further development.

Impact assessment of NORM (LCIA), as an integrative part of the LCA, was carried out by evaluating effective doses to workers, the public, and non-human biota under different exposure scenarios in mineral processing industries. Doses received by workers were generally low—typically below the 1 mSv/year, dose criterion recommended by international organisations such as the EC and IAEA. Nevertheless, protective measures, monitoring, and control remain necessary to ensure workplace safety and optimise RP. In many cases, compliance with OHS regulations—particularly regarding dust hazards—can sufficiently mitigate exposure. For example, a known risk in phosphoric acid production arises during maintenance operations via dust inhalation; however, standard protective measures against non-radioactive hazards (e.g., ventilation systems and respiratory protection equipment) are generally adequate to protect against radiation exposure as well.

This study highlights that, due to the dust hazard, industries processing NORM cannot be automatically exempted from regulatory notification based solely on NORM activity concentrations without screening, and, when needed, further assessment steps within a graded approach should be conducted. Other factors and real conditions in exposure scenarios, such as the chemical composition of dust, disequilibrium within decay series, and whether protective measures are in place and which ones (i.e. different assumptions and parameters in assessments) influence exposure doses, and therefore, characterization should also include information and data on all relevant exposure factors.

Public exposure to NORM from mineral processing industries was found to be negligible in most cases. However, this investigation emphasized the scarcity of available quantitative data concerning liquid effluents, atmospheric discharges, and NOR activity concentrations (from NORM involving industries) in recipient environmental compartments. Besides OSPAR reports, only limited national data were specifically available for our study. This also applies to RadoNorm data on the transport and mobilization of NORM in environmental media (e.g., rivers, lakes, seas, air, soil), its transfer to biota, incorporation into food chains, and related processes, which have been gathered from various countries, but only to a relatively limited extent. Future research

should focus on improving knowledge of NORM behaviour not only in industrial contexts, but also in the environment and different ecosystems – connected to industrial facilities when they are the main sources of NORM.

The circular economy and LCA are complementary approaches that support sustainable development. The circular economy promotes efficient and sustainable systems through reuse, recycling, and regeneration of materials. In parallel, LCA evaluates environmental impacts across all stages of a product's life cycle—from raw material extraction to final disposal (a “cradle-to-grave” analysis). As such, the ionising radiation impact category—specifically the NORM subcategory—should be considered when evaluating circular economy strategies involving NORM-containing residues.

In this work, the consideration and evaluation of conditions for applying LCA to ionising radiation impacts were undertaken using phosphoric acid production as a case study. The proposed method can serve as an early warning system for risks associated with secondary raw materials or alternatively help build confidence in their safe use. Further research at the intersection of circular economy strategies and the management of NORM-containing residues and waste is essential for improving understanding of their environmental fate and developing effective and sustainable management practices.

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**Data availability** The data related to the present paper are publicly restricted due to confidentiality issues.

## Declarations

**Competing interests** The authors declare no competing interests.

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