Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in
Environmental Science & Health

Cd content in phosphate fertilizer: Which potential risk for the environment and human health?

Nicoleta Alina Suciu[1,2], Romano De Vivo[2], Niccolò Rizzati[2] and Ettore Capri[1,2]

Abstract

Cadmium (Cd) is a heavy metal that accumulates in soil and in living organisms and causes severe and permanent damage. Its presence in the soil depends largely on the use of phosphate fertilizers. Phosphorite and apatite rocks used in phosphate fertilizers production contain several other minerals, including Cd. The amount of Cd incorporated in phosphate fertilizers depends on the type of phosphorite and apatite rocks (with low or high Cd content). Cd is present in soil mainly in insoluble form and has no bioavailability for plants. However, plants can increase Cd solubility by releasing root exudates that change the pH of the rhizosphere, therefore increasing Cd accumulation. Once crops absorb Cd, it enters the food chain. Food is the primary source of Cd exposure (for the non-smoking population), with cereals, nuts and legumes, and fish and shellfish being the major contributors. Progressive accumulation of Cd in humans impairs kidney function, affects the liver, and causes bone demineralization. Cd classification as a human carcinogen goes back to the 1990s. The European Union adopted Regulation (EU) 2019/1009, limiting Cd content in organo-mineral fertilizer having total phosphorus (P) content of 5% P_2O_5 equivalent at 60 mg kg^{-1} P_2O_5. This threshold seems inadequate compared to the threshold values for Cd currently in place in some EU countries: 12 member states have a Cd threshold between 20 and 50 mg kg^{-1} P_2O_5, 8 have the same threshold as that proposed in the regulation, and 2 have a higher threshold. Meanwhile, the new EU Regulation on CAP Strategic Plans explicitly references soil health and fertility protection and the limitation of contaminants in fertilizers. Fertilizers with low Cd content, with thresholds no higher than 20 mg kg^{-1} P_2O_5, would effectively limit bioaccumulation. As stopping P fertilizer application cannot be an option, strategies such as the use of P fertilizers with low Cd content, the use of cultivars that accumulate less Cd in their consumed parts, production of mineral P fertilizers with higher nutrient use efficiency than those actually produced, the decadmiation of P rocks from the raw materials, soil phytoremediation before crops cultivation, and increased use of recovered nutrients, should be adopted.

Addresses

[1] Università Cattolica Del Sacro Cuore, Department for Sustainable Food Process, Via Emilia Parmense 84, 29122 Piacenza (PC), Italy
[2] European Observatory on Sustainable Agriculture (OPERA), Università Cattolica Del Sacro Cuore, Via Emilia Parmense 84, 29122 Piacenza (PC), Italy

Corresponding author: Suciu, Nicoleta Alina (nicoleta.suciu@unicatt.it)

Current Opinion in Environmental Science & Health 2022, **30:**100392

This review comes from a themed issue on **Environmental Impact Assessment 2022: Sustainability in the agro-food ecosystem: policies, measure and measurement**

Edited by **Ettore Capri**

For complete overview of the section, please refer to the article collection - Environmental Impact Assessment 2022: Sustainability in the agro-food ecosystem: policies, measure and measurement

https://doi.org/10.1016/j.coesh.2022.100392

Keywords

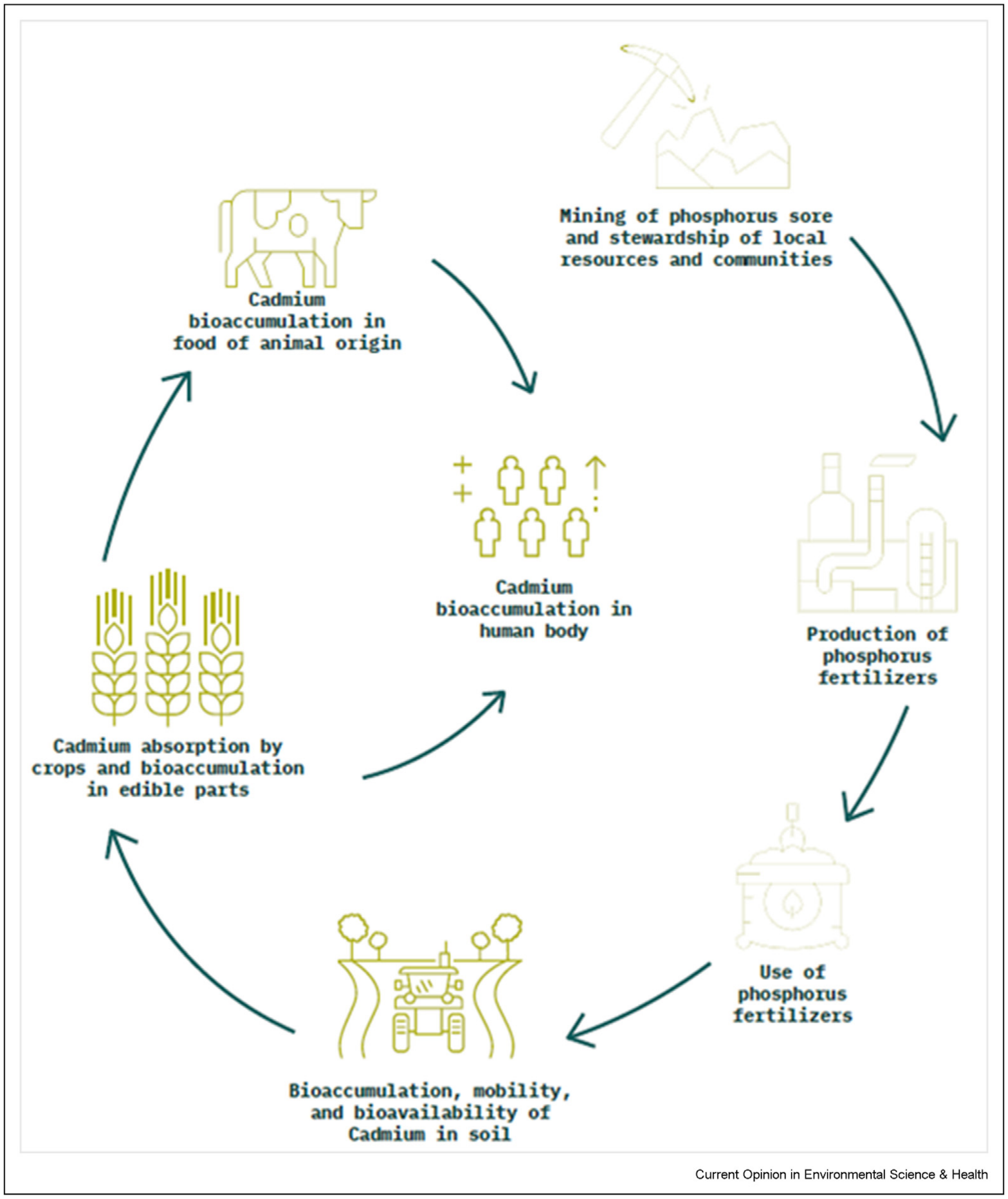
Cadmium, Heavy metals, Environmental contamination, Human health exposure, Sustainable agriculture.

Background

Several studies point to the impact of mineral fertilizers as a significant source of Cadmium (Cd) contamination in agricultural soils and, consequently, in Europeans' diets (Figure1) [1]. Cd is a toxic contaminant that can have severe and often irreversible effects on human health and natural ecosystems [2–4]. The application of mineral phosphate (P) fertilizers is mainly responsible for the accumulation of Cd in agricultural soils and watersheds [5]. Accumulation in the soil increases Cd levels in plants and the potential for humans to ingest amounts that exceed the level at which no adverse health effects occur [6]. In addition, Cd can enter freshwater reservoirs and animal feed [4,7]. In Europe, mineral P fertilizers contribute 45% of the total Cd contamination of cropland. At the same time, 55% of the total dietary Cd intake of the average European consumer is related to Cd accumulation in soil [8].

Given the role as Guest Editor, Ettore Capri Lorenzo had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Damia Barcelo Culleres, Editor in Chief.

Figure 1



Life cycle of cadmium in phosphorous fertilizers.

The long-term consequences of Cd contamination on the soil ecosystem are not entirely predictable. Moreover, some studies show that even at low Cd concentrations in soil, in the presence of efficient Cd transfer from soil to plants, the Cd accumulations in the edible parts of plants may exceed the values recommended for human consumption, with no toxicity symptoms for plants [9]. Therefore, although current concentrations of soil Cd are estimated to meet provisional safe intake limits for Cd uptake in Europe (2.5 μg kg body weight^{-1} per week), several studies pointed out that other jurisdictions like the US have set much lower limits (0.7 μg kg body weight^{-1} per week). These limits are exceeded in most of the world [10]. Furthermore, concentrations of Cd in foodstuffs are important in relation to the trade of food commodities and are the subject of disputes regarding restrictive trade rules under the World Trade Organization's jurisdiction [11]. Hence it is prudent that agricultural systems be managed to limit Cd accumulation in soil, and to utilize agronomic and genetic management to minimize Cd uptake by crops and animals prone to Cd accumulation. The main scope of the present review is to assess and identify future actions and research directions, to meet European consumers' requirements for safe food and environment.

Research and actions to fill the gaps

Use of phosphate fertilizers in Europe

Although the non-substitutable nutritional element secures our food production, P fertilization in European agriculture is often inefficient. While soils in some regions of Europe are showing nutrient deficiencies and thus losing their productive capacity, elsewhere, especially in regions with high livestock density, large amounts of P accumulate in the European soils [12]. The European Union (EU) relies on more than 90% of mineral P imports [13]. Based on supply risk and economic importance, the EU continues to identify phosphate rock and white phosphorus as Critical Raw Materials in 2020 [14], and the Stockholm Resilience Centre places the cycles of P and N in the risk zone of 'planetary boundaries' [15]. Recent studies highlighted natural radioactivity and radiation hazard associated to mineral phosphate fertilizer production [16]. Along with the world population growth, P demand in both agriculture and biofuels sectors is increasing over the years. Europe has an unsustainable consumption of P, with only 16% of the P present in fertilizer reaching human food, while the main fraction is lost through net accumulation in agricultural soils, soil erosion, or crop residues [17]. According to EUROSTAT [18], the consumption of inorganic fertilizers based on P reached about 1.1 Mt P_2O_5 in 2018 in the EU countries, with a slight reduction of 1.2% since 2008. USA has an average consumption of about 4.0 Mt of P_2O_5 (1990–2015), almost four times higher than in the EU [19]. As announced in the New Circular Economy Action Plan, the EU revised the previous 2003/2003 fertilizer regulation also to encourage the supply of safe and high-quality fertilizer products coming from domestic organic sources [8]. Thus, it is expected that the European Commission develop shortly the Integrated Nutrient Management Action Plan (INMAP), to ensure more sustainable application of nutrients and boost the markets for recovered nutrients [20].

Cd content in fertilizers and its transfer to soil

Cd in mineral phosphate fertilizers depends on phosphate rocks (apatite and phosphorite), by far the most important phosphorus-bearing raw material used in the fertilizer industry [21]. Different types of phosphate rocks have different levels of Cd, based on the type of ore (igneous or sedimentary) and geographic provenance. It is well established that phosphate from igneous deposits contains low Cd concentrations (range 1–4 mg kg^{-1}) and such deposits are in South Africa and Russia. Higher Cd concentrations (range < 1–150 mg kg^{-1}) are reported in phosphate rock from sedimentary deposits derived from Morocco, Togo, Senegal, and Idaho, USA [11]. Data for countries among the top world producers is shown in Table 1 [22,23].

Table 1

Cadmium content (mg/kg) and dominant minerals in phosphate rocks around the world [22,23].

Origin	Dominant minerals	Cd content (mg kg^{-1})
Wyoming–USA	Fluoapatite	1.45
Florida–USA	Hydroxyapatite	3.31
Idaho–USA	Hydroxyapatite, carbonate fluorapatite	199
Morocco	Carbonate fluorapatite	507
Sludanka - Russia	Hydroxyapatite	0.15
Okinawa - Japan	Hydroxyapatite	29.5
Taiba Senegal	–	87
Zin- Israel	–	31
Tunisia	–	40
Phalaborwa -South Africa	–	1
Araxa -Brazil	–	2
Tongo	–	58
El-Hasa - Jordan	–	5
Kaiyang - China	–	<2

When a phosphate fertilizer comes into contact with the soil, it undergoes various biochemical, microbiological, and physical processes through which it is progressively reduced and retained in the soil. The contaminants in the fertilizers (mineral/chemical) tend to follow the same destiny [24] even if studies show that on addition to moist soil, granules of single superphosphate (SSP) lost all their P in 8 days but 60% of the Cd (and Ca) was retained in the granule [11]. Soil organic matter, oxyhydroxides of Al, Fe, and Mn and clay minerals are the main Cd sorbents in soil. Cd is strongly bound in soil and only minute fractions of it are present in soil solution and, hence, Cd removal by vertical leaching is small unless the soils are very acidic and low in organic matter. Despite this, the vertical leaching of Cd has become a focal point of attention and even controversy in the debate on the Cd limits in fertilizer in Europe that took place between about 1998 and 2018 [5,11]. Annual net accumulation of Cd in the soil is about 1% of the amount already present in agricultural soils [25]. In New Zealand from the 1950–2000s, the Cd presence in P fertilizers determined an enrich of soil Cd by 50–400% above natural background concentrations [10]. The researchers estimated that stopping P fertilizer applications in New Zealand soil reduced Cd concentrations after more than 21 years. Nevertheless, another recent study of a no-P pasture found no change in total soil Cd concentrations over 22 years [26]. Additional studies highlighted that in soils fertilized with products containing 1–20 mg kg^{-1} P_2O_5, Cd tends to accumulate very slowly or even decrease after 100 years, whereas at a concentration of more than 60 mg kg^{-1} P_2O_5, soil accumulation would be relatively high [25].

Strategies to reduce soil Cd concentrations other than stopping P fertilizer would be required to prevent production losses. Such strategies could include substantially lowering the Cd concentration in P fertilizers, lowering soil pH, or using plants that hyperaccumulate Cd [10,27,28]. However, their efficacy is unproven in the long term. It is therefore likely that a mix of strategies is required that considers the local production system, climate, and soil type [10].

Cd accumulation in crops

Cd is present in soil mainly in insoluble form and has no bioavailability for plants. However, plants can increase Cd solubility by releasing root exudates that change the pH of the rhizosphere, therefore increasing Cd accumulation, despite it varies between and within plant species [29]. Cd behavior is very similar to that of zinc (Zn), an element that is necessary for good plant development. When the soil has an insufficient mineral supply of Zn to meet the crop's needs, the similarity between the two elements causes the plant to take Cd instead of Zn [30]. Recently, in maize, Tan et al. [31] individuated double mutations of two Zn transporter genes, that synergistically regulate the uptake of Zn and Cd. Therefore, Cd contamination is a significant stressor for plants that may result in genotoxic effects, leaf chlorosis, reduced growth rates, inhibition of respiration and photosynthesis, increased oxidative damage, and reduction in nutrient uptake ability [30].

A widespread low concentration of soil contamination together with efficient transfer of Cd from soil to plants means that even in the presence of low levels of contamination, and even if the plants do not exhibit symptoms of toxicity, the edible parts of plants may exhibit Cd accumulations higher than those allowed for human consumption [32]. Over the two last decades, numerous publications have addressed the biomolecular processes of Cd accumulation in plants with the scope of creating cultivars that accumulate less Cd in their consumed parts [33]. Targets for future research should include the crystal structure of plant Fe/Zn/Mn transporters, identification of desirable allelic variants, and design of a protein specific for substrate transport [30].

The impact of Cd on human health

Cadmium is a non-essential element for humans that is almost absent from the body at birth and accumulates with age in the kidney and liver to peak at around age 50 [11]. It can cause bone demineralization and it is classified as a human carcinogen [1]. Foods are the primary source of Cd exposure, accounting for approximately 90% of the total Cd intake for the non-smoking general population [3]. Cereals and cereal products, vegetables, nuts and legumes, and fish and shellfish are the most significant contributors to human exposure [11].

Most of the Cd absorbed by the human body is excreted, but between 5% and 10% is retained, mostly (>50%) in the kidneys [11]. The biological half-life of Cd is within 6–38 years in the kidneys and 4–19 years in the liver [1]. Damage to the kidneys occurs when the Cd concentration in the renal cortex exceeds approximately 200 mg kg^{-1} (wet weight), as evidenced by the excretion of proteins (proteinuria) and calcium (Ca). The latter leads to osteomalacia which is the underlying cause of itai–itai disease [34]. Recent European and French studies have shown that the risk related to Cd dietary exposure cannot be ruled out for a part of the population [1].

EU and MSs position on Cd limits

The European Union has been concerned about Cd since the 1970s, but it was only in June 2019 that the EU Council officially adopted the Regulation 2019/1009, which introduced limits on the Cd content in organo-mineral fertilizer having total phosphorus (P) content of 5% P_2O_5-equivalent set at 60 mg/kg P_2O_5 [1]. The new limit of 2019 is based on the "stand still principle" or "zero net accumulation", not on health risk assessment and several member states (MSs) had claimed to have local soil, climate, land use, or crop use conditions that justified their national limit [11]. Indeed, 12 MS already adopted lower threshold values, 8 MS have similar values, and 2 MS have set higher thresholds so that it is challenging to consider the new limit a breakthrough or a harmonization of the internal market. Harmonized rules provide a transparent and predictable legal framework for all businesses (e.g., agricultural technology providers, farmers, food processors, and distributors), which is a prerequisite for healthy competition and greater awareness along the value chain of risks and risk mitigation strategies.

In October 2020, the European Parliament successfully adopted a few amendments during the current CAP review process, linking the CAP to reducing heavy metals in fertilizers. The text was part of the European Parliament's negotiating position with the Council. In June 2021, EU agriculture ministers confirmed the preliminary agreement with the European Parliament on CAP reform. On September 9, 2021, the European Parliament's AGRI Committee approved by a large majority the complete CAP package agreed upon during the informal trialogue in June. The preliminary agreement contained an explicit reference to protecting soil health and fertility and reducing contaminants in fertilizers. Art. 47 of Regulation (EU) 2021/2115 on CAP Strategic Plans was adopted on 21 December 2021 and is set to enter into force on 1 January 2023. This explicitly refers to the reduction of contaminants in fertilizers as one of the measures where MS interventions could be envisaged. This creates first-ever financial incentives for farmers to use low-Cd phosphates [24].

Remarks

Cd dietary exposure cannot be ruled out for a part of the European consumers. Progressive accumulation of Cd in humans impairs kidney function, affects the liver, and causes bone demineralization. Mineral phosphate (P) fertilizers are the main source of Cd in the environment and food. The European Union adopted Regulation (EU) 2019/1009, limiting Cd content in organo-mineral phosphate fertilizers at 60 mg kg^{-1} P_2O_5. This threshold seems inadequate compared to the threshold values for Cd currently in place in some EU countries: 12 member states have a Cd threshold between 20 and 50 mg kg^{-1} P_2O_5, 8 have the same threshold as that proposed in the regulation, and 2 have a higher threshold. Stopping P fertilizer cannot be an option and strategies able to reduce soil Cd concentrations, by considering the local production system, the climate, and the soil type should be adopted. Such strategies could include (i) the use of P fertilizers with low Cd content, (ii) the use of cultivars that accumulate less Cd in their consumed parts, (iii) soil phytoremediation before crops cultivation, (iv) the production of mineral P fertilizers with higher nutrient use efficiency than those actually produced, (v) the decadmiation of P rocks from the raw materials, and (vi) increased use of recovered nutrients. For all these options additional research is needed for a better understanding and optimization of the processes and an evaluation of the economic benefits and impacts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Università' Cattolica del Sacro Cuore contributed to the funding of this research project and its publication.

References

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

1. Carne G, Leconte S, Sirot V, Breysse N, Badot PM, Bispo A, Deportes IZ, Dumat C, Rivière G, Crépet A: **Mass balance approach to assess the impact of cadmium decrease in mineral phosphate fertilizers on health risk: the case-study of French agricultural soils**. *Sci Total Environ* 2021, 143374, https://doi.org/10.1016/j.scitotenv.2020.143374.

2. Wang LX, Feia J, Wang XM, Xie GF, Cao P, Zhang C, Zhao H, Fua L, Cao W: **Environmental cadmium positively correlates with autophagy and apoptosis in chronic obstructive pulmonary disease patients**. *Atmos Pollut Res* 2021, **13**, 101275, https://doi.org/10.1016/j.apr.2021.101275.

3. Li Y, Chen W, yang Y, Wang T, dai Y: **Quantifying source-specific intake risks of wheat cadmium by associating source contributions of soil cadmium with human health risk**. *Ecotoxicol Environ Saf* 2021, **228**, 112982, https://doi.org/10.1016/j.ecoenv.2021.112982.

4. Srivastava R, Basu S, Kumar R: **Phosphorus starvation response dynamics and management in plants for sustainable agriculture**. *J Plant Biochem Biotechnol* 2021, **30**: 829–847, https://doi.org/10.1007/s13562-021-00715-8.

5. Park hJ, Kim sU, Jung KY, lee S, choi YD, Owens VN, Kumar S, Yun SW, Hong CO: **Cadmium phytoavailability from 1976 through 2016: changes in soil amended with phosphate fertilizer and compost**. *Sci Total Environ* 2021, **762**, 143132, https://doi.org/10.1016/j.scitotenv.2020.143132.

6. * Zea M, Souza A, Yang Y, Lee L, Nemali K, Hoagland L: **Leveraging high-throughput hyperspectral imaging technology to detect cadmium stress in two leafy green crops and accelerate soil remediation efforts**. *Environ Pollut Vol* 2022, **292**, 118405, https://doi.org/10.1016/j.envpol.2021.118405. Part B.

Authors highlighted the potential of the biochar to reduce Cd bioavailability in soil. The technology also may be helping in elucidating mechanisms mediating how biochar can influence plant growth and stress responses.

7. Anderson CWN, Smith SI, Jeyakumar P, Thompson-Morisson H, Cavanagh JO: **Forage crops and cadmium: how changing farming systems might impact cadmium accumulation in animals**. *Sci Total Environ* 2022, **827**, 154256, https://doi.org/10.1016/j.scitotenv.2022.154256.

8. * Marini M, Caro D, Thomsen M: **The new fertilizer regulation: a starting point for Cd control in European arable soils?** *Sci Total Environ* 2020, 140876, https://doi.org/10.1016/j.scitotenv.2020.140876 [online] 745.

Authors highlighted the need for complementary policy instruments to protect and conserve agricultural soil health and individuated the EU Soil Framework Directive (SFD) as a meaningful complementary policy tool in the context of a renewed effort to pursue protection and conservation of soil health.

9. Wielgusz K, Praczyk M, irzykowska l, Swerek D: **Fertilization and soil pH affect seed and biomass yield, plant morphology, and cadmium uptake in hemp (Cannabis sativa L.)**. *Ind Crop Prod* 2022, **175**, 114245, https://doi.org/10.1016/j.indcrop.2021.114245.

10. * McDowell RW, Gray CW: **Do soil cadmium concentrations decline after phosphate fertilizer application is stopped: a comparison of long-term pasture trials in New Zealand?** *Sci Total Environ* 2022, **804**, 150047, https://doi.org/10.1016/j.scitotenv.2021.150047.

Authors demonstrated through modelling evaluation that stopping P fertiliser inputs especially over 20 years may impair pasture production, and individuated additional strategies able to decrease soil Cd quickly.

11. McLaughlin MJ, Smolders e, Zhao FJ, Grant C, Montalvo D: **Chapter One - managing cadmium in agricultural systems**. *Adv Agron* 2021, **166**:1–129, https://doi.org/10.1016/bs.agron.2020.10.004. 2021.

12. Garske B, Ekardt F: **Economic policy instruments for sustainable phosphorus management: taking into account climate and biodiversity targets**. *Environ Sci Eur* 2021, **33**:56, https://doi.org/10.1186/s12302-021-00499-7.

13. United States Geological Survey (USGS): *Mineral commodity summaries*. Reston, Virginia, United States: USGS; 2020.

14. European Commission: *COM (2020) 474 final. Communication from the commission to the European parliament, the Council, the European economic and social committee and the committee of the regions: critical raw materials resilience: charting a path towards greater security and sustainability*. Brussels: European Commission; 2020.

15. Cornell S: *Planetary boundaries research stock*. Resil; 2020. Cent, https://www.stockholmresilience.org/research/planetary-boundaries.html. Accessed 13 May 2022.

16. Zrelli RE, Rabaoui l, van Beek P, Castet S, Marc Souhaut M, *et al.*: **Natural radioactivity and radiation hazard assessment of industrial wastes from the coastal phosphate treatment plants of Gabes (Tunisia, Southern Mediterranean Sea)**. Elsevier *Mar Pollut Bull* 2019, **146**:454–461. ff10.1016/j.marpolbul.2019.06.075ff. ffhal-03487369f.

17. Santos AF, Almeida PV, Alvarenga P, Gando-Ferreira LM, Quina MJ: **From wastewater to fertilizer products: alternative paths to mitigate phosphorus demand in European countries**. *Chemosphere* 2021, **248**, 1311258, https://doi.org/10.1016/j.chemosphere.2021.131258.

18. EUROSTAT: *Mineral fertilization consumption*. 2020. ttps://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_mineral_fertiliser_consumption.

19. Capua F, Sario A, Ferraro A, Petrella A, Race M, Pirozzi F, Fratino U, Spasiano D: **Phosphorous removal and recovery from urban wastewater: current practices and new directions**. *Sci Total Environ* 2022, **823**, 153750, https://doi.org/10.1016/j.scitotenv.2022.153750.

20. European Commission: **A new circular economy action plan for a cleaner and more competitive Europe**. *EU Circ Econ Action Plan* 2020 [WWW Document], https://ec.europa.eu/environment/circular-economy/; 2020 (Accessed May 2022).

21. El Bamiki R, Seranne M, Chellai H, Merzeraud G, Morzoqi M, Dobrinescu MC: **The Moroccan High Atlas phosphate-rich sediments: unraveling the accumulation and differentiation processes**. *Sediment Geol* 2020, **403**, 105655, https://doi.org/10.1016/j.sedgeo.2020.105655.

22. Roberts TL: **Cadmium and phosphorous fertilizers: the issues and the science**. *Procedia Eng* 2014, **83**:52–59.

23. Mar SS, Okazaki M: **Investigation of Cd contents in several phosphate rocks used for the production of fertilizer**. *Microchem J* 2012, **104**:17–21, https://doi.org/10.1016/j.microc.2012.03.020.

24. Amarasinghe T, Madhusha C, Munaweera I, Kotegoda N: **Review on mechanisms of phosphate Solubilisation inrock phosphate fertilizer**. *Commun Soil Sci Plant Anal* 2022, **53**, https://doi.org/10.1080/00103624.2022.2034849.

25. OPERA: *Cadmium limits in phosphorous fertilizers*. 2021. https://operaresearch.eu/it/download/cadmium-limits-in-phosphorous-fertilizers/.

26. * Gray CW, McDowell RW, Condron LM, McLenaghen RD: **Changes in soil cadmium concentrations with time following cessation of phosphorus fertilizer inputs**. *J Environ Qual* 2020, **49**:1054–1061, https://doi.org/10.1002/jeq2.20086.

Authors investigated whether the application of nitrogen (N) could increase plant uptake of Cd and reduce soil Cd concentrations. It was found that there was no significant change in total or labile soil Cd concentrations after Cd inputs stopped. The application of N did not significantly increase dry matter yield or increase Cd solubility. As a result, N did not enhance plant uptake of Cd.

27. Hussain B, Ashraf MN, Shafeeq-ur Rahman, Abbas A, Farooq M: **Cd stress in paddy fields: effects of soil conditions and remediation strategies**. *Sci Total Environ* 2021, **754**, https://doi.org/10.1016/j.scitotenv.2020.142188. Article 142188.

28. Wang W, Kong W, Shen T, Man Z, Zhu W, He Y, Liu F, Liu Y: **Application of laser-induced breakdown spectroscopy in detection of Cd content in rice stems**. *Front Plant Sci* 2020:2073, https://doi.org/10.3389/fpls.2020.599616 [online] 11.

29. Zhang J, Zhu Y, Yu L, Yang M, Zou X, Yin C, Lin Y: **Research advances in cadmium uptake, transport, and resistance in rice (Oryza sativa L.)**. *Cells* 2022, **11**:569, https://doi.org/10.3390/cells11030569.

30. Luo JS, Zhang Z: **Mechanisms of cadmium phytoremediation and detoxification in plants**. *Crop J* 2021, **9**:521–529, https://doi.org/10.1016/j.cj.2021.02.001.

31. Tan L, Qu M, Zhu Y, Peng C, Wang J, Gao D, Chen C: **ZINC TRANSPORTER5 and ZINC TRANSPORTER9 function synergistically in Zinc/Cadmium uptake**. *Plant Physiol* 2020, **183**:1235–1249, https://doi.org/10.1104/pp.19.01569.

32. Haider FU, Liqun C, Coulter JA, Cheema SA, Wu J, Zhang R, Wenjun M, Farooq M: **Cadmium toxicity in plants: impacts and remediation strategies**. *Ecotoxicol Environ Saf* 2021, **211**, 111887, https://doi.org/10.1016/j.ecoenv.2020.111887.

33. Sterckeman T, Thomine S: **Mechanisms of cadmium accumulation in plants**. *Crit Rev Plant Sci* 2020. ff10.1080/07352689.2020.1792179ff.

34. Nordberg GF, Akesson A, Nogawa K, Nordberg M: *Chapter 7 – cadmium, handbook on the toxicology of metals*. 5th ed. 2022:141–196, https://doi.org/10.1016/B978-0-12-822946-0.00006-4.