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Global Food Security Threatened by Potassium Neglect

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Food security and healthy ecosystems are placed in jeopardy by poor potassium management. Six actions may prevent declines in crop yield due to soil potassium deficiency, safeguard farmers from potash price volatility, and address environmental concerns associated with potash mining.

Inadequate potassium management jeopardises food security and freshwater ecosystem health. Potassium, alongside nitrogen and phosphorus, is a vital nutrient for plant growth[1] and will be fundamental to achieving the rapid rises in crop yield necessary to sustain a growing population. Sustainable nutrient management is pivotal to establishing sustainable food systems and achieving the UN Sustainable Development Goals. While momentum to deliver nitrogen[2] and phosphorus sustainability[3] builds, potassium sustainability has been chronically neglected. There are no national or international policies or regulations on sustainable potassium use equivalent to those for nitrogen and phosphorus. Calls to mitigate rising potassium soil deficiency by increasing potassium inputs in arable agriculture are understandable[4,5]. However, substantial knowledge gaps persist regarding the potential environmental impacts of such interventions. We outline six proposed actions that aim to prevent crop yield declines due to soil potassium deficiency, safeguard farmers from price volatility in potash (i.e. mined potassium salts used to make fertiliser) and address environmental and ecosystem concerns associated with potash mining and increased potassium fertiliser use.

The potassium threat

An estimated 20% of global agricultural soils face severe potassium deficiency; most critically in South-East Asia (44%), Latin America (39%), Sub-Saharan Africa (30%), and East Asia (20%)[6]. Despite varying data reliability, the global trend over recent decades shows more potassium is removed than applied in harvests[1,6]. Large agricultural areas, including 75% of China's rice paddy soils and 66% of the Southern Australian wheat belt are reportedly deficient in 'crop-available' soil potassium[7,8]. Depleting crop-available potassium threatens crop productivity and food security in multiple countries[5,9]. Notably, in India, despite the perception of potassium-rich soils, negative soil potassium balances are causing crop-yield losses[5]. These issues, exacerbated by limited or absent potassium fertilisation, emphasise the need for site-specific management. Similarly, declining crop fertility due to potassium deficiency in historically high-potassium soils in the Southern Cone of Latin America, North Africa, and Western USA has been reported[5].

However, increasing the application of potassium fertilisers presents notable and often overlooked challenges.

Firstly, geological reserves of potash are limited to a few countries. Potash encompasses mined and manufactured salts containing water-soluble potassium (e.g. potassium chloride and sulfate). Over 90% of mined potash is used in fertiliser; the remainder for industrial water treatment, animal feed, cement, fire extinguishers and textiles[10]. Canada, Belarus, and Russia collectively possess approximately 70% of the world's potash reserves. In terms of potash production, Canada, Russia, Belarus, and China combined contribute approximately 80% of the global output (Table 1). Consequently, food systems in most countries rely on potassium fertiliser imports making them vulnerable to supply disruptions. Although peak potash is projected by 2057[10], current shortages for farmers are driven by production, economics, and politics.

Global consumption of fertiliser nutrients has consistently risen since the 1960s and is currently at an all-time high (Figure 1a). Currently, twelve countries dominate the $15 billion international market for potassium fertiliser, representing a quarter of the total fertiliser market value[12]. Canada (38%), Belarus (22%), and Russia (20%) collectively supply 80% of international potash exports[13]. In 2021, global potash consumption reached 45 million tonnes (Mt)[11]. Global annual potash production capacity has been projected to increase to 69 Mt by 2025, supported by new mines and expansion projects in Belarus, Canada and Russia, as well as planned projects in Australia, Eritrea and the UK[11]. Anticipated expansion is expected to lead to elevated emissions of pollutants into the air, soil, and water, potentially impacting ecosystems and local communities[14]. Potash mining activities have raised human rights concerns, including the displacement of indigenous populations, potential labour rights violations, and social disruptions in affected regions[15,16,17].

Secondly, potash prices are prone to volatility; prices spiked in 2009 and 2021 (Figure 1b). In 2009, potash prices spiked by ~240% reaching 682 \$ t^{-1}[18]. This was likely due to a combination of factors, including rising fossil fuels costs, Indian fertiliser subsidies and rising biofuel prices, that also impacted the price of other commodities including phosphorus[19]. In

2021, a ‘perfect storm’ of drivers including rising fertiliser demand, economic recovery from COVID-19, Russia’s invasion of Ukraine, escalating fuel prices, and several ‘knee jerk’ government policies to protect domestic fertiliser supplies (e.g. China halting fertiliser exports), led to a rapid escalation in the price of fertilisers and other commodities[19]. In the same year, the global potash market faced more turbulence, with the EU, UK, US and Canada imposing potash import sanctions on Belarus and Russia[20]. By April 2022, potash price spiked by ~500%, reaching 1202 $\$Mt^{-1}$[18]. Countries that could afford to stockpiled, whilst many farmers were forced to significantly reduce potassium fertiliser use[21]. At present, potash prices are below 50% of the 2022 peak, attributed to higher-than-anticipated supplies from Russia and Belarus entering global markets[21].

The 2022 fertiliser price spike raised global concerns that farmers will not be able to access sufficient fertiliser to produce food using existing farming systems[23,24]. These price spikes, also observed for nitrogen and phosphorus, highlighted the urgent need to future-proof food systems to fertiliser price instability and reduce farmers' vulnerability to fertiliser price spikes, exacerbated by heavy reliance on synthetic fertilisers[19,22].

Thirdly, potash mining is exerting substantial environmental impacts on the atmosphere, surface water, groundwater, soil and vegetation[25]. Over the past decade, potash production has risen by 9%, driven particularly by increased demand in South-East Asia[11]. Addressing growing agricultural demand necessitates an escalation in both potash ore mining and processing. Like other mining activities, the potash industry generates millions of tonnes of tailings, with approximately three tonnes of tailings (comprising solid halite waste, clay–salt slurry and saturated brines) produced for each tonne of extracted potash[25,26].

These mining wastes are commonly disposed of in tailing piles, forming artificial mountains predominantly composed of sodium chloride (Figure 2). This storage approach, often in open locations near mines, has significant environmental ramifications. Uncontrolled discharge of hypersaline effluents from potash waste disposal sites leads to soil, groundwater and surface water salinisation, causing substantial harm to fauna and flora[25,27,28]. Direct ecological impacts include a reduction in total biomass and species diversity in aquatic ecosystems with a prevalence of halophilic species[29]. Such ecological impacts have been observed in Spain[26], Germany[30], Russia and Belarus[25] and Canada[31], and range from local to catchment scale. Despite potential management measures such as brine collectors, challenges persist as salts can still dissolve through rain and humidity, and leaks may occur from collecting and retention infrastructures[27,32].

In contrast to nitrogen and phosphorus, the effects of anthropogenic potassium enrichment in freshwaters are poorly understood. Issues like harmful algal blooms typically arise from excess nitrogen or phosphorus rather than excess potassium[33]. However, potassium soil deficiency can reduce crop nutrient use efficiency for both nitrogen and phosphorus, potentially increasing the risk of nitrogen and phosphorus pollution. Where crop yields are limited by insufficient potassium, applications of nitrogen and phosphorus must be accordingly reduced. This is essential to prevent an unnecessary build-up of these nutrients in the soil, which may not be utilized by the crop. In addition, available studies suggest that potassium is among the most toxic ion for freshwater biodiversity[34,35], however the physiological mechanisms that regulate potassium toxicity are still unclear[36]. Overall, the effects of increased potassium loading, and, more broadly, increased salinity, on freshwaters requires further attention[37].

A call for international action

We propose the following six actions to prevent potential severe declines in crop yield due to soil potassium deficiency, safeguard farmers from the potash price volatility and address environmental concerns associated with (the poorly regulated expansion of) potash mining:

1. Review current potassium stocks and flows.

Initiate global scale assessment of current potassium soil stocks to identify the most at-risk countries and regions. This assessment should acknowledge the different fractions of bioavailable and non-bioavailable potassium in soils and roots[8]. A quantified life cycle analysis of potassium flows throughout the anthropogenic potassium cycle/food system (as depicted in Yakovleva et al., 2021) is also needed. Such analyses are essential to pinpoint opportunities for reducing losses, enhancing potassium recycling[39] and identifying more sustainable practices.

2. Establish capabilities for monitoring and predicting potassium price fluctuations.

It is imperative to develop national-scale potassium supply and demand monitoring and forecasting capabilities to safeguard farmers and mitigate food security risks arising from potash price volatility. A thorough review of current potash reserves and resources, production and consumption will be essential to understanding and managing the risks associated with trade channels between potash-producing and consuming nations. Governments must acknowledge potash supply risks, emphasising the necessity for accurate data on reserves, resources, and supply and demand[10]. International schemes for classifying and reporting raw material resources can enhance potassium data accuracy. UN regional bodies, like the ‘Aarhus Convention’ on environmental information access, may facilitate improved public access to global potassium reserve and fertiliser production data. The focus should extend to examining connections within local and global mineral supply chains, promoting responsible consumption and production while acknowledging the environmental and social implications of mining and processing minerals for agriculture.

3. Help farmers maintain sufficient soil potassium levels

Defining 'sufficient’ potassium to avoid crop yield losses involves local assessment. Studies conducted in the UK demonstrated spring barley yield in response to nitrogen application was ~40% lower in soils with low compared to high potassium levels[40]. However, further research is required to better assess the yield implications of potassium limitation across diverse crops and soils. Such assessment should consider soil potassium stocks, soil characteristics, crop types and leaching potential, and may be significantly affected by the incorporation of measures to reduce potassium losses[4]. National-scale assessments are essential to address knowledge gaps and to develop targeted fertiliser recommendations for optimal crop yield and environmental sustainability.

Challenges to ensuring sufficient potassium soil levels will vary between regions and shape national approaches. Some countries may prioritise affordable potassium fertiliser access, necessitating credit, subsidies and improved infrastructure. Others may look to optimise the recycling of potassium-rich materials like manure and food waste. This will require public education, agricultural extension services, and in some cases enhanced infrastructure. Governments have an additional chance to consider utilising ‘International Commodity Agreements’ for safeguarding food security in developing economies with high market exposure[41]. This approach could follow a ‘fair and equitable benefit-sharing’ model, akin to examples seen in various natural resource sectors[42]. Multilateral and bilateral agreements could be employed to ensure a stable potassium supply for nations lacking domestic resources, with reciprocal arrangements securing agricultural exports from these vulnerable countries. Equitable trade of potash and potassium fertilisers is crucial, demanding international cooperation, exemplified by the World Trade Organization (WTO) mediations[43].

4. Evaluate the environmental effects of potash mining and increased potassium application to identify sustainable practices.

There is a pressing need for a synthesis of evidence concerning environmental damage attributable to potash mining. The impact of potash mining on river ecosystems, although a global contributor to river salinisation, is not well understood[27]. A combination of laboratory, mesocosm and field studies is advised to establish safe potassium concentrations for aquatic life and understand the implications of potash pollution for ecosystem integrity. Additionally, specific biotic indices should be developed for detecting salt pollution[34] and anticipating ecological disasters[27]. A priority lies in responsible and transparent recording of the environmental consequences of potash mining, supported by stringent regulations to minimise pollution[44]. Evaluating and implementing mining process innovations to better manage polluting wastewater, such as electro-separation[45], will be crucial for transitioning to a more environmentally conscious mining sector.

Polyhalite, a potassium mineral, has been suggested as a substitute for potash as a source of potassium in fertilisers. Polyhalite has a lower chloride content and therefore salinisation risk associated with its production. While it has a lower potassium concentration than potash, it contains additional crop micronutrients (e.g. sulfur, magnesium, calcium). A new polyhalite mine in England, backed by a multi-billion investment, is sparking debate over its potential to disrupt the global potash market[46].

There is also an urgent need to promptly enhance our understanding of the potential environmental repercussions resulting from the increased application of potassium fertilisers to soils and the associated risk of potassium leaching. Addressing global soil potassium deficiency necessitates careful consideration, especially when evidence points to potential toxicity to freshwater organisms due to elevated potassium levels[34]. Addressing potassium deficiency has the potential to decrease the environmental impact of nitrogen and phosphorus losses through enhanced crop yields and nutrient use efficiency. An integrated approach to the sustainable management of nitrogen, phosphorus and potassium in agriculture and wastewater, focussed on limiting pollution of freshwater and coastal ecosystems, is long overdue.

5. Develop a global strategy to transition to a circular potassium economy.

Establishing a circular potassium economy will require coordinated efforts of multiple stakeholders across the supply chain, including agriculture, wastewater, food industries and society[38]. Key measures involve potassium-efficient farm practices, such as precision/low emission fertiliser application and erosion control to mitigate potassium losses. Investigating potential amendments and bio-fertilisers to release non-bioavailable potassium in soils is also crucial. The growth of potassium recovery industries should play a key role but requires further research and will likely need policy backing and financial support to accelerate innovation and improve competitiveness. Exploring unconventional potassium sources from waste ash (e.g. cocoa waste, plantain waste, market waste, and water hyacinth) shows promise but remains underutilised[39]. A societal shift towards diets with lower potassium footprints, aligning with healthier and less meat-intensive choices, supports this overall transition. The overarching goal is to reduce reliance on mined potassium sources[38], thereby mitigating vulnerability to price fluctuations and environmental pollution associated with potash production.

6. Accelerate intergovernmental cooperation as a catalyst for change.

Potassium management is largely disregarded in the food and environmental policy agendas of most countries. These gaps stem from a lack of awareness and coordination, particularly evident in current national policies that inadequately address the environmental harm resulting from potash mining wastewater salinisation[27]. In January 2024, the United Nations Environment Programme (UNEP) Working Group on Nitrogen, in conjunction with the Global Partnership on Nutrient Management (GPNM), hosted by UNEP, delivered a phosphorus sustainability update to the national focal points of the UN working group. Ahead of United Nations Environment Assembly 6, the UNEP Executive Director's Report highlighted that phosphorus has been a "..blind spot in international cooperation around nutrients" and raises the opportunity for member states to advance on this issue (UNEP/EA.6/2). We highlight a similar issue and opportunity for potassium. Similar UN momentum on potassium, aligned with actions on phosphorus and nitrogen, will increase awareness on the need for action on integrated nutrient management globally. This is essential if the Kunming-Montreal Global Biodiversity Framework Targets 2 and 7 are to be met by 2030.

We call for international action on potassium, advocating for the creation or expansion of an intergovernmental coordination mechanism, similar to that being developed for nitrogen[47]. Prompted by the European Parliament's acknowledgement of food security risks tied to Belarusian potash reliance amid geopolitical events[48], this mechanism should aid governments, conventions, and stakeholders in fostering integrated action on potassium sustainability. An international framework to consolidate knowledge on potassium cycles, set globally agreed targets, and quantify the economic benefits of action, would appear essential in support of this. A future UNEA resolution on potassium provides a key opportunity for intergovernmental action, showcasing a strong commitment to fostering positive change.

Data Availability

All data supporting the findings of this comment are publicly available and listed in the references section.

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Contributions

W.J.B. co-conceived the idea of the manuscript, led the writing of the paper, and collated and conducted data analysis. P.A., M.M., M.C.A., M.A.S., and B.M.S. contributed to writing the paper.

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Competing interests

The authors declare no competing interests.

Figure 1. The monthly price, January 2007 to June 2022, of nutrients used in fertiliser production (US$ $tonne^{-1}$)[18]; potassium chloride, triple super phosphate and urea. The price of potassium chloride peaked in 2008 and increased sharply again in 2021. Key national responses impacting the trade of potassium include; **Jan-2008 to Jun-2009:** Demand led price spike – likely due to multiple interacting factors including rising fossil fuels costs, Indian fertiliser subsidies and rising biofuel prices; **Jan-2013:** Fragmentation of the Belarusian Potash Company (representing Uralkali and Belaruskali) caused international potash prices to fall; **Jan-2020**: COVID-19 outbreak impacts prices of multiple commodities including potash and potassium fertiliser; **March-2022**: Russia halts fertiliser exports (after invading Ukraine in Feb-22); **May to Sept-2022**: EU, UK, US and Canada imposing potash import sanctions on Belarus.

Figure 2. Global consumption of nutrients used in fertiliser production between 1961 and 2021[49]; potassium (Mt of K in K_2O); nitrogen (Mt of N), phosphate (Mt of P in P_2O_5).

Table 1. Potash production in 2020 and 2021 and estimated potash reserves in 2021 for Belarus, Canada, China and Russia as percentages of World totals[11].

Country	**Potash production (% of World total)**		**Potash reserves in 2021 (% of World total)**
	2020	**2021**	
Belarus	16%	8%	23%
Canada	31%	40%	33%
China	13%	15%	5%
Russia	20%	13%	12%

References

1. Zörb, C., Senbayram, M. & Peiter, E. Potassium in agriculture – Status and perspectives. *J Plant Physiol* **171**, 656–669 (2014).

2. Sutton, M. A. *et al.* The nitrogen decade: mobilizing global action on nitrogen to 2030 and beyond. *One Earth* **4**, 10–14 (2021).

3. *Our Phosphorus Future*. (UK Centre for Ecology & Hydrology, 2022). doi:10.13140/RG.2.2.17834.08645.

4. Leverich Nigon, L. & Bruulsema, T. Assessing Soil Potassium: Basic Principles and New Developments. *Crops & Soils* **56**, 29–34 (2023).

5. *Improving Potassium Recommendations for Agricultural Crops*. (Springer International Publishing, 2021). doi:10.1007/978-3-030-59197-7.

6. Grzebisz, W., Szczepaniak, W., Potarzycki, J. & Ukowiak, R. Sustainable Management of Soil Potassium – A Crop Rotation Oriented Concept. in *Soil Fertility* (InTech, 2012). doi:10.5772/53185.

7. Mengel, K. & Kirkby, E. *Principles of plant nutrition*. (Kluwer Academic Publishers, 2001).

8. Römheld, V. & Kirkby, E. A. Research on potassium in agriculture: needs and prospects. *Plant Soil* **335**, 155–180 (2010).

9. Sheldrick, W. F., Syers, J. K. & Lingard, J. A conceptual model for conducting nutrient audits at national, regional, and global scales. *Nutr Cycl Agroecosyst* **62**, 61–72 (2002).

10. Al Rawashdeh, R. World peak potash: An analytical study. *Resources Policy* **69**, 101834 (2020).

11. Jasinski, S. 2022 Minerals Yearbook - Potash. *U.S. Geological Survey* (2022).

12. Chatham House. 'resourcetrade.earth'. https://resourcetrade.earth/ (2021).

13. Government of Canada. Potash Facts. (2023). https://natural-resources.canada.ca/our-natural-resources/minerals-mining/minerals-metals-facts/potash-facts/20521

14. Martin, A. & Iles, A. The Ethics of Rare Earth Elements Over Time and Space. in *Ethics of Chemistry* 317–346 (World Scientific, 2021). doi:10.1142/9789811233548_0012.

15. Myette, E. & Riva, M. Surveying the complex social-ecological pathways between resource extraction and Indigenous Peoples' health in Canada: A scoping review with a realist perspective. *Extr. Ind. Soc.* **8**, 100901 (2021).

16. Fernandes, S., Fernandes, G. W. & Fearnside, P. M. Viewpoint: Sovereignty and reversing Brazil's history of Amazon destruction. *Land use policy* **133**, 106868 (2023).

17. Al Rawashdeh, R., Campbell, G. & Titi, A. The socio-economic impacts of mining on local communities: The case of Jordan. *Extr. Ind. Soc.* **3**, 494–507 (2016).

18. World Bank. World Bank Commodities Price Data (The Pink Sheet). (2023).

19. Brownlie, W. J. *et al.* Phosphorus price spikes: a wake-up call for phosphorus resilience. *Front Sustain Food Syst* (2022).

20. Baffes, J. & Koh, W. Soaring Fertilizer Prices Add to Inflationary Pressures and Food Security Concerns. Available. *World Bank Data Blog* (2021).

21. Hook, L. Ukraine war thrusts fertiliser minerals to centre of food security debate. *Financial Times* (2023).

22. Alexander, P. *et al.* High energy and fertilizer prices are more damaging than food export curtailment from Ukraine and Russia for food prices, health and the environment. *Nat Food* **4**, 84–95 (2022).

23. UN GCRG. Global Impact of war in Ukraine on food, energy and finance systems. **Brief no 1**, (2022).

24. World Bank Group. *Commodity Markets Outlook: The Impact of the War in Ukraine on Commodity Markets, April 2022.* (World Bank, 2022).

25. Ushakova, E. *et al.* Environmental Aspects of Potash Mining: A Case Study of the Verkhnekamskoe Potash Deposit. *Mining* **3**, 176–204 (2023).

26. Gorostiza, S. & Saurí, D. Naturalizing pollution: a critical social science view on the link between potash mining and salinization in the Llobregat river basin, northeast Spain. *Philosophical Transactions of the Royal Society B: Biological Sciences* **374**, 20180006 (2019).

27. Cañedo-Argüelles, M. *et al.* Effects of potash mining on river ecosystems: An experimental study. *Environmental Pollution* **224**, 759–770 (2017).

28. Haj-Amor, Z. *et al.* Soil salinity and its associated effects on soil microorganisms, greenhouse gas emissions, crop yield, biodiversity and desertification: A review. *Science of The Total Environment* **843**, 156946 (2022).

29. Feld, C. K., Lorenz, A. W., Peise, M., Fink, M. & Schulz, C.-J. Direct and indirect effects of salinisation on riverine biota: a case study from river Wipper, Germany. *Hydrobiologia* **850**, 3043–3059 (2023).

30. Coring, E. & Bäthe, J. Effects of reduced salt concentrations on plant communities in the River Werra (Germany). *Limnologica* **41**, 134–142 (2011).

31. Baberschke, N., Irob, K., Preuer, T., Meinelt, T. & Kloas, W. Potash mining effluents and ion imbalances cause transient osmoregulatory stress, affect gill integrity and elevate chronically plasma sulfate levels in adult common roach, Rutilus rutilus. *Environmental Pollution* **249**, 181–190 (2019).

32. Gorostiza, S., March, H., Conde, M. & Sauri, D. Corrosive flows, faulty materialities: Building the brine collector in the Llobregat River Basin, Catalonia. *Environ Plan E Nat Space* 251484862211058 (2022).

33. Talling, J. F. Potassium - A Non-Limiting Nutrient in Fresh Waters? *Freshwater Reviews* **3**, 97–104 (2010).

34. Schulz, C. & Cañedo-Argüelles, M. Lost in translation: the German literature on freshwater salinization. *Philosophical Transactions of the Royal Society B: Biological Sciences* **374**, 20180007 (2019).

35. Mount, D. R. *et al.* The acute toxicity of major ion salts to Ceriodaphnia dubia : I. influence of background water chemistry. *Environ Toxicol Chem* **35**, 3039–3057 (2016).

36. Griffith, M. B. Toxicological perspective on the osmoregulation and ionoregulation physiology of major ions by freshwater animals: Teleost fish, crustacea, aquatic insects, and Mollusca. *Environ Toxicol Chem* **36**, 576–600 (2017).

37. Cunillera-Montcusí, D. *et al.* Freshwater salinisation: a research agenda for a saltier world. *Trends Ecol Evol* **37**, 440–453 (2022).

38. Yakovleva, N., Chiwona, A. G., Manning, D. A. C. & Heidrich, O. Circular economy and six approaches to improve potassium life cycle for global crop production. *Resources Policy* **74**, 102426 (2021).

39. Adeoye, G. O., Sridhar, M. K. C. & Ipinmoroti, R. R. Potassium recovery from farm wastes for crop growth. *Commun Soil Sci Plant Anal* **32**, 2347–2358 (2001).

40. Johnston, A.E. & Milford, G.F.J. Potassium and nitrogen interactions in crops. https://www.pda.org.uk/technical-potash-notes/potassium-and-nitrogen-interactions-in-crops/#l3. Potash Development Association (2012).

41. Oehl, M. E. *Sustainable Commodity Use*. vol. 21 (Springer International Publishing, 2022).

42. Morgera, E. The Need for an International Legal Concept of Fair and Equitable Benefit Sharing. *European Journal of International Law* **27**, 353–383 (2016).

43. Karapinar, B. China's export restriction policies: complying with 'WTO plus' or undermining multilateralism. *World Trade Review* **10**, 389–408 (2011).

44. Schuler, M. S. *et al.* Regulations are needed to protect freshwater ecosystems from salinization. *Philosophical Transactions of the Royal Society B: Biological Sciences* **374**, 20180019 (2019).

45. Jena, S. A Review on Potash Recovery from Different Rock and Mineral Sources. *Min Metall Explor* **38**, 47–68 (2021).

46. Dempsey, H. & Susannah, S. Anglo American's high-stakes bet on a new way to feed the world. *Financial Times* **November 23rd**, (2023).

47. UNEP. Roadmap for Action on Sustainable Nitrogen Management 2020-2022. Implementation of UNEA-4 Resolutions: Follow-up to UNEP/EA.4/Res.14. **Inf. Doc.**, (2019).

48. European Parliament. European Parliament resolution of 24 March 2022 on the need for an urgent EU action plan to ensure food security inside and outside the EU in light of the Russian invasion of Ukraine (2022/2593(RSP)). (2022).

49. Food and Agriculture Organization of the United Nations (FAO). FAOSTAT. *Food and Agricultural Data* https://www.fao.org/faostat/en/#data/RFN (2023).