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**Peter Hirner**

# Interdependencies in a Global Production Network

## Phosphorus Supply Chain

The contemporary global economy relies on complex and highly interconnected international supply chains. Disruptions increasingly affect industrial production as well as the availability of essential goods such as food, hygiene products, and medical supplies. Reliable access to these goods critically depends on the stable functioning of supply chains. Recent crises and geopolitical tensions have exposed structural vulnerabilities, particularly in countries with limited domestic production capacities (Gerschberger et al., 2023).

Phosphorus fertilizers are a cornerstone of global food production. Alongside nitrogen and potassium, phosphorus is indispensable for plant growth and contributes to approximately half of global crop yields. Beyond agriculture, phosphorus plays a fundamental role in cellular energy transfer (ATP) and in structural components such as bones and teeth (Mew et al., 2018). Ensuring a reliable phosphorus supply is therefore essential for global food security and resilient agricultural systems.

### Structures, Risks, and Recycling

Phosphate rock extraction is highly concentrated. Just five countries—Morocco, China, the United States, Russia, and Jordan—account for around 80 % of global phosphate mining, while a small number of firms control the majority of global production capacity. In 2023, global phosphate rock output reached approximately 319 million tonnes, of which nearly 93 % was ultimately used for food production. Declining ore grades, finite reserves, and low recycling rates leave many countries dependent on a small group of producers and key processing hubs. As production is largely company-driven, firms play a central role in building supply chain resilience through transparency, which enables effective risk management and organizational preparedness (Felbermayr & Janeba, 2024).

Environmental and supply challenges are further exacerbated by inefficient use and resource-intensive processing. Only 5–10 % of the phosphorus applied in food production ultimately reaches human consumption; the remainder is lost through processing inefficiencies, by-products, waste streams, or long-term accumulation in soils and construction materials. Recovery from secondary sources—such as wastewater, manure, and food industry residues—is increasingly promoted as a strategic environmental and supply measure. However, recycling alone cannot eliminate dependence on primary

producers. In Europe, recycling could potentially cover 10–20 % of demand (Fraunhofer ISI, 2024). Medium-term physical scarcity is considered unlikely, partly due to the reclassification of economically viable reserves.

## Methodological Framework and Case Studies

To systematically assess structural dependencies, the presented framework is based on physical mass flows along the phosphorus value chain. The chain is divided into five product categories, ranging from phosphate rock extraction (upstream) to finished mixed fertilizers (downstream). This structure allows international trade flows to be interpreted as linked transformation processes. Countries are classified according to their dominant roles—miner, transformer, trader, or consumer—and structural equivalences are identified using clustering methods based on inflow and outflow patterns. Risk exposure is quantified using concentration and diversification metrics, including the Herfindahl–Hirschman Index (HHI), highlighting countries that are particularly vulnerable due to dependence on a limited number of suppliers. This quantitative approach enables policymakers and firms to identify not only immediate supply risks but also potential cascading effects within the global network.

Application of the framework reveals substantial national differences. Non-mining countries such as Belgium, Germany, the Netherlands, Spain, and Israel function as trading and transformation hubs, linking upstream producers with downstream consumers. China and Morocco, by contrast, internalize large segments of the value chain, converting raw phosphate into higher-value fertilizer products in order to capture economic benefits domestically. Countries such as Jordan and Russia focus primarily on upstream extraction and exports, with limited involvement in downstream product categories. These structural differences shape both economic advantages and systemic vulnerabilities, influencing the global distribution of value added and downstream dependencies.

A detailed case application to the Netherlands illustrates how supply disruptions can propagate across product categories. Disruptions in category 2 (intermediate products immediately following phosphate rock mining) can cascade into categories 3–5, potentially affecting industrial users and agricultural production beyond national borders. Effective mitigation requires the identification of alternative suppliers with distinct supply structures in order to reduce shared vulnerabilities. Based on this approach, Belgium, France, Spain, and Israel emerge as plausible alternatives for specific product categories. The framework thus supports import diversification strategies by guiding the selection of suppliers that combine sufficient capacity with structural independence from existing dependencies. When combined with proactive policy instruments—such as strategic stockpiling and flexible trade agreements—this approach can significantly enhance national and regional supply chain resilience. Beyond direct trade relationships, the framework also highlights the complexity of corporate networks within the global phosphorus value chain.

## Geopolitical Dimensions and Conclusions

The global phosphorus supply chain is closely intertwined with broader geopolitical and technological dependencies. Many countries rely heavily on China, given its dominant role in phosphorus extraction, processing, and exploration, as well as its position in rare earth production. This concentration creates strategic vulnerabilities, particularly in the context of uneven global resource distribution and geopolitical volatility. Policies aimed at strengthening supply chain resilience must therefore integrate environmental, economic, and geopolitical considerations to ensure the stability of food systems and industrial supply networks.

Overall, the presented approach shows that phosphorus supply security is influenced less by imminent physical scarcity than by the structure and organization of global value chains, the diversification of trade partners, and the role of firms in maintaining supply continuity. Countries with diversified sourcing strategies and strong trading hubs are generally less exposed to disruptions, while those dependent on a narrow set of upstream suppliers face elevated risks. Industrial strategies such as vertical integration and domestic value addition can mitigate exposure and increase national economic benefits, but may also create new, concentrated points of failure.

By combining physical mass flow analysis with role classification and concentration metrics, the methodology provides a data-driven tool for identifying structural dependencies, assessing risk propagation, and designing targeted mitigation strategies. It supports the evaluation of alternative trade routes, substitution possibilities, and the prioritization of strategic stockpiles. These insights are relevant not only for policymakers and firms directly involved in phosphorus supply, but also for broader efforts to ensure resilient global food production, sustainable resource management, and adaptive responses to geopolitical uncertainty.

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