

Ruggedizing Haber-Bosch: Allocation, Efficiency, and Resilience in Fertilizer-Dependent Food Systems Under Supply Shock

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1. The crisis

On 28 February 2026, military escalation between the United States, Israel, and Iran led to the closure of the Strait of Hormuz and severe, ongoing disruption of the fertilizer trade that passes through it. Roughly one-third of globally traded seaborne fertilizer — on the order of 16 million tonnes annually — transits the Strait. The Persian Gulf accounts for approximately 43% of seaborne urea exports, roughly 44% of seaborne sulfur trade, and more than a quarter of global ammonia trade. The sulfur exposure is the one most easily missed, and it is why phosphate fertilizer prices moved while phosphate rock did not: sulfur is a feedstock for phosphate processing well outside the Gulf, and industry analysis puts roughly two-thirds of tradable sulfur supply currently out of the market — about half stranded behind the Strait, and a further 17% removed by a Russian export ban. The binding constraint on phosphate today is not rock in the ground; it is the sulfur needed to process it.

Prices moved immediately, and unevenly across the three macronutrients. Fertilizer price pressures intensified from February through April 2026, with urea surging over 80% — including a 46% month-on-month step — while DAP and TSP rose approximately 16% and 23% respectively, reflecting energy cost pass-through and trade-route uncertainty. Potash and phosphate rock prices showed no movement, insulated from the geopolitical and energy dynamics driving nitrogen and phosphate volatility. The World Bank’s April 2026 *Commodity Markets Outlook* projects fertilizer prices averaging 31% higher across 2026 than the prior year, reaching their least affordable levels since 2022. The World Bank characterises the closure of the Strait of Hormuz as the defining market event of the period, triggering the largest commodity supply disruption on record.

By August 2026 the three nutrients had visibly decoupled, and the divergence is itself diagnostic. In the US retail series — a national delivered price in short tons, distinct from the FOB benchmarks above and separated from them by freight and retail margin — nitrogen has retreated substantially from its spring peak: urea ran from \$574 per ton in January to \$864 in May, then fell to \$678 by the first week of August, while anhydrous peaked at \$1,126 in May and eased to \$963. Phosphate has not followed: DAP stood at \$917 and MAP at \$959 in early August, near the top of their twelve-month range. Potash barely moved at all, from \$484 in August 2025 to \$495 in August 2026. Seven of the eight tracked products remain above year-ago levels.

The pattern tracks the mechanism. Nitrogen eases as gas and shipping conditions partially normalise. Phosphate stays elevated because its binding constraint is sulfur, which has not been restored. Potash stays flat because its supply was never short. For a paper about which interventions to fund, that ordering matters: the nutrient showing the least relief is the one this paper’s largest section addresses, and it is also the nutrient whose replacement can be drawn from stock already present in the soil.

There is no internationally coordinated fertilizer reserve, in contrast to the strategic petroleum reserve architecture maintained for energy security. Several states do hold national buffers: India’s Department of Fertilizers reported 177.31 lakh metric tonnes across all grades in March 2026, an operational buffer equivalent to roughly 30–45 days of import-dependent supply, and China maintains a state reserve alongside an export quota system. What does not exist is a multilateral mechanism, or any meaningful strategic reserve for nitrogen at global scale.

The human consequence is measurable. The FAO-WFP *Hunger Hotspots* report of 17 June 2026, covering the June–November 2026 outlook period, identifies 13 countries and territories where acute food insecurity is expected to deepen. Six are at the highest concern level, where populations already face or risk entering Catastrophe (IPC Phase 5): **Sudan, South Sudan, Yemen, Palestine, Nigeria, and Somalia**. Three are at very high concern: Afghanistan, the Democratic Republic of the Congo, and Haiti. A risk of famine persists in four contexts: Sudan, South Sudan, the Gaza Strip, and Somalia. Conflict is the principal driver in 12 of the 13 hotspots.

The precedent set in 2025 is what makes the current input shock dangerous rather than merely expensive. Famine was confirmed in two places concurrently that year — the Gaza Strip in August 2025, and, by the IPC Famine Review Committee, the towns of El Fasher and Kadugli in Sudan in September 2025 — the first time two famines have been

confirmed simultaneously in the IPC's history. Conditions in Gaza have since improved following the October 2025 ceasefire and expanded humanitarian and commercial access; the IPC analysis for 16 April – 30 June 2026 places approximately 1.2 million people, 59% of the population, in Crisis or worse rather than in Famine. The improvement is real and should be stated as such. It is also partial: the World Bank's May 2026 assessment records truck inflows still well below pre-crisis levels, food stocks sufficient for only 10–14 days, and a 50% gap in key staples. What the improvement does not do is retire the risk — famine risk persists in four contexts, and the 2025 precedent established that the global system can reach famine in two places at once.

The World Food Programme's *2026 Global Outlook* projects approximately 318 million people in Crisis-level acute food insecurity (IPC Phase 3 or above) during 2026, of whom roughly 41 million are projected at Emergency (Phase 4) or worse. WFP further estimates that sustained high energy prices could push up to 45 million additional people into acute food insecurity. FAO's assessment is that the fertilizer-specific yield impact of this disruption has not yet fully arrived: the worst effects on harvests are projected for late 2026 into 2027. The interventions in this paper therefore have a real window to matter before, rather than after, the worst of the impact lands.

That window is not clear of other traffic. The World Bank places a 61–87% probability on an El Niño emerging by mid-2026 and persisting into 2027, threatening crop production across South Asia, Southern Africa, and parts of East Asia, with rice output potentially falling 20–50% in affected producers — in the Philippines, 15 provinces were already flagged in April 2026 as at risk of severe drought. The overlap is what matters for targeting. An early El Niño is expected to bring below-normal June–September 2026 rainfall across Ethiopia's Kiremt-producing areas, western Kenya, South Sudan, Sudan, and Karamoja in Uganda. Two of those are in the highest-concern tier above. The fertilizer shock's yield impact and an El Niño rainfall deficit are therefore converging on the same countries in the same seasons, from independent causes. A household that loses yield to unaffordable nitrogen and then loses the rains does not experience two moderate shocks; it experiences one severe one. Scale matters for how this should be read. Global rice output for the 2026–27 marketing year is projected toward 536 million tonnes, with El Niño-attributed losses estimated near 9 million tonnes — of order 1.7% of world production. That is not a global shortfall, and analyses of the current episode note that world inventories may absorb much of the physical shock. The relevant precedent is 2007–08, when a supply change of comparable magnitude produced a price crisis through export restrictions and precautionary purchasing rather than through physical scarcity. The exposure therefore falls on import-dependent countries and on policy response, not on global availability — which is precisely the population Section 2.3 places in Class B, and it is why the instruments that matter there are buffers, storage and restraint on export controls rather than agronomy.

This is the strongest available argument for acting inside the window rather than at the end of it, and it applies with most force to the interventions that need no supply chain.

This paper provides a systems analysis of replacement and resilience options across all three macronutrients — nitrogen, phosphorus, and potassium — ranked by deployment speed, cost, and scale. We identify seven interventions deployable within 12 months, several requiring no new technology at all, that could meaningfully close the current supply gap. An appendix records a line of enquiry that has been deprecated: an originally proposed physics-based route to phosphorus release, removed from the analysis for the reasons set out there.

2. The structural problem: supply concentration and the phosphorus lock

2.1 Supply concentration

Fertilizer production for all three macronutrients is concentrated among fewer than five countries each: nitrogen (urea) production is dominated by China, Russia, Qatar, Saudi Arabia, and Iran (~70% of exports); phosphorus by China, Morocco, Russia, the US, and Jordan (~75% of exports); potassium by Canada, Russia, Belarus, Morocco, and the US (over 90% of exports). This structure is a geological and economic feature of concentrated mineral deposits and Haber-Bosch capital intensity, not a market failure — which is precisely why diversification alone will not solve it, and why supply-independent interventions matter.

2.2 The phosphorus lock

Independent of any geopolitical disruption, phosphorus deficiency limits crop yields on an estimated 30–40% of the world's arable land, and phosphorus use efficiency in agricultural fields runs at only 15–20%. The cause is fixation: applied phosphate reacts on contact with soil to form sparingly soluble compounds — iron and aluminium phosphates (FePO_4 , AlPO_4) in acid soils, calcium phosphates ($\text{Ca}_3(\text{PO}_4)_2$) in alkaline ones — that plants cannot directly absorb. In acid soils, more than 80% of soil phosphorus becomes immobile and inaccessible to plant uptake.

The scale of the locked stock is easy to understate. Total soil phosphorus typically runs 50–3,000 mg/kg, but the soil solution — the pool a root can actually draw on at any moment — holds only 0.01 to 1 ppm. Soil phosphorus sits in three pools in slow equilibrium: solution P, labile P, and non-labile or fixed P, and conversion from the non-labile pool back to available forms is slow. The resource is present and already paid for; what is missing is access to it.

One qualification governs where that argument applies, and it cuts against a naive reading of this section. Roughly half of the world's soil-available phosphorus in agricultural systems is now derived from mineral fertilizer — a global anthropogenic signature of about 47% ($\pm 8\%$). That figure exceeds 60% in Western Europe, North America and Asia, sits near 40% in South America, and falls below 30% in Africa. The locked phosphorus this paper proposes to release is therefore predominantly a Northern and Asian asset. African soils are not phosphorus-rich soils whose stock is merely inaccessible; they are soils that have never received much phosphorus. **Release interventions are strongest exactly where legacy has accumulated, and weakest where the deficit is genuine.**

The scale of that deficit is quantifiable. Phosphorus fertilizer application averages roughly 196 kg/ha in Asia and about **5 kg P/ha in sub-Saharan Africa**. Set against the sorption-derived standard phosphorus requirements in Appendix A — 17 kg P/ha for the most responsive soil studied, 140 kg P/ha for the least — sub-Saharan application runs at roughly one third of what the most responsive Sahelian soil needs to reach a standard agronomic solution concentration, and around one twenty-eighth of what the least responsive needs. The 2026 supply shock is therefore acting on a system already chronically under-applied, not on one operating near its optimum.

Releasing already-present, already-purchased phosphorus, without any new external supply, is the highest-leverage single intervention available **in soils that hold a legacy stock**, and it is the thread connecting most of what follows. Where no such stock exists, the binding problem is access to external phosphorus, and Section 7 addresses it as such.

2.3 Classifying zones by nutrient-system properties rather than by region

Interventions in this paper do not sort by continent. They sort by a small number of measurable soil and system properties, and zones sharing those properties take the same prescription regardless of where they sit. Four classes cover the cases this paper addresses.

Class	Discriminants	Representative zones	Binding constraint	Interventions that work
A. Legacy-rich, over-applied	Anthropogenic P signature >60%; application ~100-200 kg/ha	Western Europe, North America, intensive East and South Asia	None acute. The opportunity is drawdown	Precision and variable-rate application; legacy drawdown; balanced nutrition; the release interventions of Section 4, which work here because there is a legacy to release
B. Climate-exposed, import-linked	Moderate application; rainfed or monsoon-dependent staple production; net importer of staples or inputs	Southeast Asia, rainfed South Asia, island and coastal states	Climate variance, price transmission, and producer export restrictions	Post-harvest loss reduction and storage; buffer stocks; variable-rate application where rates are high; planting-date and varietal timing
C. Nutrient-poor, allocation-limited	Signature <30%; application under ~10 kg P/ha; response variance of order 10×	Sahel, Lake Chad Basin, much of sub-Saharan Africa	Affordability and allocation — not physical availability	Allocation of existing tonnage by soil response; legumes with a phosphorus starter; short-term incentives; residue return; post-harvest storage
D. Access-constrained	Conflict is the principal driver; populations at IPC Phase 4-5	Sudan, South Sudan, Yemen, Palestine, Somalia, Haiti	Physical access, security, and logistics	Agronomic interventions largely cannot reach these zones. Delivery is the intervention

Two features of this classification deserve emphasis, because both cut against a comfortable reading.

The first is that Classes A and C are complementary rather than competing. Class A holds the accumulated phosphorus and applies at rates far above requirement; Class C has almost nothing to release and applies far below it. Demand reduction in Class A is therefore not merely a domestic efficiency gain — it frees supply that Class C can use, which is the mechanism Section 7.4 builds on.

The second is harder. **Conflict is the principal driver in twelve of the thirteen hotspots** identified in the June 2026 monitoring, which means the zones with the worst outcomes are largely Class D, and Class D is the class this paper's agronomic toolkit cannot serve. Mycorrhizal inoculants do not reach a besieged governorate. Soil-specific

targeting requires extension services that conflict has dismantled. This paper is most useful in Classes B and C, where the system functions but wastes what it has; in Class D its only honest contribution is to say that the constraint is access, and that agronomy is not the binding one.

3. Nitrogen replacement options

3.1 Green ammonia via electrolysis (near-term)

Green ammonia replaces natural-gas-sourced hydrogen with electrolytic hydrogen from renewable electricity. China held roughly 320,000 tonnes/year of green ammonia capacity by the end of 2025, about half of global capacity. Cost-competitiveness with conventional ammonia is projected by approximately 2030. Solar-rich regions — the Sahara, the Atacama, the Australian outback, the US Great Plains — have a structural advantage as future nitrogen-independent producers.

3.2 Biological nitrogen fixation (BNF) enhancement (medium-term)

Pivot Bio's PROVEN product, deploying nitrogen-fixing bacteria on maize roots, achieved a 25 lb/acre reduction in nitrogen need across 10 million acres in 2024. Engineering stable BNF into cereal genomes remains a 5–15 year moonshot with the potential to reduce synthetic nitrogen requirement substantially across a large share of global cropland. It should not be presented as a route to eliminating mineral nitrogen: the prevailing expert position is that soil fertility cannot be built or sustained without fertilizer, and that organic inputs transferred from elsewhere supply only a fraction of requirement while depleting the source.

3.3 Legume intercropping and rotation (immediate, zero cost)

Unlike engineered BNF, legume intercropping and rotation with existing crop varieties requires no new technology and is deployable this planting season. Cereal-legume rotations and intercrops (maize-cowpea, sorghum-groundnut, and similar pairings already in regional use) supply nitrogen to the following cereal crop through residual fixed nitrogen and reduced planted nitrogen-demanding area. The literature reports this as an absolute nitrogen replacement value rather than a percentage: 18–46 kg N/ha in East African trials, with legume nitrogen contributions of 32–83 kg/ha measured across Bambara groundnut, groundnut, mung bean, black gram and cowpea. West African trials in Niger and Burkina Faso recorded higher cereal yields and higher soil mineral nitrogen under legume rotation at every site. Expressed as a share of synthetic requirement the benefit depends entirely on the baseline application rate, which is why it is largest in exactly the low-input smallholder systems this paper targets — a credit of a few tens of kg N/ha covers a far greater fraction of requirement at Sahelian rates than at intensive-system rates. This is the single fastest nitrogen-side lever available precisely because it needs no supply chain, no capital investment, and no new input — only a planting decision. It is directly actionable in the West and Central Africa lean season (June–August) and in smallholder systems across the current highest-risk hotspots.

3.4 Nitrogen recovery from waste streams

Struvite (MgNH_4PO_4) precipitation from sewage sludge recovers nitrogen and phosphorus simultaneously; global municipal wastewater could supply an estimated 15–20% of combined N+P demand if recovery were mandated at treatment plants. Commercially deployed (Ostara, NuReSys); scaling requires policy mandate, not new invention.

4. Phosphorus replacement options

4.1 Mycorrhizal fungi network restoration (immediate, low cost)

Arbuscular mycorrhizal fungi extend root networks 100–1,000× and access mineral phosphorus via organic-acid secretion, which dissolves FePO_4 and AlPO_4 through acidification and chelation. An estimated 70% of global cropland has damaged mycorrhizal networks from tillage and synthetic-phosphorus history. Restoration via reduced tillage and AMF spore inoculants (\$15–30/ha) is the fastest available phosphorus intervention, closing an estimated 15–25% of demand. One unresolved discrepancy should be stated rather than smoothed over: a review of soil legacy phosphorus reports that mycorrhizal inoculation can reduce the recommended phosphate fertilizer rate by nearly 80%, more than three times the figure used here. This paper does not resolve the difference. The conservative value is used throughout, and the larger one should be treated as unconfirmed for any programme sizing.

4.2 Phosphate-solubilizing bacteria (immediate, low cost)

Bacillus, *Pseudomonas*, and *Aspergillus* species produce organic acids that dissolve mineral phosphates directly. Field trials report yield gains equivalent to 30–50 kg P_2O_5 /ha; combined with AMF inoculants, the synergistic effect exceeds either alone.

4.3 Biochar soil amendment (immediate to near-term)

Biochar amendment increases phosphorus availability through several concurrent mechanisms: it raises soil pH in acidic tropical soils, where much phosphorus fixation occurs; it provides sorption sites that reduce phosphorus binding to Fe and Al oxides; and it hosts the same phosphate-solubilizing microbial communities described in 4.2 at elevated density. Application rates of 5–10 t/ha in field trials show phosphorus-use-efficiency gains in the same range as dedicated inoculants, with the added benefit of carbon sequestration and multi-year persistence — biochar does not need reapplication each season the way microbial inoculants may. Cost and feedstock availability vary regionally; this is best positioned as a near-term, not zero-cost, intervention.

4.4 Precision and variable-rate application (immediate)

A structurally different lever from the interventions above: rather than releasing more phosphorus from soil, reduce how much purchased fertilizer is wasted. Variable-rate application guided by soil testing or low-cost canopy/soil sensors routinely reduces total phosphate fertilizer use by 10–20% with no yield penalty, by matching application to actual field-level need rather than uniform blanket rates. In a supply-constrained crisis, this is mathematically equivalent to a 10–20% supply increase at zero new production cost, and requires only soil-testing infrastructure and extension support, not new fertilizer sourcing.

4.5 Phosphorus recovery from wastewater (medium-term)

Struvite recovery from sewage sludge produces a slow-release fertilizer at approximately 12% P_2O_5 , agronomically equivalent to commercial phosphate fertilizer, without dependence on phosphate rock mining. Global wastewater could supply an estimated 20% of phosphorus demand.

5. Potassium replacement options

Potassium is the macronutrient least exposed to this particular shock. Potash prices showed no movement through the February–April 2026 escalation, and potash supply is comfortable — running ahead of demand, with further production coming online. What has kept the price from softening is freight rather than scarcity: the cost of moving a railcar, barge, vessel, or truck has risen across every mode at once, and producers pass part of that through. The distinction matters for policy, because a freight-driven price responds to logistics measures while a scarcity-driven price does not. The magnitude is worth stating plainly: US retail potash moved from \$484 to \$495 per ton between August 2025 and August 2026 — a 2% change across a year that contained the closure of the Strait of Hormuz. The interventions below are therefore resilience measures against the concentration risk identified in Section 2.1 rather than responses to a current price emergency. They remain worth deploying now because they are free or near-free, and because the concentration that makes potassium safe today is the same concentration that would make it dangerous under a different disruption.

5.1 Crop residue cycling (immediate, zero cost)

Potassium remains as ionic K^+ in crop residue rather than being metabolized into organic matter; returning residue to the field returns 60–80% of removed potassium. Ending residue burning and removal costs nothing and closes an estimated 30–50% of the potassium demand gap immediately.

5.2 Potassium-weathering bacteria (immediate, low cost)

Bacillus mucilaginosus and related species weather feldspar — about 60% of continental crust by weight — releasing plant-available K^+ . Field trials report yield gains equivalent to 50–100 kg K_2O /ha.

6. Reducing post-harvest food loss

An estimated 30–40% of food produced globally is lost between farm and table, disproportionately in exactly the regions now facing the sharpest fertilizer-driven supply pressure, where post-harvest storage and cold-chain infrastructure is weakest. Every kilogram of nutrient applied to a crop that is subsequently lost to spoilage, pest damage, or inadequate storage is fertilizer wasted twice over — once in production cost and once in the nutrition it never delivers. Low-cost hermetic storage bags, already commercially deployed for grain at approximately \$2–3 per 50 kg capacity, and small-scale cold storage can reduce post-harvest loss by 20–50% depending on crop and region. This does not replace fertilizer, but it multiplies the effective value of every unit of nutrient that goes into the ground, and is deployable with existing technology in the same 0–12 month window as the other Horizon 1 interventions.

7. Policy: allocation before volume

7.1 The finding that should set policy

Crop response to applied nutrient is not approximately uniform. It varies by roughly an order of magnitude, and the variation has been measured twice over, independently, in two nutrients.

For nitrogen, response across sub-Saharan Africa ranges from **5 to 53 kg of grain per kg of N applied** — a 10.6-fold spread, varying not only between countries but within them, and within individual farms. For phosphorus, the sorption analysis in Appendix A gives a ten-fold spread in the fraction of applied or released phosphorus that reaches soil solution across four soil series in a single country, and an eight-fold spread in the quantity required to reach a standard agronomic concentration: 17 kg P/ha on the most responsive soil, 140 kg P/ha on the least.

The policy consequence is direct. **The same tonnage, allocated by soil response rather than spread uniformly, does several times the work.** No new production, no new supply, no subsidy, no new technology. In a supply-constrained year this is the cheapest intervention available, and it is the only one that becomes cheaper as it becomes better targeted.

7.2 Prior art, conceded in full

None of this is a new diagnosis. The 2006 Africa Fertilizer Summit at Abuja set a target of 50 kg nutrients/ha; average use in sub-Saharan Africa has since risen from 8 to about 20 kg/ha — a substantial move that fell well short. Subsidy programmes reached two-thirds of countries and roughly 40% of regional consumption, and a comprehensive assessment found their costs outweighed their benefits. The failure was not tonnage. It was distribution, agro-dealer networks, road access, and recommendations issued as national blanket figures that ignored variation in soils, past nutrient use, and farming system. The field's current position already calls for spatially targeted recommendations, improved affordability and availability, and farmer incentives, within the Integrated Soil Fertility Management framework.

This paper does not propose that agenda. It adds one thing to it: **a sorption-based method for quantifying the targeting term**, using Langmuir parameters that are cheap to measure, so that “target spatially” becomes a number per soil series rather than a principle.

7.3 Availability is not the binding constraint everywhere

A strategic reserve addresses availability. That matters where supply is physically interrupted. It does not address affordability, and in sub-Saharan Africa affordability appears to bind first: most fertilizer produced in the region is currently exported because domestic demand is too low. Adding volume to a market that already exports for want of buyers will not reach the farms this paper is concerned with.

Two further constraints compound it. Rainfall risk is itself a strong disincentive to purchasing fertilizer, so the El Niño exposure described in Section 1 does not merely coincide with the input shock — it suppresses the response to it. And farmers will not invest in soil health absent short-term returns, because the benefits are visible only over the medium to long term.

7.4 A two-sided instrument

The legacy-phosphorus asymmetry of Section 2.2 makes a reserve worth building on both sides rather than one. Regions with anthropogenic phosphorus signatures above 60% — Western Europe, North America, much of Asia — hold decades of accumulated soil phosphorus and apply at rates near 196 kg/ha. They are where the release and efficiency interventions of Section 4 work best, and where drawing down accumulated fertility reduces mineral demand without reducing yield. Regions below 30%, sub-Saharan Africa foremost, have little to release and need external supply they can afford.

The instrument therefore has two halves that finance each other. Demand reduction in high-signature regions frees rock-phosphate supply; a coordinated reserve, sized against the import demand of the most exposed food-insecure states rather than a single large importer's consumption, directs it. National-scale versions of the reserve have been proposed recently at 60–90 days of supply with a two-tier structure of physical stock plus government-to-government take-or-pay contracts; that sizing and structure are adopted here rather than restated as new.

7.5 What this means in practice

Ranked by cost per unit of nutrient delivered to a responsive soil:

Priority	Instrument	Requires
1	Reallocate existing tonnage by soil response	Soil testing and extension; no new supply
2	Short-term incentives tied to complementary practices	Programme design; uses fertilizer as the delivery vehicle
3	Demand reduction in high-legacy regions	Efficiency and release interventions where legacy exists
4	Internationally held reserve for exposed importers	Capital and coordination
5	New production capacity	Capital, long lead times, and demand that can pay

The ordering matters because the first two require no new supply at all, and the evidence says they command the largest available multiplier.

8. Systems integration: a roadmap targeted to current need

The interventions above are complementary, and they are assigned by the zone class of Section 2.3 rather than uniformly. Class A zones take precision application, legacy drawdown, and balanced nutrition; Class B takes storage, buffers, and timing; Class C takes allocation, legumes with a phosphorus starter, and incentives; Class D takes none of them until access is restored. Within that assignment, we propose a three-horizon roadmap, targeted to the hotspots identified in the June 2026 FAO-WFP monitoring: **Sudan, South Sudan, Yemen, Palestine, Nigeria, and Somalia** at highest concern, and **Afghanistan, the Democratic Republic of the Congo, and Haiti** at very high concern, alongside the broader West and Central Africa lean-season population (nearly 52.9 million people projected to face acute food and nutrition insecurity at IPC Phase 3 or worse during the June–August 2026 lean season, concentrated in conflict-affected areas of the central Sahel, the Lake Chad Basin, and northeastern Nigeria — the same geography that drove Nigeria’s elevation to highest concern).

Horizon	Timeline	Interventions	Expected contribution
Horizon 1: Immediate	0–12 months	Legume intercropping (N); mycorrhizal + PSB inoculants (P); biochar amendment (P); precision application (P, N, K); KSB bacteria + residue return (K); post-harvest loss reduction; wastewater struvite recovery (N+P) where treatment infrastructure exists	Largest immediately available effect. Magnitude is soil-specific and bounded by sorption capacity (Appendix A); not expressible as a single figure.
Horizon 2: Near-term	1–5 years	Green ammonia in solar regions (N); strategic reserve mechanism; wastewater N+P recovery mandated; soil-testing capacity built out to support allocation by response	Adds new supply and reduces exposure. Depends on capital build-out and policy, not on soil chemistry.
Horizon 3: Structural	5–20 years	BNF in cereals (N moonshot); full green ammonia grid; rapid field-scale multi-element soil measurement to relieve the bottleneck on allocation	Reduces exposure structurally. Independence from mineral fertilizer is not the target: organic and biological sources alone cannot build or sustain soil fertility, and biomass transferred from elsewhere supplies roughly a tenth of requirement while degrading the source soil. Speculative by construction.

Why this column carries no percentage. An earlier formulation of this table gave numeric gap-closure ranges. They cannot be reconstructed. The component interventions are quoted against different denominators — fraction of demand, absolute kg/ha credits, fraction of a recovered waste stream — and the phosphorus interventions act on a single locked pool, so their effects do not sum. Appendix A reports a re-derivation. It establishes a real physical ceiling in soil sorption capacity, but the partition coefficient required to convert released phosphorus into plant-available phosphorus is not available in the literature for these soils. Until it is, a ranking is honest and a percentage is not.

The most important near-term action is the one ranked first in Section 7.5: reallocating existing tonnage by soil response, which requires no new supply and no new technology.

8.1 Deployability is not adoption

The horizons above describe technical readiness. They do not describe farmer uptake, and conflating the two would mislead anyone reading this as programme design. A recognised bottleneck in engaging smallholder farmers in soil-health-restoring practices is that such practices take a relatively long time to deliver benefits the farmer can actually see; absent incentive programmes, farmers require short-term benefits generated within their own farming systems. Several Horizon 1 entries — mycorrhizal restoration, biochar amendment, phosphate-solubilizing inoculants — sit squarely in that slow-visible-benefit class. They are deployable within twelve months. They are not, on that timescale, self-evidently worth adopting from the farmer's side. A programme that treats technical readiness as sufficient will underperform, and the interventions most likely to be taken up quickly are those delivering a visible within-season return: legume rotation, residue retention, and post-harvest storage. Advice on complementary practices also multiplies the complexity of what must be communicated, which is why delivery at scale has moved toward bundled, frequently digitally enabled services rather than single-practice extension.

8.2 Prior art: Integrated Soil Fertility Management

The combination proposed here — mineral fertilizer together with organic inputs, legumes, and soil-specific targeting — is not novel as a framework. It is Integrated Soil Fertility Management, an established approach built on the position that fertilizer alone is insufficient and that auxiliary interventions are required alongside it. This paper does not propose ISFM and does not claim to. It applies ISFM logic to an acute supply disruption, and adds the sorption-based, soil-specific targeting derived in Appendix A. The framework is conceded in full; the narrow contributions are the crisis application and the quantified targeting.

8.3 What the expert literature includes, and what it does not

One check on this paper's intervention list should be reported rather than left for a reader to discover. The most recent comprehensive expert review of fertilizer and soil health in sub-Saharan Africa — a multi-author synthesis by the authorities who defined the Integrated Soil Fertility Management framework — was searched in full for the interventions recommended here. It discusses mineral fertilizer rates and subsidies, organic inputs, manure, crop residues, legumes and biological nitrogen fixation, soil organic carbon, liming, and balanced nutrition at length. It does **not** discuss biochar, mycorrhizal inoculants, phosphate-solubilizing bacteria, struvite recovery, or variable-rate application at all.

That is an absence rather than a contradiction, and absences carry less weight than stated positions. But four of the seven interventions named as deployable in this paper fall outside what that review treats as the toolkit for this geography, and readers should weight them accordingly: the legume, residue and rate-allocation recommendations here sit inside the expert consensus, while the biological-inoculant, biochar and struvite recommendations sit outside it and rest on the commercial and field-trial evidence cited in Section 4 rather than on expert-review endorsement.

Two explanations account for the pattern, and they compound rather than compete. The first is institutional scope: the review was published by a fertilizer-development organisation, and interventions that are not fertilizer fall outside that remit by construction. The second is more interesting, because this paper's own framework predicts it. **Every one of the omitted interventions presupposes conditions that define Class A in Section 2.3, and Class C is defined by their absence.** Mycorrhizal restoration presupposes networks damaged by tillage and synthetic-phosphorus history — but sub-Saharan smallholder systems have hand tillage and almost no phosphorus history, so there is little damage to restore. Phosphate-solubilizing bacteria presuppose a locked mineral stock, which is precisely what a sub-30% anthropogenic signature says is not there. Biochar presupposes surplus biomass, in systems where residues already compete against fodder, fuel and construction. Struvite presupposes municipal wastewater treatment. Variable-rate application presupposes over-application, and there is none at 5 kg P/ha.

One case in the review functions as a control on this reading. It does endorse an inoculant — rhizobium for soybean, common bean and groundnut — describing high-quality products now packaged for smallholder needs. That is the one microbial intervention whose preconditions do hold in these systems, and its inclusion indicates an evidence and applicability threshold rather than a category prejudice against biological approaches.

The interventions in question are therefore not refuted here. They are, on this reading, **misfiled by geography**: they belong to the legacy-rich, over-applied zones of Class A, where the stock, the biomass, the infrastructure and the over-application they each depend on are all present. Section 2.3 already assigns them there. This section records that the expert literature for Class C reaches the same conclusion by omission.

The same search surfaces one intervention this paper omits and that review engages with directly: **liming of acid soils**. Given that phosphorus fixation is pH-dependent, and that two of the four soil series in Appendix A are acid (pH 4.30 and 5.02), liming is likely to be a better-evidenced phosphorus intervention for those soils than several of the options developed above. It is not assessed here, and that omission is a limitation of this paper rather than a judgement about the practice.

8.4 Sequencing on degraded soils

Fertilizer response is limited on degraded soils, and where degradation is advanced, rehabilitation investment should precede fertilizer-efficiency interventions rather than accompany them. Horizon 1 as stated assumes soils still capable of responding. Where they are not, the first intervention is rehabilitation, and the horizons shift accordingly.

9. Discussion

The 2026 fertilizer shock is a symptom of a structural vulnerability that predates the current conflict, and FAO's warning is that its worst effects are still ahead. The response with the largest, fastest, most defensible impact is not a new technology. It is the deployment, at scale and specifically targeted to the current hotspot list, of interventions that are already proven: mycorrhizal and phosphate-solubilizing inoculants, legume rotation, biochar, precision application, residue return, and post-harvest loss reduction. All have commercial deployment or peer-reviewed field-trial data behind them. The barrier is adoption incentive and distribution logistics into conflict- and poverty-constrained regions, not further research. The converging El Niño risk sharpens rather than changes this conclusion: a second, independent shock arriving in the same seasons raises the value of every intervention that can be started from a planting decision instead of a purchase order. The August 2026 price divergence points the same way. Nitrogen has begun to ease and phosphate has not, which means the nutrient under the most sustained cost pressure is precisely the one whose replacement is already sitting in the ground, locked in mineral forms, waiting to be released.

One mechanism recurs across the phosphorus interventions, and it is worth stating precisely rather than broadly. **Reductive dissolution** — the reduction of Fe(III) to the more soluble Fe(II), releasing phosphate bound in iron-phosphate phases — is the dominant release pathway in iron-rich soils and in soils that are periodically anoxic, paddy and flooded systems especially. It is part of what biochar's redox activity contributes, and it is the reason flooded rice systems mobilise phosphorus seasonally as anoxia develops.

It is not a universal control variable, and this paper does not claim it as one. Two of the three mineral pools named in Section 2.2 do not operate through iron redox at all: aluminium is redox-inert under soil conditions, so AlPO_4 release is driven by acidification and chelation; and calcium-phosphate dissolution is acid-driven. The principal mechanism of mycorrhizal and bacterial solubilization is organic-acid production — proton release and chelation of Ca, Fe, and Al — together with phosphatase activity on organic phosphorus. Chelation is not reduction.

The defensible statement is narrower and more useful for deployment. **Iron reductive dissolution is the largest single lever in iron-rich and periodically anoxic soils; organic-acid chelation and acidification are the corresponding levers in calcareous and aluminium-dominated soils.** Which lever applies is a property of the soil, not of the intervention. That has a practical consequence: phosphorus interventions should be selected by soil type rather than deployed uniformly, and the soil-testing infrastructure required to make that selection is the same infrastructure Section 4.4 requires for variable-rate application. One investment serves both.

10. Conclusions

1. The 2026 fertilizer crisis is real and ongoing, and its worst agricultural impact — per FAO — has not yet arrived, giving near-term interventions a genuine window to matter. That window coincides with a 61–87% probability of El Niño persisting into 2027, whose projected rainfall deficits fall on Sudan and South Sudan among others: two independent shocks converging on the same countries in the same seasons.
2. Seven interventions are assessed as deployable within 12 months using existing technology, several at zero direct cost — but they are not uniformly applicable, and this paper does not claim they are. Legume rotation, residue return and rate allocation sit inside the expert consensus for low-input systems. Mycorrhizal and phosphate-solubilizing inoculants, biochar, struvite recovery and variable-rate application each presuppose a condition — accumulated legacy stock, surplus biomass, wastewater treatment infrastructure, or existing over-application — that characterises legacy-rich zones rather than nutrient-poor ones. They are not refuted; they are assigned to the wrong class when deployed uniformly.
3. Agricultural zones sort by nutrient-system properties rather than by region, and four classes cover the cases here: legacy-rich and over-applied; climate-exposed and import-linked; nutrient-poor and allocation-limited; and access-constrained. The first and third are complementary — demand reduction in the first frees supply for the third. The fourth cannot be served by the agronomic interventions in this paper, and conflict is the principal driver in twelve of the thirteen current hotspots.
4. Iron reductive dissolution ($\text{Fe(III)} \rightarrow \text{Fe(II)}$) is the largest single phosphorus-release lever in iron-rich and periodically anoxic soils; organic-acid chelation and acidification govern calcareous and aluminium-dominated soils. Because the operative mechanism is set by soil type, phosphorus interventions should be selected by soil test rather than deployed uniformly.
5. A strategic macronutrient reserve has been proposed at national scale for India at 60–90 days of supply. The gap this paper identifies is the absence of an *internationally held* reserve sized against the import demand of the most exposed food-insecure states, which are generally not the states able to finance national buffers.
6. The single most useful action available to a programme is to reallocate existing tonnage by soil response. It requires no new supply, no new production, no subsidy and no new technology, and on the evidence assembled here it commands the largest available multiplier.

Appendix A. The sorption ceiling and the partition coefficient

Every phosphorus intervention in Section 4 releases phosphate into the same soil solution, and that solution sits against a finite, largely unfilled set of sorption sites. The ceiling is measurable, the partition between sorbed and solution phases is calculable, and both are strongly soil-specific.

A.1 Measured sorption parameters. Four representative soil series in Sahelian Mali, fitted with the linearised Langmuir isotherm under Tilemsi phosphate rock:

Soil series	FAO type	X _{max} (mg/kg)	K _L (L/mg)	r ²	DPS (%)	Clay (%)	SOM (%)
Longorola	Gleysol	200	1.66	0.79	2.39	45	2.70
Danga	Fluvisol	166	0.30	0.78	6.02	20	1.23
Niessoumana	Arenosol	167	0.85	0.98	6.47	12	1.20
Konobougou	Acrisol	59	0.56	0.89	3.47	4.2	1.00

Sorption maxima correlate with clay ($r = 0.78$) and organic matter, and the affinity constant with exchangeable acidity ($r = 0.95$) and organic matter ($r = 0.91$). Degree of phosphorus saturation is far below the 25% critical limit in every soil.

A.2 The ceiling. Taking a 0–20 cm plough layer at bulk density 1.4 g/cm³, 1 kg P/ha $\approx$ 0.357 mg P/kg soil. At the 16 kg P/ha rate used in the same study's field experiment, one season's application is $\sim$ 5.7 mg/kg against unfilled sorption capacity of 57–195 mg/kg. **These soils can absorb roughly 10 to 34 seasons of applied phosphorus before approaching saturation.** Phosphorus freed from the locked pool therefore re-enters a solution heavily under-saturated with respect to sorption sites.

A.3 The partition coefficient. X_{max} and K_L together determine the isotherm, so the split between sorbed and solution phases is calculable rather than assumed. For a marginal addition at low loading, the fraction remaining in solution is $V/(V + K_L \cdot X_{\text{max}})$, where V is solution volume per kg soil:

Soil series	$K_L \cdot X_{\max}$	Fraction in solution	P required to reach 0.2 mg/L in solution
Longorola (Gleysol)	332.0	0.054%	140 kg P/ha
Niessoumana (Arenosol)	141.9	0.126%	68 kg P/ha
Danga (Fluvisol)	49.8	0.357%	26 kg P/ha
Konobougou (Acrisol)	33.0	0.538%	17 kg P/ha

A ten-fold spread in partition, and an eight-fold spread in the phosphorus required to reach a standard agronomic solution concentration. Because $K_L \cdot X_{\max}$ greatly exceeds V in every soil, the fraction reduces to approximately $V/(K_L \cdot X_{\max})$, which means **the ratios between soils are independent of the soil-water assumption** and depend only on measured sorption parameters.

A note on provenance: the source study treats standard phosphorus requirement — the quantity needed to reach 0.2 mg/L in soil solution — as a variable in its correlation and principal-component analyses, but does not tabulate per-soil values for it. The figures in the right-hand column above are therefore derived here from that study's reported Langmuir parameters rather than quoted from it, and can be recomputed from $X_{\max}$ and K_L by anyone who wishes to check them. Absolute values assume field capacity at 0.25 m³/m³; the comparison does not.

A.4 What this explains, and what it implies. The field experiment supporting these parameters applied 11 and 16 kg P/ha on the Acrisol — the single soil whose standard phosphorus requirement is 17 kg P/ha. The trial rate essentially met that soil's requirement, which is consistent with the yield response observed. The identical treatment on the Gleysol would require roughly nine times the rate to reach the same solution concentration.

The implication for deployment is direct and quantitative. A uniform kilograms-per-hectare recommendation cannot be correct across these soils, because the phosphorus needed to achieve the same plant-available concentration varies eight-fold between them. This is the same conclusion Section 9 reaches from redox chemistry and that extension practice reaches from site-specific soil assessment, now with a number attached: **select phosphorus interventions and rates by soil test, and expect an order-of-magnitude difference in what the same intervention delivers.**

A.5 Limits of this calculation. Three constraints must be stated. First, this is the instantaneous equilibrium partition, not seasonally integrated availability — the solution pool is continuously replenished by desorption from the labile pool as roots deplete it, so a small solution fraction does not imply a correspondingly small seasonal uptake. Second, the parameters derive from seven-day batch equilibration in 0.01 M CaCl₂, not from field conditions. Third, and most consequential for Section 4: biological solubilization by mycorrhizal fungi and phosphate-solubilizing bacteria acts partly by occupying or blocking sorption sites through organic-acid and organic-matter interactions, which would alter both $X_{\max}$ and K_L rather than operating against fixed values. The equilibrium partition above is therefore a conservative floor for what biological interventions can achieve, and measuring how those interventions shift the isotherm is the single highest-value follow-up this analysis identifies.

Appendix B. A deprecated line of enquiry: physics-based phosphorus release

This work began as a proposal to release soil-bound phosphorus by physical means — radiation-induced reduction of Fe(III) to the more soluble Fe(II), which dissolves iron-phosphate phases. The idea reached soil science from pion-capture work in radiotherapy, where the surrounding matrix is carbon, nitrogen, oxygen and hydrogen. It does not survive the transfer to soil. It has been removed from the analysis above rather than carried as a speculative horizon, and the three findings that terminated it are recorded here so that others need not re-derive them.

No elemental selectivity. The original premise was that negative-pion capture would target phosphorus preferentially. Which element in a compound captures a stopped particle is governed by atomic capture, which follows approximately the Fermi-Teller Z-law, not by the nuclear-absorption scaling that motivated the claim. In mineral soil the competition is dominated by oxygen, silicon, aluminium and iron on abundance alone, and iron outcompetes phosphorus on atomic number. Phosphorus is a trace constituent by mass. There is no useful selectivity, and the premise fails at its foundation.

Penetration depth. The cheap surrogates for the same chemistry — ultraviolet illumination and semiconductor photocatalysis — act only at an illuminated surface, while the phosphorus is distributed through the plough layer. They work in a stirred suspension and do nothing to a field.

Energy and delivery. Electrochemical reduction reaches depth in principle, but the charge required per hectare is prohibitive at realistic field efficiencies. Beam-based delivery does not miniaturise: accelerator length, shielding mass and power draw all scale with beam energy, so no field-deployable version exists or should be projected. At facility scale, where delivery would be straightforward, acidulation with sulfuric acid — the existing industrial route to phosphate fertilizer — outcompetes radiation by orders of magnitude.

The underlying mechanism is real and well established. Flooded rice systems run it seasonally as anoxia develops, which is why Section 9 identifies iron reductive dissolution as the dominant release pathway in periodically anoxic soils. What fails is every attempt to deliver it deliberately at a cost that competes with what already works.

These proposals were therefore deprecated from the intervention list so as not to distract from the class-based structure of the main analysis. The full derivation, including the falsification test designed for them and the arithmetic behind each of the findings above, is retained in the first version of this record.

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Verification status. This is a preprint by an independent researcher. The sourcing of its figures is uneven, and a reader should be able to see that rather than infer it.

Traced to primary sources. The fertilizer price movements, Gaza access figures and West and Central Africa lean-season projection (World Bank Food and Nutrition Security Update 122); the 31% annual price projection (World Bank Commodity Markets Outlook, April 2026); hotspot classifications and famine-risk contexts (FAO-WFP Hunger Hotspots, June 2026); famine confirmations and current classifications (IPC); the 318 million projection (WFP 2026 Global Outlook); Sahelian sorption parameters, saturation degrees and field application rates (Kouyate et al., 2023); phosphorus fixation and use-efficiency figures (Johan et al., 2021); anthropogenic phosphorus signatures (Demay et al., 2023); regional application rates and immobilisation fractions (Solangi et al., 2023); the Abuja outcome, agronomic efficiencies, response variability, adoption bottleneck and ISFM framing (Vanlauwe et al., 2023). Appendix A's partition coefficients are derived here from the measured Langmuir parameters and can be recomputed from them.

Cited but not independently verified. The following are reported as they appear in industry, commercial or secondary sources and have not been re-derived: mycorrhizal root-network extension of 100–1,000×; 70% of global cropland with damaged mycorrhizal networks; inoculant cost of \$15–30/ha; mycorrhizal demand closure of 15–25%; phosphate-solubilizing-bacteria yield gains of 30–50 kg P₂O₅/ha; potassium-weathering bacteria at 50–100 kg K₂O/ha; biochar application at 5–10 t/ha; struvite recovery at 15–20% of combined nitrogen and phosphorus demand, 20% of phosphorus demand, and approximately 12% P₂O₅ content; variable-rate application reductions of 10–20%; crop-residue potassium return of 60–80% and gap closure of 30–50%; feldspar at about 60% of continental crust; hermetic storage bags at \$2–3 per 50 kg; post-harvest loss of 30–40% and reduction of 20–50%; the export-concentration percentages in Section 2.1; Chinese green ammonia capacity of 320,000 t/yr; and the Pivot Bio deployment figures. These support the argument. None is load-bearing for the paper's central claims, which rest on the sources traced above.

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Reference 14 carries an unconfirmed publication year and is marked accordingly. No other citation in this list is unresolved.