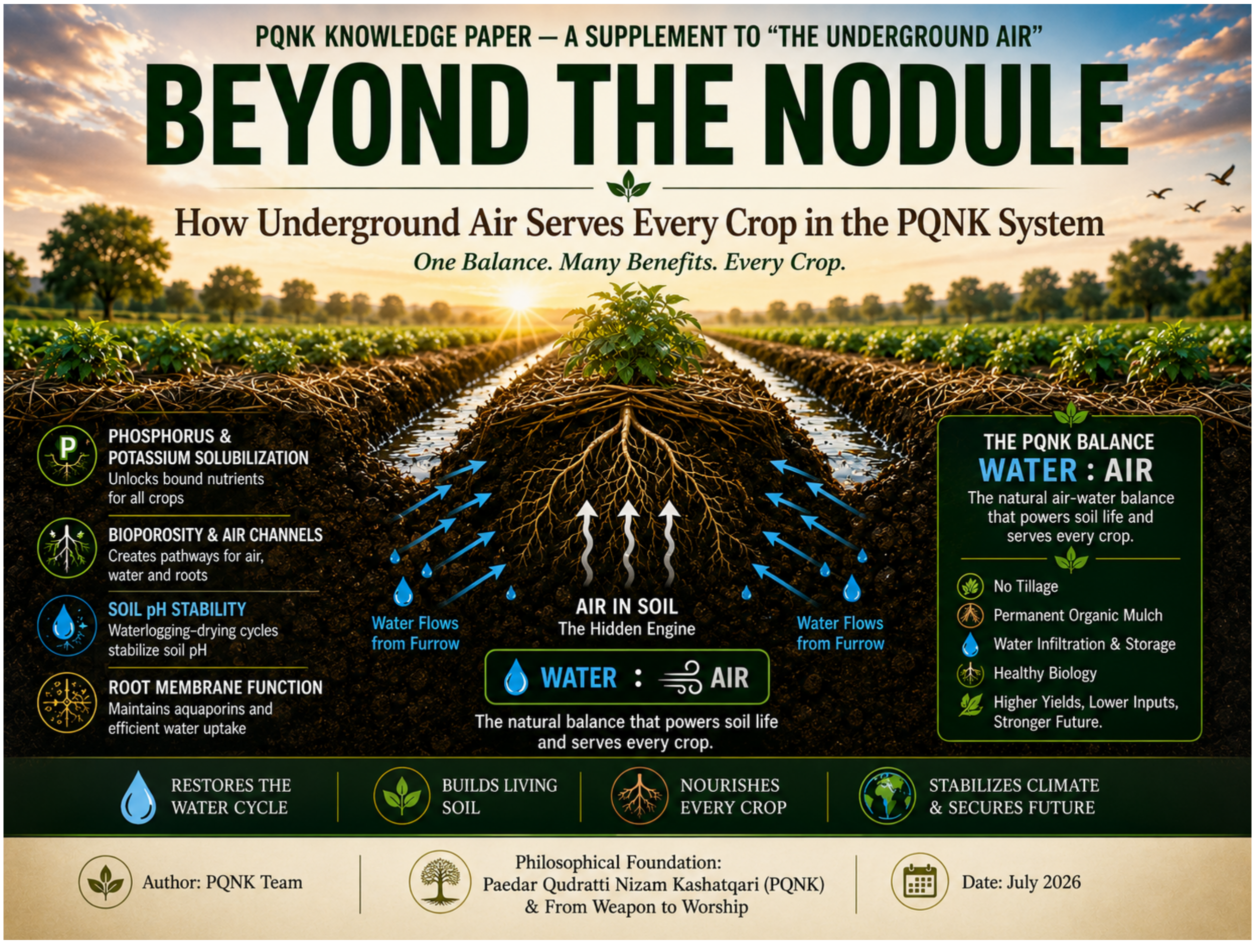

PQNK Knowledge Paper — A Supplement to "The Underground Air"

Beyond the Nodule

How Underground Air Serves Every Crop in the PQNK System

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ABSTRACT

"The Underground Air" argued that biological nitrogen fixation in Sesbania aculeata (Jantar) depends on a carefully managed soil air-water balance, the water : air condition, because the nitrogenase enzyme is oxygen-sensitive wherever it is found, inside a legume nodule or inside a free-living soil bacterium. After reading that paper, Professor Norman Uphoff of Cornell University, the researcher most responsible for carrying the System of Rice Intensification to international recognition, offered a specific and constructive response: the argument for legumes is well made, but soil aeration's benefits reach non-leguminous crops by an entirely different route, a more diverse and more active soil biological community that solubilizes phosphorus and potassium, builds air channels through the soil profile, regulates soil pH, and keeps plant roots physically capable of taking up water and nutrients. This paper takes up that request directly. It shows that the same water : air balance central to nodulation is,

independent of any nitrogen-fixing organism, the physical variable that governs four further services, phosphorus and potassium solubilization, soil bioporosity, pH stability, and root membrane permeability, each grounded in published research and each as relevant to wheat, rice, maize, vegetables, and oilseeds as it is to Jantar. It also takes up, in the terms Professor Uphoff himself uses, the distinction between active soil aeration (deliberate mechanical disturbance) and passive soil aeration (the raised bed's own architecture), and traces both through to PQNK practice.

1. INTRODUCTION: A SECOND QUESTION FROM THE SAME INSIGHT

“The Underground Air” began with a PQNK farmer's field observation: Jantar grown on raised beds seemed to carry larger, more numerous root nodules than the same crop on conventional flat beds. That observation led to a hypothesis, that nitrogen-fixing microbes use underground air rather than atmospheric air, and the paper spent its length validating that hypothesis against the published science of nitrogenase, rhizobial nodules, free-living diazotrophs, and the Casparian strip.

Professor Uphoff's response, after reading that paper, raised a point the original argument had left unaddressed:

“Your presentation nicely explains in scientific terms how soil aeration, active and passive, enhances particularly leguminous crops. I would be glad to see a little more attention to how it boosts non-leguminous crop, but making soil systems inhabited by more and more diverse soil organisms, micro to macro, which provide a lot of services to growing plants — P solubilization, creating air channels up and down and across in the soil, affecting soil pH, making soil more permeable for roots, etc. But this could be added easily.”

The observation is exactly right, and it deserves its own paper rather than a footnote. Nitrogenase is the most dramatic example of an oxygen-sensitive soil process, but it is one example among several. Wheat, rice, maize, potato, and every other non-leguminous crop in the PQNK rotation has no nodule and fixes no nitrogen of its own, yet every one of them depends on a soil community whose other services, unlocking bound phosphorus and potassium, building and maintaining the pore network the root grows through, holding soil pH in a workable range, and keeping the root's own water-uptake machinery switched on, are governed by the identical water : air balance. This paper sets out that argument, service by service, then returns to the specific distinction Professor Uphoff draws between active and passive aeration and to a parallel he offered alongside it: that ragi (finger millet) farmers in Maharashtra had independently discovered, through an ox-drawn inter-row root-cutting implement, the same active-aeration principle his own SRI research established for rice. That a farmer's direct observation of Jantar nodulation and a Cornell professor's decades of rice research converge on the same underlying physical variable is, itself, a small demonstration of the paper's argument: attentive observation of soil, wherever it happens, keeps arriving at water : air.

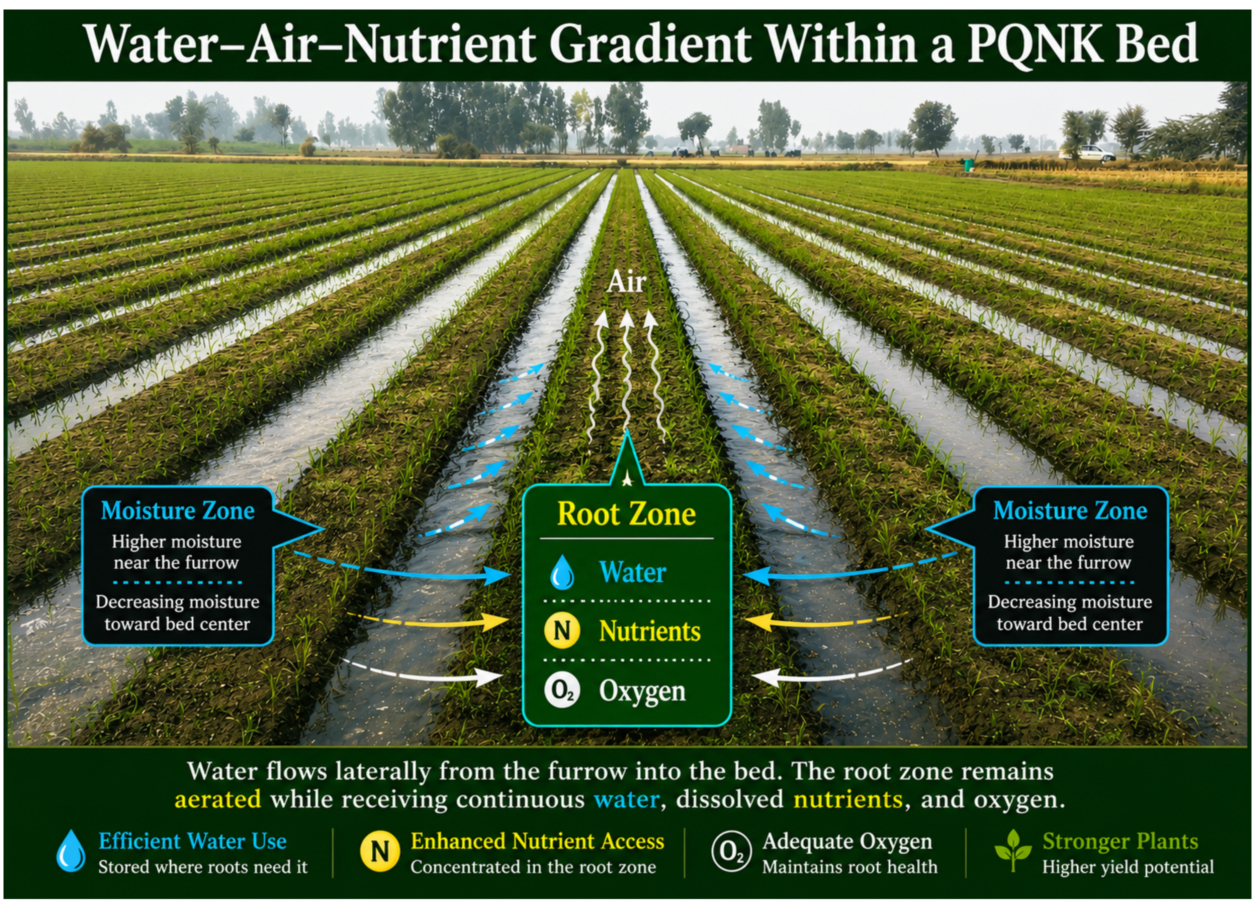
One caveat is stated here rather than left implicit. This paper is a synthesis: it takes services already established in the published soil-science literature and reasons from PQNK's known architecture, raised beds, permanent mulch, lateral seepage, no-till, to how that architecture should affect each service. It is not, unlike the Sesbania nodule-count data in “The Underground Air,” a report of new field trials measuring these services specifically on PQNK beds under non-leguminous crops. Section 9 returns to this point and to where that direct evidence can come from next.

2. ONE PRINCIPLE, NOT ONE ENZYME

“The Underground Air” already anticipated this paper's argument, briefly, in its Section 2.5. The oxygen paradox of nitrogen fixation was described there as “a specific, especially dramatic instance of a much more general rule: the balance of air and water in soil pore space, water : air, is the master variable that determines which microbial guild is active in any given pocket of soil, and how efficiently it works” (Tecon & Or, 2017). That section distinguished three conditions along one gradient, aerobic, microaerobic, and anaerobic, and noted that different microbial guilds, aerobic decomposers, nitrifiers, nitrogen-fixers, and anaerobic denitrifiers, each occupy their own band along it.

This paper simply follows that gradient into the guilds the original paper did not have space to cover: the aerobic and facultative organisms responsible for phosphorus and potassium solubilization, the soil engineers, earthworms, fungi, and roots themselves, that build the pore network the gradient depends on, the chemistry that sets soil pH, and the plant's own root-cell water gates. None of these require a nodule. All of them require a soil that is neither waterlogged nor bone-dry, which is precisely what a raised bed's water : air balance is built to sustain.

3. ACTIVE AND PASSIVE AERATION, BEYOND RICE



Professor Uphoff's own research draws a specific distinction between two routes to the same aerated soil condition. Passive soil aeration in the System of Rice Intensification comes from alternate wetting and drying, letting a paddy dry out, sometimes to the point of visible surface cracking, between irrigations rather than keeping it continuously flooded. Active soil aeration comes from the mechanical push-weeder SRI farmers use to control weeds between wide-spaced rows, which physically churns and opens the surface soil around each plant while it works. Research reviewing SRI's effect on rice-soil rhizospheres found that both routes raise populations of aerobic beneficial organisms together, not separately: free-living nitrogen-fixing bacteria and phosphate solubilizers both increased under SRI management, in some cases by close to seventy-five percent, alongside higher enzyme activity indicating greater nitrogen and phosphorus availability to the plant (Anas, Rupela, Thiyagarajan, & Uphoff, 2011). Rice is not a legume. This finding is therefore already direct evidence, from Professor Uphoff's own research programme, that soil aeration's benefit to phosphate-solubilizing organisms operates in a non-leguminous crop exactly as it does in Jantar.

The Maharashtra ragi farmers Professor Uphoff describes had arrived at the active half of this same principle independently, through field observation rather than laboratory research, using an ox-drawn implement to cut the roots of weeds between eighteen-inch finger millet rows, disturbing the top five to ten centimetres of soil and boosting tillering and yield. The parallel to the PQNK farmer's Jantar observation that opened “The Underground Air” is direct: a working farmer, in a different country, on a different continent, on a crop with no nodule at all, noticed that disturbing the soil around the root zone in a specific, limited way made the crop perform better, years before either observation was connected to a documented physical mechanism.

PQNK's raised-bed geometry already supplies the passive half of this pairing without requiring any separate aeration step. The permanent, undisturbed bed, its upper shoulders balanced between the saturated furrow and the well-aerated mound, is a standing passive-aeration structure rather than an intermittent one achieved through a wetting-drying cycle. What PQNK does not yet include, and what this parallel makes worth testing directly, is a deliberate active-aeration step of the kind SRI and the Maharashtra ragi farmers both use, a shallow, targeted inter-row disturbance layered on top of the raised bed's passive baseline, for non-leguminous crops where root systems can tolerate it. Whether that addition compounds the benefit on a PQNK bed the way it does in an SRI paddy is an open, testable question this paper flags rather than answers.

4. PHOSPHORUS AND POTASSIUM SOLUBILIZATION: UNLOCKING WHAT IS ALREADY THERE

Most agricultural soils, including much of the calcareous, alkaline soil common across Punjab, are not actually short of phosphorus or potassium in absolute terms. What they are short of is available phosphorus and potassium: both elements readily form insoluble complexes, phosphorus with calcium, iron, and aluminium, potassium locked within the crystal lattice of clay minerals such as mica and feldspar, in forms a plant root cannot take up regardless of how much total P or K a soil test reports.

Phosphate-solubilizing bacteria and fungi release that locked phosphorus mainly by secreting low-molecular-weight organic acids, gluconic, citric, oxalic, and several others, which lower the local pH and chelate the calcium, iron, or aluminium ions holding the phosphate in place, alongside phosphatase enzymes that mineralize organically bound phosphorus directly (Rodríguez & Fraga, 1999). Potassium-solubilizing bacteria use a closely related toolkit, organic acids and exopolysaccharides that dissolve or chelate the mineral lattice, releasing potassium into soil solution; a potassium-releasing strain of Bacillus edaphicus, for example, has been shown to directly improve potassium uptake and growth in cotton and rape (Sheng, 2005).

The organisms carrying out both processes are predominantly aerobic or facultative heterotrophs. The metabolic pathways that generate their organic acids run most efficiently under oxygen-dependent respiration, the same energetic currency nitrogenase itself depends on, described in Section 2 of “The Underground Air.” This produces an instructive contrast rather than a contradiction: nitrogenase must be shielded from oxygen, while phosphate- and potassium-solubilizing organisms need enough of it to run their own chemistry, yet both are optimized by the same moderate, well-aerated-but-not-dry water : air band rather than by opposite extremes. A waterlogged soil starves both processes at once; the Anas et al. (2011) findings on rice already confirm this pattern operating in a single field, since both free-living nitrogen-fixers and phosphate solubilizers rose together under the same aeration regime.

The practical stakes are concrete. Wheat, rice, maize, chickpea, lentil, canola, sesame, potato, tomato, and every other crop named in PQNK's current comparative nutrition testing programme with the Punjab Agriculture, Food and Drug Authority depends on available phosphorus for root development, energy transfer, and seed formation, and on available potassium for water regulation and disease resistance. A soil's water : air balance, not its total nutrient reserve, is what decides how much of that already-present phosphorus and potassium each of those crops can actually reach.

PQNK's own field synthesis puts this scarcity-versus-access distinction in concrete, regional terms. For a representative two-tonne-per-acre wheat yield in the subcontinent, the top six inches of soil in a single acre holds an estimated 800 kilograms of total phosphorus, against a crop removal, in grain and straw combined, of only about 4.4 kilograms, a bank-to-withdrawal ratio of roughly 182 to 1. The same accounting for potassium runs closer to 1,167 to 1 (PQNK Knowledge Initiative, 2025). Two further reserves sit beneath the topsoil figure used in that ratio, a larger, slower-moving subsoil and weathered-bedrock tier, and a virtually limitless unweathered parent-rock tier below that, each a further store the topsoil bank draws on as it is depleted. Read alongside the organisms described above, the argument sharpens considerably: phosphate- and potassium-solubilizing bacteria are not manufacturing these elements from nothing, they are drawing down a reserve already present in the soil at a scale one to three orders of magnitude larger than a single season's crop demand. PQNK's own account of this process organizes it into three functional roles that map directly onto the biology already described: primary mineral weathering by lithotrophic bacteria and mycorrhizal fungi acting on parent rock, solubilization of the liberated but still-insoluble compounds by organic-acid-producing bacteria such as Pseudomonas, and transport of the solubilized nutrient to the root by the mycorrhizal hyphal network itself, a sequence triggered and paced by the plant's own root exudates rather than run on a fixed schedule (PQNK Knowledge Initiative, 2025). Every one of those three roles is carried out by an aerobic or facultative organism. The mineral reserve is, by this accounting, rarely the limiting factor; the water : air balance that keeps its aerobic workforce active is.

5. AIR CHANNELS AND THE LIVING ARCHITECTURE OF SOIL

Professor Uphoff's phrase, air channels up and down and across in the soil, describes a real and well-documented structure: soil macroporosity, built and maintained largely by the organisms living inside it rather than by any external tillage.

Earthworms are the best-studied of these soil engineers. A single earthworm can construct one to two metres of burrow, and earthworm populations collectively displace more than one hundred kilograms of soil per square metre of ground each year, leaving behind a network of channels that serve as preferential pathways for water infiltration and gas exchange and that are readily reused by growing roots once formed (Blouin et al., 2013). Earthworm activity of this kind has been linked to specific crop yield increases of up to twenty-five percent.

Fungal networks contribute a second, complementary structure. Arbuscular mycorrhizal fungi extend a web of extraradical hyphae far beyond the depletion zone immediately around a root, increasing the effective absorptive surface available for phosphorus and water uptake alike. These same fungi secrete glomalin, a glycoprotein that binds soil particles into stable aggregates, and hyphal length together with glomalin content has been shown to be a strong predictor of soil aggregate stability (Rillig, 2004; Smith & Read, 2008). Stable aggregates, in turn, are what hold macropores open against collapse and support continuous air and water movement between them.

One honest qualification belongs here. Arbuscular mycorrhizal colonization is widespread but not universal: several crop families on PQNK's own representative list, canola and mustard among the Brassicaceae, and spinach among the Chenopodiaceae, are largely non-mycorrhizal and gain little from this specific fungal route. For these crops, the bacterial and bioturbation-based routes described in this paper, phosphate and potassium solubilization, earthworm channels, and pH regulation, remain fully operative and are, if anything, the more important pathway.

PQNK's own no-till, permanent-bed management is what allows all of these channels, earthworm burrows, decayed root channels, and fungal hyphal networks alike, to persist and accumulate from one season to the next rather than being severed and reset by annual ploughing, exactly the mechanism "The Underground Air" already describes for Jantar's own deep taproots in Section 6.4. That description need not be limited to Jantar. Every deep-rooted crop in a PQNK rotation leaves the same kind of reusable channel behind it, and the raised bed's undisturbed structure is what lets those channels compound across a rotation rather than resetting with each crop, which is the literal mechanism behind the Regenerative Amplification Loop described in Section 7 of "The Underground Air," now understood to apply to the whole rotation and not only to the nitrogen-fixing crop within it.

6. SOIL PH: THE QUIET VARIABLE EVERY CROP DEPENDS ON

Availability of most essential plant nutrients, phosphorus, iron, zinc, manganese, and boron among them, the same mineral panel PQNK's comparative testing programme measures directly, is tightly bound to soil pH, with each nutrient reaching peak solubility within its own fairly narrow window. Soil pH is not a fixed background property; it is actively set and reset by the same microbial community this paper has been describing. Nitrification, the oxidation of ammonium to nitrate, releases hydrogen ions and acidifies the surrounding soil; organic acid secretion, by roots and by the phosphate- and potassium-solubilizing organisms of Section 4 alike, does the same locally and deliberately; and ordinary aerobic respiration releases carbon dioxide, which forms carbonic acid in soil water.

Waterlogged, oxygen-depleted soil runs a different and less stable chemistry. Once oxygen is exhausted, microbial metabolism shifts to reduction reactions, iron and manganese oxides are reduced, and, at the extreme, sulfate is reduced to sulfide, each of these reactions consuming rather than releasing protons. The result is a soil pH that swings toward neutrality from whatever direction it started, an instability documented directly in oxygen and redox profiling of soil aggregates, where a saturated aggregate's anoxic core supports an entirely different, reduction-driven chemical regime from its aerated exterior only millimetres away (Sexstone, Revsbech, Parkin, & Tiedje, 1985).

A soil held within the aerobic-to-microaerobic water : air band avoids this redox-driven churn and holds a more stable, moderate pH, one in which the mineral panel above stays within reach of the root. This is not a nitrogen-fixation-specific benefit; it applies equally to a wheat field, a tomato bed, or a stand of okra, and it is the same underlying reason PQNK's raised-bed architecture is designed to prevent waterlogging in the first place.

PQNK's own field measurements show this stabilizing effect directly, and at a scale worth stating in full. On a matured PQNK bed, a soil sample drawn twelve inches from a plant measures a bulk pH of roughly 8, typical of Punjab's calcareous, alkaline soils; a sample drawn from inside that same plant's own root net, on the same bed, measures roughly 7, a full unit lower. This is not an anomaly requiring a special explanation. Root-induced pH change of exactly this kind is a well-documented rhizosphere effect, driven by the mechanisms already described above: the release of protons to balance an uptake of more cations than anions, sharpest where nitrogen is taken up as ammonium rather than nitrate, organic acid exudation by roots and their associated microbial community, and root and microbial respiration (Hinsinger, Plassard, Tang, & Jaillard, 2003). The magnitude PQNK measures is, if anything, conservative against the published literature. A controlled study of peach and nectarine grown in calcareous and alkaline soils under ammonium-based nitrogen supply measured rhizosphere pH running two to three full units below bulk soil pH, in the same direction and for the same underlying reason (Tagliavini, Masia, & Quartieri, 1995). A matured PQNK bed builds exactly the conditions that study's ammonium treatment did by design: permanent roots, an active associated microbial community, and nitrogen released through organic decomposition and biological fixation rather than nitrate-based fertigation. The one-unit swing PQNK measures from furrow-adjacent bulk soil to root net is the expected, and comparatively modest, signature of that same process.

7. ROOT PERMEABILITY: AQUAPORINS AND THE WATER-NUTRIENT GATEWAY FOR EVERY ROOT

“The Underground Air” described the Casparian strip as the gatekeeper that forces water and solutes out of the passive apoplastic pathway and through the living membrane of each endodermal cell. That description leaves one question open: once water is forced to cross the membrane, what does it actually cross through? The answer is aquaporins, water-channel proteins of the plasma-membrane intrinsic protein family, and they turn out to be governed by the same air-water balance as everything else in this paper.

Research on plant water transport under low-oxygen conditions has shown that oxygen deprivation triggers cytosolic acidosis inside root cells, and that this drop in internal pH directly gates aquaporins shut, cutting a root's hydraulic conductivity within minutes of the onset of waterlogging (Tournaire-Roux et al., 2003). Because aquaporins, not the Casparian strip itself, are the specific channel through which water crosses the endodermal membrane, this closure acts downstream of the gatekeeper described in the original paper: even a fully intact, well-functioning Casparian strip cannot deliver water to the plant if the aquaporins on the other side of it have shut. The effect has since been confirmed across a range of crop species, from sunflower to pearl millet, and applies to any plant root, legume or otherwise.

The practical consequence follows the same logic as every other section of this paper. A waterlogged soil does not just drown roots of oxygen; it actively switches off the specific molecular gate those roots use to take up water and, with it, whatever nutrients are moving in that water stream. A water : air-balanced raised bed keeps roots aerated enough that this gate stays open, in Jantar exactly as in wheat, maize, or any vegetable crop growing beside it.

8. SYNTHESIS: THE RAISED BED AS A UNIVERSAL PLATFORM

Five mechanisms, one now specific to legumes and four that are not, have been traced through this paper and its companion, and all five answer to the identical physical variable.

Mechanism	Oxygen Relationship	Crop Applicability
Nitrogenase / rhizobial nodulation	Requires protection from oxygen (microaerobic)	Legumes and free-living diazotrophs (“The Underground Air”)
Phosphorus & potassium solubilization	Requires oxygen-dependent respiration to drive organic-acid metabolism	All crops
Bioturbation & mycorrhizal networks	Aerobic organisms; channels enable gas exchange	All crops (AMF benefit uneven across families)
Soil pH stability	Waterlogging drives destabilizing redox pH swings	All crops
Root aquaporin function	Closes under low-oxygen-triggered cytosolic acidosis	All crops

PQNK's raised-bed water : air architecture was not designed as a nitrogen-fixation technology, and this paper's argument is that it should not be understood as one. It is a general soil-biology and plant-physiology platform, and every crop drawn into a PQNK rotation, and every crop named on the sixteen-item representative list now entering PAFDA-authenticated testing, wheat, rice, maize, chickpea, mung bean, lentil, canola, sesame, cottonseed, potato, tomato, spinach, okra, kinnow, mango, and guava, draws on the same underlying mechanism, whether or not that crop carries a single nodule.

9. AN HONEST NOTE ON EVIDENCE

Every mechanism described in this paper is drawn from published, peer-reviewed research, and the reasoning connecting each mechanism to PQNK's raised-bed architecture follows directly from that architecture's documented physical properties. What this paper does not contain is new field data measuring phosphate-solubilizer populations, biopore density, pH stability, or root hydraulic conductivity specifically on PQNK beds growing non-leguminous crops. That is a meaningful difference from “The Underground Air,” whose central claim, enhanced Sesbania nodulation on raised beds, rested on published nodule-count field trials, not on inference alone.

That gap has a clear next step, and it is already underway rather than merely proposed. PQNK's SOP for Comparative Nutrition, Density & Diversity Testing, prepared jointly with the Punjab Agriculture, Food and Drug Authority, specifies a soil and irrigation-water baseline at every trial site, including soil organic matter, soil microbial biomass and activity, and optional 16S / ITS soil microbiome sequencing, run across all sixteen representative crops, most of them non-leguminous, sourced from ancient-conventional, modern industrial, and matured PQNK systems side by side. When that programme's soil baseline results are compiled, they will be positioned to test this paper's claims directly, whether matured PQNK soils in fact carry larger populations of phosphate and potassium solubilizers, more stable pH, and denser biopore networks than the other two systems, rather than relying on inference from mechanism alone, exactly the standard “The Underground Air” was able to meet for Jantar and nodulation.

10. CONCLUSION: THE SAME AIR, EVERY ROOT

A PQNK farmer, watching Jantar roots on a raised bed, wondered whether the microbes around them were breathing a different air than the one above ground. A Cornell professor, reading the paper that grew from that wondering, pointed out that the same underground air the paper described so carefully for one crop and one enzyme is doing comparable work for every other crop in the field, through phosphate and potassium solubilizers, earthworms and fungal hyphae, the chemistry that sets soil pH, and the molecular gates that let a root drink at all. Neither insight came from a laboratory first. Both came from close, patient attention to a working field, which is where this paper, like its companion, ultimately rests its case: underground air was never only about nitrogen. It is the condition every root in a PQNK field depends on, whether or not that root ever forms a nodule.

KEY TAKEAWAYS

One Variable, Many Guilds: water : air is the physical variable that governs nitrogen fixation, phosphorus and potassium solubilization, soil bioporosity, pH stability, and root water uptake alike; nitrogenase is simply its most dramatic example, not its only one.

Active and Passive Aeration Apply Beyond Rice: Professor Uphoff's own SRI research shows both aeration routes raising phosphate solubilizers and nitrogen-fixers together in a non-leguminous crop, a finding independently echoed by Maharashtra ragi farmers using an ox-drawn active-aeration implement of their own design.

Phosphorus and Potassium Are Usually Present, Not Absent: most soils hold ample total P and K locked in insoluble forms; aerobic and facultative solubilizing bacteria, not fertiliser, are what make them available, and their metabolism runs best in the same well-aerated band nitrogenase needs.
Soil Structure Is Biologically Built: earthworm burrows and mycorrhizal hyphal networks, not machinery, construct and maintain the macropores through which air, water, and roots move; PQNK's no-till management is what lets these structures persist and compound season over season.
Aquaporins Are the Gate Behind the Gate: the Casparian strip forces water through the endodermal membrane; aquaporins are the channel it crosses, and they close within minutes under low-oxygen stress, in any crop's root, not only a legume's.
The Evidence Gap Is Already Being Closed: the PAFDA soil-baseline testing programme now underway is positioned to measure these mechanisms directly on PQNK beds across sixteen crops, most non-leguminous, turning this paper's inference into the same kind of field-trial evidence “The Underground Air” already has for Jantar.

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