growing AFRICA

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SPECIAL FOCUS

Enhancing Global Phosphorus Efficiency Along the Mining-Use-Recovery Pathway

WHY IS P CENTRAL TO AFRICAN DEVELOPMENT?

ENHANCING P EFFICIENCY

INNOVATING TOWARDS LOCAL P USE SOLUTIONS

MORE INSIDE!

ACTIONABLE SCIENTIFIC INFORMATION ON PLANT NUTRITION

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Inside this Issue

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Welcome to the second issue of *Growing Africa* for 2025. This edition spotlights **phosphorus management**, featuring insights from APNI's session *"Enhancing Global Phosphorus Efficiency along the Mining–Use–Recovery Pathway"* at the **8th Sustainable Phosphorus Summit (SPS8)** in Accra, Ghana. International experts shared science-based strategies for sustainable phosphorus use across Africa.

We also present field research aligned with our core themes of **precision plant nutrition, soil health for improved livelihoods, and climate & weather-smart plant nutrition for resilience.** Highlights include:

- A Moroccan study on optimizing fertilizer under deficit irrigation to sustain olive yields and improve oil quality.
- Tanzanian research on zinc fertilization in rice systems to combat hidden hunger and strengthen food security.
- Malawian work on legume-based intercropping and residue management to restore nitrogen dynamics and reduce fertilizer dependence in drought-prone regions.

This issue celebrates innovation through **EXCEL Africa**, APNI's awards and grants program, showcasing graduate and early-career research—from cassava nutrition in Côte d'Ivoire to climate-smart soil management in Ethiopia. It's an inspiring cohort that reflects well on the ongoing commitment and growing capacity to address the key challenges faced by African agriculture.

Our **GrowthCharts** series returns with a global view of maize intensification versus extensification, and we announce winners of the **Annual Photo Contest.**

Join us in advancing science-driven solutions for African agriculture! Submission guidelines are available at https://growingafrica.pub/about, or contact our team directly.

Sincerely,

Senior Editor | Communications Lead

Growing Africa Style Guide
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Unlocking Africa's Food Systems: Why Phosphorus Management Is Central to Sustainable Intensification

By Kaushik Majumdar

Phosphorus deficiency severely limits crop productivity in Africa, threatening food security and sustainability. *Current application rates are far below global needs, requiring a five-fold increase. Solutions include improving fertilizer access, reducing supply chain costs, and adopting 4R Nutrient Stewardship for efficient, context-specific phosphorus use to restore soil health and resilience.*

Spot application of a calibrated rate of P fertilizer at planting time.

The 8th Sustainable Phosphorus Summit (SPS8) was held in Africa for the first time this year—an important milestone that coincides with growing consensus that Africa must substantially increase fertilizer use to meet food security goals. Decades of continuous cropping, minimal fertilizer inputs, and low recycling of organic matter have resulted in widespread soil nutrient depletion across the continent. Among these constraints, phosphorus (P) deficiency stands out as one of the most yield-limiting factors, severely compromising soil productive capacity (Tauro et al., 2024).

The consequences of chronic P deficiency are far-reaching. Low crop productivity, soil degradation, persistent hunger, and loss of livelihoods are direct outcomes. Declining soil fertility has also encouraged expansion into extensive agriculture, driving deforestation, greenhouse gas emissions, and biodiversity loss. Addressing P deficiency is therefore not only an agronomic imperative, but also a social, economic, and environmental necessity.

The scale of the phosphorus challenge

Analyses suggest that a five-fold increase in P application will be required to sustain food security in Africa (Sattari et al., 2012). Relative to 2016 levels, the elemental P required to feed Africa's projected 2050 population is estimated at between 1.7 and 3.4 million t annually (Magnone et al., 2022). These figures highlight the magnitude of the challenge and the urgency for action.

Compelling evidence shows that balanced, context-specific P use can substantially raise crop yields across diverse African agro-ecologies. Meta-analyses of nutrient omission trials (Njoroge et al., 2019; Zingore et al., 2022) demonstrate significant cereal yield responses to P across all soil fertility classes, often exceeding 1 t/ha. Balanced P application not only increases yields, but also improves yield stability and nutrient use efficiency, reinforcing its central role in sustainable intensification.

Yet, despite its importance, P use in Africa remains extremely low. Application rates are generally below 10 kg P/ha/yr. While average inorganic fertilizer use is approximately 23 kg/ha, farmers in sub-Saharan Africa typically apply only about 7 kg P/ha, with many regions using even less. This stark gap between need and practice underscores a systemic failure rather than a lack of agronomic potential.

Policy momentum and persistent systemic barriers

Increasing fertilizer use is essential to achieve food security, reduce poverty, and halt land degradation. At the 2024 Africa Fertilizer and Soil Health (AFSH) Summit in Nairobi, African Heads of State reaffirmed their commitment—under the African Union—to improve access to affordable fertilizers and boost crop productivity. The endorsed 10-year Action Plan aims to triple fertilizer use and double food production across the continent.

While such ambitions are critical, achieving them requires a coordinated roadmap that tackles the structural constraints that have historically suppressed fertilizer use. Access, defined by both availability and affordability, remains the dominant bottleneck. Evidence shows that transaction and transportation costs over relatively short distances (approximately 35 km) can raise fertilizer prices by 50% and reduce use by up to 75% (Minten et al., 2013). In some cases, farmers located just 10 km from a distribution center face costs comparable to transporting fertilizer over 1,000 km from international ports.

"Increasing fertilizer use is essential to achieve food security, reduce poverty, and halt land degradation.

These last-mile supply chain constraints account for a disproportionate share of fertilizer prices in African countries. Farm-gate prices can reach up to four times those in Europe (Njoroge et al., 2023), severely undermining affordability and adoption. Reducing these inefficiencies is therefore central to any strategy aimed at increasing P use.

From access to effective use: the knowledge Imperative

Improving physical access to fertilizers must be complemented by empowering farmers with knowledge to use them efficiently and profitably. African smallholders operate across an overwhelming diversity of climate–soil–crop combinations, demanding context-specific agronomic solutions. Limited access to actionable, locally relevant information increases production risks and lowers returns on fertilizer investments, particularly for P, which is prone to fixation in the continent's predominantly acidic soils.

The 4R Nutrient Stewardship principles—applying the right source at the right rate, at the right time, and in the right place—offer a robust framework for improving P use efficiency. However, these principles must be carefully contextualized for dominant crops and cropping systems through farmer-centric engagement. For example, in the highly acidic, P-fixing soils of East Africa, spot application of P fertilizer

Young maize crop showing severe symptoms of P deficiency.

is often far more effective than broadcasting, which increases soil–P contact and accelerates fixation, thus reducing its plant availability.

Conclusion

The urgency of sustainably increasing P use in Africa was strongly endorsed at SPS8 as a prerequisite for future food and nutrition security, as well as environmental sustainability. Removing supply and value-chain constraints, improving the availability and affordability of P fertilizers, and scaling scientifically credible, contextually relevant agronomic practices are all essential pillars of sustainable P management. Together, these actions can unlock Africa's soil productivity, accelerate sustainable intensification, and support resilient food systems for generations to come. ■

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Enhancing Global Phosphorus Efficiency Along the Mining–Use–Recovery Pathway

By Yassine Taha and Mostafa Benzaazoua

Innovative strategies to improve phosphorus efficiency along the mining–use–recovery pathway are highlighted through the approaches developed by OCP Group and UM6P's Geology & Sustainable Mining Institute. *Key measures include advanced orebody modeling for selective extraction, sensor-based ore sorting, water recycling, and desalination. Near-zero-waste mining creates value from low-grade ores and legacy waste that are integrated with circular economy principles and mine rehabilitation. These approaches offer a roadmap for sustainable phosphate management and environmental stewardship.*

Phosphorus (P) is an essential and irreplaceable nutrient for all living organisms, forming the backbone of global food production through fertilizers. However, it is a non-renewable resource extracted almost exclusively from phosphate rock deposits that are geographically concentrated in a few regions, particularly Morocco. The growing demand for food and the expected increase in global population have made the efficient management of P along its entire life cycle, from mining to its end-of-life recovery, an urgent global challenge.

Current estimates indicate that less than 20% of mined P eventually reaches human consumption due to inefficiencies across the mining, processing, agricultural, and waste management stages. The rest is lost as waste rock, tailings, or dispersed into soils and water bodies. Consequently, improving global P efficiency requires a holistic approach that integrates orebody knowledge, optimized production chains, and sustainable waste valorization.

Promising approaches being developed by the Geology & Sustainable Mining Institute (GSMI) of UM6P along with OCP Group are enhancing P efficiency along the mining–use–recovery pathway.

Orebody knowledge and characterization

Comprehensive orebody knowledge forms the foundation of sustainable mining. It enables optimized extraction, efficient beneficiation, and strategic waste management. Phosphate deposits, being sedimentary and highly heterogeneous, often contain a complex assemblage of mineralized layers interbedded with non-phosphatic lithologies such as carbonates, flints, and clays. Understanding this spatial variability is essential to reduce P losses and to valorize the full range of materials present in the orebody.


Phosphate deposit at Benguérir, Morocco mine site.

OCP has undertaken a systematic drilling and core-sampling campaign across its main phosphate basins (Khouribga, Benguerir and Gantour).

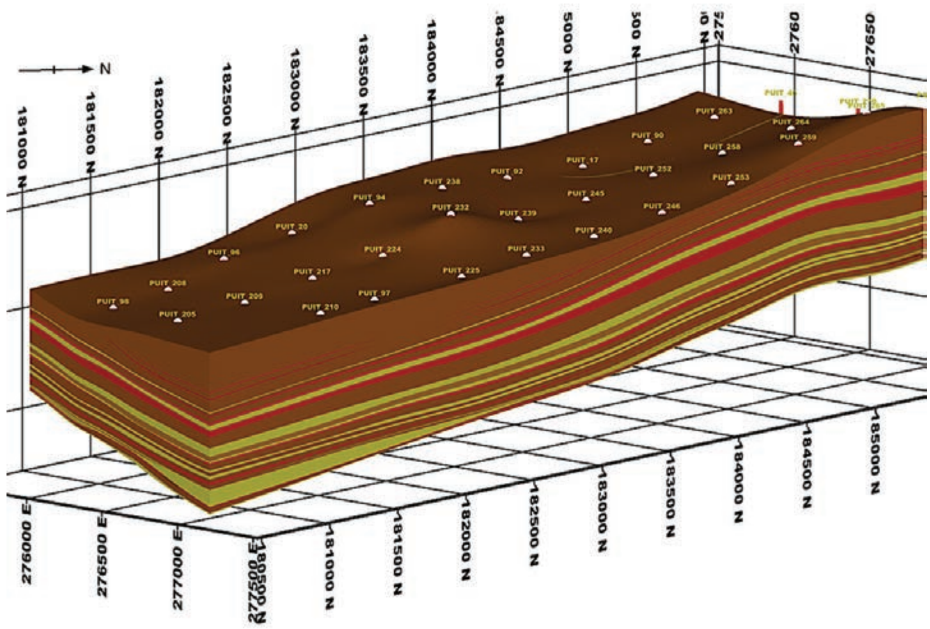

Figure 1. 3D diagram of a phosphate deposit panel highlighting phosphate rock layers (yellow), overburden and interburden layers.

This program is coupled with multi-technique sample characterization, combining mineralogical, geochemical, and physical analyses to build 3D digital geological models of phosphate deposits (**Fig. 1**). These digital twins integrate data on phosphate resource distribution, physical rock properties, and the presence of bonus or penalizing elements such as magnesium (Mg), iron (Fe), or carbonates. The resulting orebody models enable predictive mine planning and selective extraction to maximize recovery while minimizing dilution and waste generation.

Furthermore, OCP is exploring P recovery from past mining wastes. Historical mining activities have generated large waste volumes, with an average of 3 t of waste rock per t of phosphate rock. These materials, although previously uneconomic, are being reassessed using advanced teledetection methods (satellite imagery, drone-based mapping) and systematic spoil sampling (**Fig. 2**). Several studies are currently underway to assess the recovery potential of these materials through lab-validated screening and sensor-based sorting flowsheets, which are being upscaled to the pilot level. Phosphate mining operations should aim to separately deposit and document waste materials to facilitate future re-extraction when recovery becomes feasible, thus advancing circular resource management and preventing permanent orebody losses.

Optimization of phosphorus flows along the mine value chain

Phosphorus efficiency cannot be achieved without optimizing flows along the entire mining value chain—from extraction and beneficiation to transportation and processing. Major inefficiencies typically arise during the upstream operations (extraction and crushing), as well as during beneficiation (screening, washing, flotation), where significant P is lost in the tailings or diluted by non-phosphatic material.

To address these inefficiencies, OCP and GSMI are developing integrated solutions that focus on reducing losses, lowering energy and water consumption, and increasing recovery rates. One of the most promising approaches is the use of sensor-based ore sorting technologies.

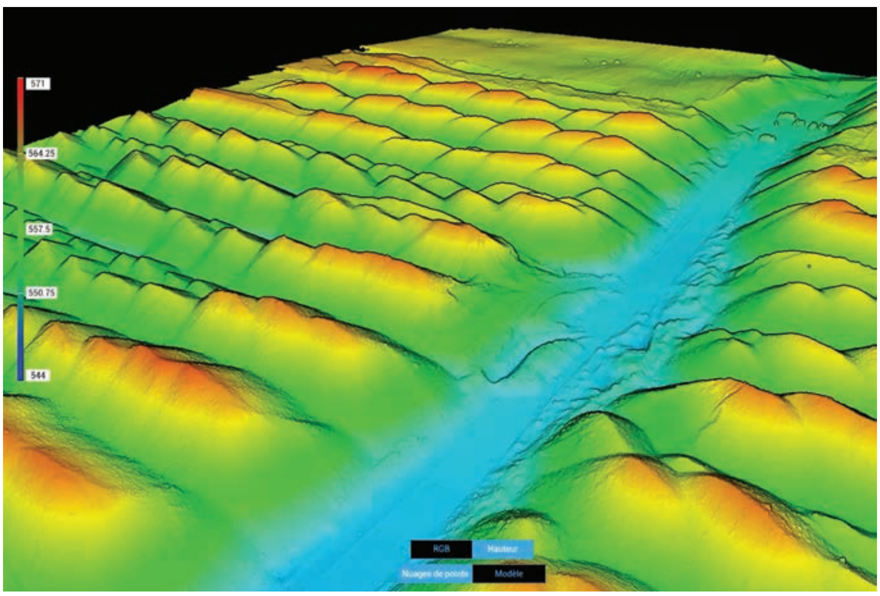

Figure 2. An example of a 3D model of waste rock dumps in Morocco.

Ore sorting technologies

Ore sorting involves the separation of mined material based on physicochemical properties detected by sensors such as X-ray transmission (XRT), near-infrared (NIR), or laser-induced breakdown spectroscopy (LIBS), etc. These systems can distinguish phosphate-rich particles from waste based on density, elemental composition, or color, allowing for real-time removal of non-valuable material prior to grinding and flotation. The benefits are multiple:

- Reduced energy and water consumption since less material needs to be processed downstream;
- Increased P_2O_5 recovery by minimizing dilution with barren lithologies;
- Extended orebody life through the economic inclusion of lower-grade ores; and
- Reduced tailings volume and environmental footprint.

Preliminary trials in sedimentary phosphate ores from OCP's mines have demonstrated that pre-sorting can increase recovery efficiency. In combination with improved orebody models, ore sorting can create a dynamic and adaptive mine plan, focusing on the right material at the right time.

Water efficiency in beneficiation

Water management remains one of the most critical sustainability challenges in phosphate rock processing. A key strategic objective for the phosphate industry is to progressively substitute natural freshwater sources with alternative water resources. Today, more than 80% of the water used in phosphate mining and beneficiation operations can be sourced from non-conventional origins, including seawater desalination plants, treated and recycled wastewater, and recovered process water.

Within the beneficiation circuit, particularly during the flotation and thickening stages, advanced flocculation-thickening systems allow the recycling of over 75% of process water, thereby reducing both freshwater intake and the environmental footprint associated with tailings storage facilities. Ongoing developments aim to further enhance water recovery by transitioning towards dry tailings management through filtration technologies, enabling near-total recycling of process water and minimizing water loss by evaporation.

In parallel, phosphate producers are increasingly adopting bio-based reagents in mineral processing to reduce dependence on imported chemical reagents, enhance supply sovereignty, and lower Scope 3 (value chain) greenhouse gas emissions. This integrated approach, combining alternative water sourcing, closed-loop recycling, and green chemistry, reflects a comprehensive commitment to sustainable water and resource management in the phosphate mining sector.

Waste valorization and the near-zero-waste approach

Mining and beneficiation generate large volumes of solid wastes, which have traditionally been considered uneconomic or inert. However, these materials often contain valuable minerals that can be recovered or repurposed, enabling a shift toward near-zero-waste mining.

The GSMI teams are pioneering a selective mining methodology that aims to extract, classify, and store different lithological layers separately for future valorization. In typical sedimentary phosphate deposits, the orebody includes:

- Phosphate rock layers (economic mineralization);
- Low-grade and difficult to exploit phosphate layers;
- Calcite-rich layers;
- Dolomite-rich layers;
- Clay-rich layers; and
- Mixed layers.

Valorization pathways

The traditional extraction approach focuses solely on the phosphate layers, while the others are mixed and dumped as overburden or waste. The selective mining strategy proposes to extract and stockpile each lithology separately, creating a diversified resource base for secondary processing.

- Calcite-rich layers: can be transformed into value-added products such as animal feed additives (DCP, MCP), cement, and lime-based construction materials. Pilot-scale results have already confirmed their suitability for such applications.
- Dolomite-rich layers: have potential uses in aggregates, magnesium metal production, struvite synthesis, and feed-grade phosphates.
- Clay-rich layers: can serve as precursors for

ceramics, eco-cements, or geopolymer materials for construction and environmental remediation.

- Low-grade phosphates: may be blended or upgraded through beneficiation or used in slow-release fertilizers.

Recovery from legacy wastes

As previously mentioned, historical mine waste dumps containing 10% P_2O_5 or more are being reconsidered as secondary resources. Through screening and ore sorting, the P-bearing fractions can be concentrated and reprocessed using the same beneficiation circuits as primary ores. This strategy not only recovers P but also reduces the long-term footprint of waste storage sites.

Integration with circular economy principles

These valorization initiatives embody a circular approach to mining, ensuring that every fraction of the orebody contributes to economic value. Instead of viewing mining residues as environmental liabilities, they become secondary raw materials for multiple industries. This transition supports local economies, reduces landfill requirements, and aligns with global sustainability goals such as the United Nations Sustainable Development Goals (SDGs 9, 12, and 13).

Restoration and rehabilitation of mine waste landfills

Sustainable phosphate mining extends beyond resource extraction to include the restoration and rehabilitation of mine waste landfills. Modern mine reclamation practices aim not only to stabilize terrain and prevent erosion but also to rebuild functional and resilient ecosystems. Early integration of rehabilitation strategies into mine planning enables reshaping of waste landforms, selective cover application, and the reintroduction of native or drought-tolerant vegetation to restore ecosystem services while minimizing irrigation needs. Emerging approaches promote value creation through restoration, transforming reclaimed lands into productive assets such as agroforestry zones, solar farms, or biodiversity corridors.

In parallel, research focuses on enhancing soil health and reducing water use through the reuse of mine-derived materials and the development of engineered soils combining tailings, clays, and organic amendments. These substrates improve fertility and water retention, enabling vegetation growth under arid conditions. The use of customized fertilizers formulated from recovered P and local minerals supports nutrient efficiency while closing material loops. By integrating soil restoration, efficient water management, and circular resource use, the phosphate mining sector can transform post-mining landscapes into sustainable ecosystems that generate environmental and socio-economic value.

Conclusion

Enhancing global P efficiency requires a systemic transformation of the mining–use–recovery pathway. OCP's approach demonstrates how a combination of data-driven orebody knowledge, technological innovation, and circular resource management can drastically improve resource efficiency and environmental sustainability.

Through systematic drilling and 3D digital mapping, OCP is unlocking a precise understanding of phosphate deposits to enable selective extraction and long-term planning. Ore sorting and optimized beneficiation are reducing energy, water and P losses, while water recycling and desalination initiatives secure the sustainability of operations in arid environments. Simultaneously, the valorization of both current and historical wastes through a selective mining methodology is transforming the concept of waste into opportunity.

Collectively, these efforts represent a paradigm shift toward "near-zero-waste" phosphate mining, ensuring that the world's largest phosphate reserves are managed responsibly and efficiently. By closing the loop between extraction, processing, and recovery, OCP's integrated model provides a tangible roadmap for global P sustainability—linking mineral efficiency with food security and environmental stewardship. ■

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Managing Phosphorus for Profitable and Sustainable Crop Production in Africa

By Robert Mikkelsen

Phosphorus is vital for crop productivity in Africa but limited by low soil reserves, strong fixation, and poor recovery. *The article emphasizes improving phosphorus use efficiency through 4R Nutrient Stewardship, soil management, and crop breeding innovations. Site-specific strategies and integrated approaches are essential for sustainable yields and food security.*

Phosphorus deficiency symptoms visible on rice leaves.

Phosphorus (P) is essential for crop growth and food security, yet it remains one of the most limiting and misunderstood nutrients in African agriculture. The soils of Sub-Saharan Africa (SSA) are among the most highly weathered on Earth, characterized by low native P reserves, high P sorption capacity, and chronic nutrient depletion. At the same time, P fertilizer can be costly and is often used sparingly, leading to low yields and inadequate economic returns for millions of farmers. Improving phosphorus use efficiency (PUE) is not just an agronomic challenge, but also an economic and food-security imperative.

The essentiality of phosphorus for plant nutrition and crop yield

Phosphorus is indispensable for nearly every biological process in plants. Its role begins at the molecular level and expands to affect every aspect of plant growth, including crop yield and quality.

The plant demand for P begins early and continues throughout the growing season, with crops such as maize taking up P continuously from emergence to physiological maturity. Deficiency in the early stages may reduce root development, limit canopy formation, and cause irreversible yield losses, even if P is supplied later.

Phosphorus requirements in African cropping systems

The highly weathered nature of most SSA soils means that they are often dominated by iron (Fe) and aluminum (Al) oxides, acidic, and consequentially low in P. This physiochemical nature further increases the transformation of added fertilizer P into less plant-available forms.

Despite this, many crops show strong yield responses to added P, even at relatively low fertilizer application rates. Yet achieving high yields requires continuous replenishment of P removed during harvest, otherwise soils become progressively depleted of nutrients. In addition to mere nutrient replacement, a positive balance (i.e., above removal) is usually required to deliver a multi-year investment in renewed soil P capital.

Why phosphorus fertilizer recovery is low

Even though P is essential for crop nutrition, it is common that only 10 to 20% of applied P fertilizer is recovered by crops in the first growing season. In African soils, recoveries can sometimes be even lower. There are two major reasons for this:

A. Soil reactions that "fix" phosphorus

Once fertilizer applied to soil, phosphate ions react rapidly with Fe, Al, and calcium (Ca) to form less soluble compounds (**Fig. 1**). These reactions include:

- **Adsorption:** Phosphate attaches to surface of clay minerals and Al/Fe oxides.
- **Precipitation:** Phosphate combines with Ca, Fe, or Al to form minerals with low solubility.
- **Occlusion:** P becomes trapped within mineral structures where roots cannot access it.

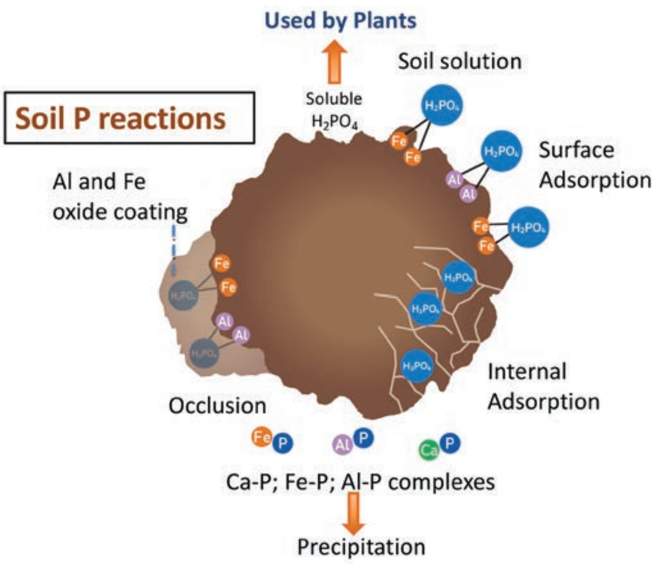

Figure 1. There are many chemical and biological processes that influence the fate of added P fertilizer in soil. Some key inorganic soil reactions are highlighted here. (modified from https://ballance.co.nz/)

The processes responsible for removing P from the soil solution begin within hours or days of fertilizer application. The gradual P conversion to less-soluble chemical compounds can continue for months or years. Although the added P still remains in the soil, its plant availability and solubility is greatly reduced during the season of application as soil minerals tie up P into forms that plants cannot readily use. Many African soils are sometimes referred to as "hungry" soils because they have a large capacity to adsorb added P fertilizer and remove it from the soil solution, and these soils are slow to release the P again.

In many African soils, where Al/Fe oxides dominate, conversion of P to less soluble forms can be extreme. A small dose of broadcast P may become largely unavailable before roots have a chance to access it and it slowly dissolves again over a longer period.

B. Limited root exploration and access

Plants can only take up P that is within a few millimeters of their root surface (**Fig. 2**). This small area surrounding each root (1 to 3 mm), termed the rhizosphere, is vastly different from the soil further from the root. Within the rhizosphere, plant roots are excreting a variety of soluble sugars, organic acids, and enzymes that facilitate a burst of microbial growth and cause P to be more soluble in the soil solution. However, since P moves slowly and diffuses very short distances, uptake is influenced by:

- **Greater root density and branching** allowing better exploration of the soil and increased interception of diffusion-limited P.
- **Root hairs** extending the reach by another millimeter or more, increasing the root surface area and uptake in the P-depletion zone.

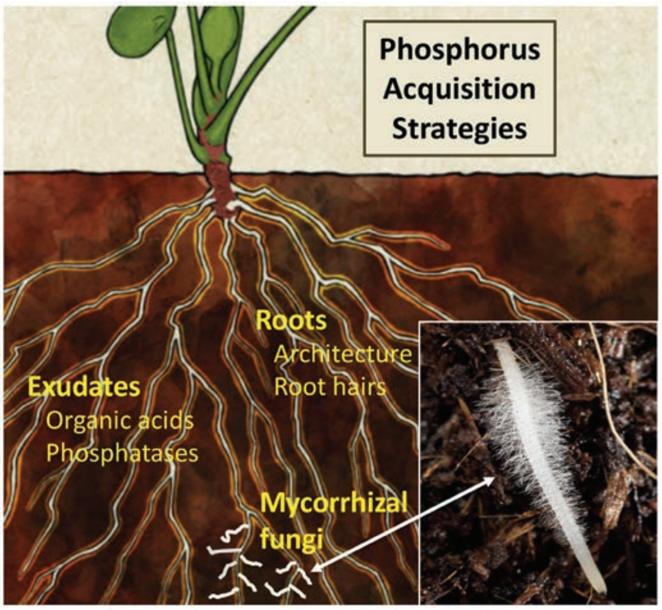

Figure 2. Healthy roots play a vital role in recovery of added P fertilizer. The presence of well-branched roots with abundant root hairs, the colonization of mycorrhizal fungi, and a healthy rhizosphere environment with abundant organic exudates and biological activity all contribute to greater uptake of P from the soil. (Credit: Steve Tjosvold. https://ucanr.edu/blog/nursery-and-flower-grower/article/take-closer-look-roots)

Table 1. Typical response of maize grain to added P fertilizer used to calculate four measures of P efficiency (hypothetical data).

Treatment	P application rate, kg P/ha	Yield, t/ha	P uptake, kg P/ha	PFP, t/kg P	AE, t/kg P	RE, kg/kg P	PNB, kg/kg P
1	0	1.0	3	–	–	–	–
2	10	2.8	8.4	0.28	0.18	0.54	0.84
3	20	4.1	12.3	0.21	0.16	0.47	0.62
4	40	5.4	16.2	0.14	0.11	0.33	0.41
5	60	6.0	18	0.10	0.08	0.25	0.30

- **Soil moisture** enabling greater P diffusion towards the root.
- **Mycorrhizal fungi and beneficial microbes** facilitating P solubilization and uptake.
- **Root exudates** solubilizing organic and inorganic forms of P.

In acidic soils, the presence of soluble Al is damaging to root hairs and can stunt the entire root system, thereby restricting uptake of P. Many African farms suffer from both low soil P concentrations and harmful effects from excessive Al at low pH. This combination of strong P fixation and limited root access contributes to the low seasonal recovery of P fertilizers in many regions.

How phosphorus use efficiency is calculated

There are large differences reported on how much of the P fertilizer is recovered by crops. Some estimates show that as little as 10% of the added P fertilizer is taken up by plants, while other reports show that P recovery can exceed 70–90%. These discrepancies arise from how P recovery is calculated and the time frame considered in the calculation.

Phosphorus use efficiency (PUE) can be expressed in several different ways, and each method answers a different agronomic question. The method of calculating PUE substantially affects the numerical estimate. When referring to PUE, it is necessary to know what it means and how it is calculated.

Here are some of the common ways of calculating "efficiency" (**Table 1, Fig. 3**).

1. Partial Factor Productivity (PFP)

PFP = Yield / P applied

Measures how productive a field is per unit of fertilizer applied, which is useful for comparing economic efficiency, but not true soil or plant recovery.

2. Agronomic Efficiency (AE)

AE = (Yield with P – Yield without P) / P applied

Shows how much yield increase is obtained per kg of P applied. AE is useful for assessing profitability. Farmers generally want to know what yield benefits they are receiving from applying nutrients and measure their yield gains from fertilizer application. However, this method requires famers to have an unfertilized strip to measure any yield gain resulting from P fertilization.

3. Recovery Efficiency (RE)

RE = (P uptake with fertilizer – P uptake without fertilizer) / P applied

This approach measures actual plant uptake of fertilizer-derived P. This requires knowing both the amount of harvested crop (kg or t), and the P concentration in the crop. The P concentration can be measured by an analytical lab or estimated from published values in the literature. This approach also requires an unfertilized strip for a comparison with fertilized areas.

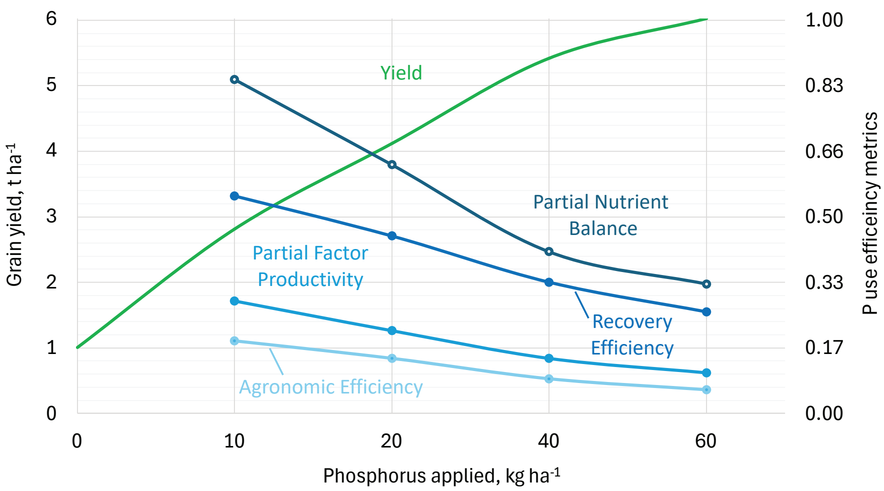

Figure 3. The response of maize to added P fertilizer and four different methods of calculating P use efficiency. Efficiency is usually greatest at the lowest rate of input, but this is not usually where yields are maximized or economic returns are greatest. This example illustrates how the many commonly used terms for "efficiency" can give very different results, even from the same data (hypothetical data presented).

4. **Partial Nutrient Balance (PNB)**

PNB = P removed in harvest / P applied

Indicates whether P applications match long-term removal. In many agro-ecosystems, PNB can exceed 70–90% when inputs and harvest outputs are matched, even if short-term P uptake remains low (Syers, et al., 2008). This explains why the difference-method (RE) can appear low, while long-term balances may look much higher. However, in many African soils nutrient balances may not provide a clear short-term picture since a high fraction of fertilizer P can be fixed in biologically unavailable forms.

Taking a multi-year approach considers the strong residual effect of P as the basis for the concept of investing in "soil P capital" to enhance long-term productivity. Repeated applications of inorganic and organic P sources will improve P fertility as a function of time. But the profitability of repeated P additions needs to be considered from an entire farm-system perspective.

Improving phosphorus recovery through soil management and 4R Nutrient Stewardship

Farmers need practical strategies to make advancements in their fertilization practices. The 4R Nutrient Stewardship framework provides a combination of agronomic, chemical, and biological approaches for improving P use efficiency.

1. Right Source

- Use soluble mineral P fertilizers where rapid crop response is needed.
- Combine mineral P with locally available organic materials (manure, compost, residues) which:
  - provide an additional input of external P,
  - supply organic acids that compete with P adsorption reactions,
  - improve soil structure and moisture-holding capacity,
  - stimulate microbial P cycling,
  - help alleviate Al toxicity to roots.
- Rock phosphate may be appropriate, especially on acidic soils and in long-term cropping systems.

2. Right Rate

- Select P fertilizer applications on local or regional soil tests where available, yield targets, and local calibration data.
- Avoid under-application, which leads to:
  - low yields and biomass,
  - limited root growth,
  - poor economic returns per unit of grain produced.
- Avoid large over-applications, which increase fixation and may also reduce economic returns.

3. Right Time

- Synchronize applications with crop demand.
- Sidedress or place P, at planting rather than broadcasting widely.
- Avoid applying early in long dry periods when diffusion is minimal.

4. Right Place

- Placement is often the most powerful tool for managing P in many African soils.
- Banded fertilizer concentrates P near the root zone, reducing soil contact and slowing P adsorption.
- Spot application (microdosing) near the seed is especially effective for smallholder farmers using low P application rates.
- Broadcast-and-incorporate techniques will improve the overall P concentration in soil but may not result in an immediate P response to the following crop.

Liming acidic soils is another critical strategy. Raising the soil pH reduces Al and Fe reactivity, thus improving P availability and encouraging healthier roots.

Moisture management through mulching, residue retention, and reduced tillage can also enhance P diffusion and P-solubilizing biological activity, improving plant access to soil P.

Future opportunities: modifying crops to improve phosphorus acquisition

While soil management is the first step for improving P efficiency, crop genetics may soon offer opportunities to improve P uptake by crops. Current research is exploring root traits that help plants better explore soil, solubilize soil P, and use internal plant P more efficiently. Below are a few examples of promising innovations (**Fig. 4**).

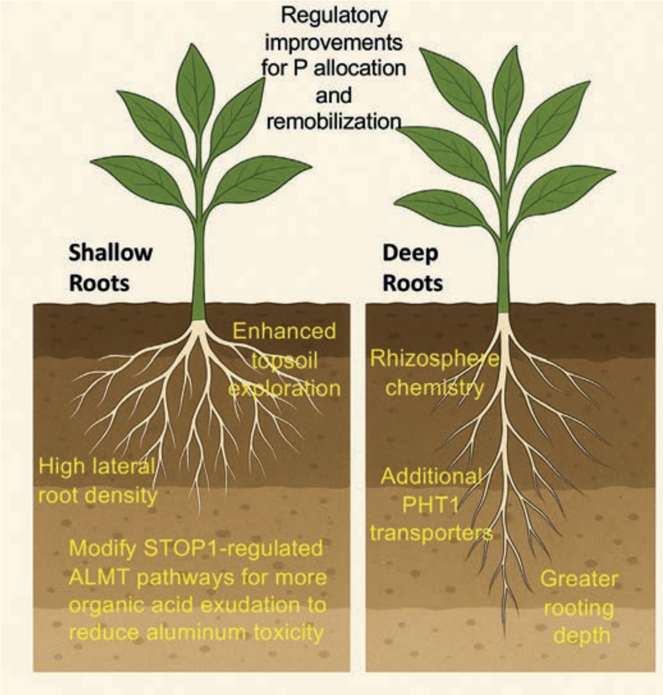

Figure 4. Advances in plant genetics and biotechnology offer promise for improvements in phosphorus acquisition and internal efficiency. These modifications might include changes in the rooting depth and morphology, enhanced expression of high-affinity PHT1 phosphate transporters under low soil P conditions, and stimulation of the STOP1-regulated ALMT pathways to increase organic acid exudation for root protection in acid soils. It might also include changes to improve internal P allocation, metabolism, and remobilization.

A. Root system architecture modifications

Modifying these traits could help crops better access fertilizer P, which is typically concentrated in the upper soil profile.

Plant breeding for:

- denser root systems,
- shallow root angles for better foraging of the P-rich topsoil,
- greater root hair length and density,
- more lateral branching for greater soil exploration.

B. Rhizosphere chemistry and exudation

Plants naturally release a variety of organic acids and P-solubilizing enzymes (such as phosphatase) that improve P solubility. Modifying the rootzone to enhance these abilities may lead to:

- improved solubilization of Al- and Fe-bound P,
- greater P release from organic P pools,
- increased stimulation of P-solubilizing microbes.

C. Improved P transporters and internal efficiency

Biotechnology tools (e.g., CRISPR/Cas editing) may allow modification of:

- PHT1 phosphate transporters for increased uptake at low soil P concentrations,
- genes controlling exudation pathways (STOP1, ALMT family) to protect roots from Al toxicity,
- regulatory systems that improve P use efficiency inside the plant.

Summary

Phosphorus is foundational to crop productivity and food security. Its management is especially critical for African agriculture. Low native soil P, strong fixation, and limited fertilizer use all combine to suppress yields and reduce profitability. Yet with improved soil management, targeted fertilizer inputs, and adoption of the 4R Nutrient Stewardship principles, P use efficiency can be significantly improved.

Getting the greatest agronomic and economic return from P fertilizer is most likely to occur when practices are customized for local soils and conditions. The wide diversity of soil, cropping, and economic capital makes broad generalizations unlikely to succeed, where site-specific management of P is needed. Advice from local experts is necessary for success.

The challenge ahead involves not only managing soil and fertilizer P more wisely but also breeding crop varieties capable of thriving in Africa's unique soil conditions. When agronomy, soil science, and plant genetics work together, farmers can achieve higher yields, reduced environmental risks, and a more resilient food system. ■

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Innovating Locally Adapted Solutions for Sustainable Phosphorus Use in Africa

By Shamie Zingore

Phosphorus deficiency is one of the most pervasive constraints to crop productivity and soil health in African farming systems. *Its use in agriculture remains extremely low, leading to widespread negative nutrient balances, declining soil fertility, and persistently low yields. An Integrated Phosphorus 4R Management Framework that links source, rate, timing and placement considerations to productivity, profitability, and long term sustainability is proposed for increasing P use and enabling efficient and sustainable phosphorus management.*

Continental context: phosphorus deficiency in African soils

Achieving sustainable agricultural intensification in Africa requires addressing chronic soil fertility constraints that limit crop productivity and undermine resilience of farming systems. Among essential macronutrients, phosphorus (P) stands out as a particularly severe and complex constraint. Unlike nitrogen, P cannot be biologically fixed from the atmosphere and must be supplied through fertilizer and rock-P or recycled sources. Average fertilizer P use in Africa remains below 5 kg P/ha, far lower than global averages, and insufficient to offset crop removal. Consequently, cereal yields remain below 30% of attainable levels. Decades of nutrient mining have resulted in widespread soil P depletion across African croplands.

Phosphorus deficiency particularly affects both inherently infertile sandy soils and highly weathered, P fixing soils (Nziguheba et al. 2015). Approximately one quarter of Africa's land area is dominated by soils with high P adsorption capacity, notably Ferralsols, Acrisols, and Nitisols in the tropical highlands in East Africa (**Fig. 1**). In these systems, large proportions of total soil P are rendered unavailable to crops due to strong sorption to iron (Fe) and aluminum (Al) oxides. In contrast, large areas of West and Southern Africa are dominated by old, highly weathered sandy soils with intrinsically low P reserves.

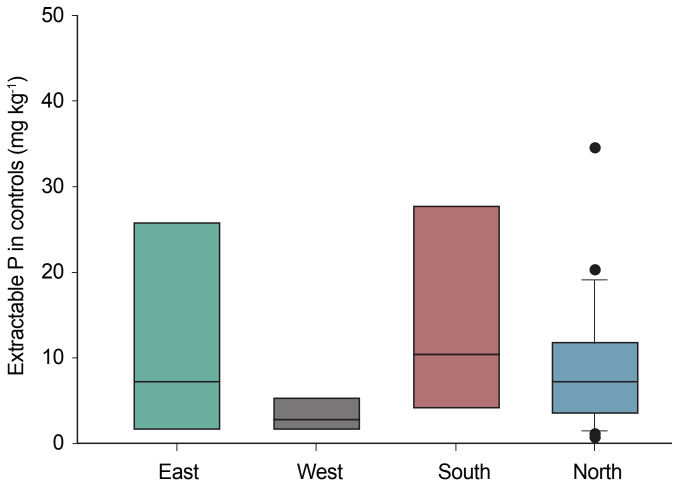

Figure 1. Contents of extractable P (Olsen) in experimental plots representative of major cereal cropping systems in four regions of Africa.

The nature of P deficiency varies regionally:

- East Africa is characterized by high P fixation in acidic soils, despite moderate total P levels.
- West Africa faces severe P scarcity due to low native P stocks in sandy soils, compounded by extremely low fertilizer use.
- Southern Africa exhibits co-limitation by nitrogen and phosphorus, particularly on granitic sandy soils.
- North Africa has significant areas under calcareous soils, where high pH and calcium levels precipitate P into unavailable forms.

These contrasting contexts demand differentiated management strategies rather than generalized P management solutions.

Agronomic responses and phosphorus use efficiency

Across Africa, crop responses to P application are consistently observed but highly heterogeneous in space and time. Meta-analyses of multi-location trials indicate that yield responses are strongest in soils with very low extractable P (Kihara and Njoroge, 2013). In such contexts, even small applications (10–20 kg P/ha) can double or triple yields. However, response variability remains high due to interactions with rainfall, soil types, soil organic matter, and management history. Initial yield gains at low P rates are high, but marginal responses decline rapidly beyond 30–40 kg P/ha under most smallholder conditions. This has profound implications for recommendation development: maximizing agronomic efficiency at low rates is not synonymous with restoring soil fertility or closing yield gaps in the medium to long term.

Agronomic PUE, expressed as kg grain increase per kg P applied, provides a useful indicator of P performance. Empirical evidence from sub-Saharan Africa (SSA) shows PUE values ranging from negative to >100 kg grain per kg P, reflecting strong site-specific effects (Kihara and Njoroge, 2013). Highest PUE values are typically observed in severely P-depleted soils, while PUE approaches zero once soil available P exceeds critical thresholds (15 mg/kg Olsen) (Nziguheba et al. 2015). A critical insight from African datasets is that high PUE frequently coincides with low absolute yields. This underscores the need to distinguish between efficiency-driven and productivity-driven P management strategies.

Phosphorus responses are strongly related to nitrogen availability and overall crop management. Numerous studies demonstrate that omission of N can reduce PUE by 30–50%, even in strongly P-deficient soils (Zingore et al. 2023). Conversely, balanced N and P application substantially increases both yield response and economic returns. Other agronomic factors, including plant population density, planting date, weed control, and varietal choice, further modulate P responses, often explaining more variability than fertilizer rate alone.

The 4R Nutrient Stewardship considerations for phosphorus

The 4R Nutrient Stewardship framework provides an operational lens through which complex phosphorus dynamics can be translated into actionable management practices. In African smallholder systems, the value of the 4Rs lies more in guidelines that support structured decision-making adapted to local availability and management constraints.

Right Source: Source selection must account for soil chemistry, crop demand, availability, affordability, and logistics.

- **Fertilizer:** Soluble mineral P fertilizers remain the most effective means of rapidly alleviating P deficiency. However, their high cost, price volatility, and limited accessibility constrain use by smallholder farmers. Fertilizer formulations and blends must therefore be adapted to local soil and cropping contexts to maximize returns.
- **Rock P:** Africa hosts numerous phosphate rock deposits, though their agronomic effectiveness varies widely. Highly reactive sedimentary phosphate rocks, such as those found in parts of West and East Africa, can be effective when applied under suitable soil conditions, particularly acidic soils. Partial acidulation, compaction with soluble fertilizers, and co-application with organics can substantially enhance their effectiveness.
- **Organic resources:** Organic inputs such as manure, compost, and crop residues generally contain low P concentrations and are available in limited quantities. While insufficient to replenish soil P stocks at large scale, they play a critical role in enhancing P availability through biological and chemical mechanisms, improving soil structure, and supporting long-term fertility.

Right Rate: Determining the right rate requires balancing short-term profitability with long-term soil fertility objectives. Evidence from long-term trials indicates that rates sufficient to generate high yield response and maximize rate of returns (10–20 kg P/ha) are often inadequate to prevent soil P depletion (Nziguheba et al., 2002). Rates above 20 kg P/ha are required to avoid depletion in many systems. This creates a delicate trade-off between short-term yield and economic objectives and long-term sustainability.

Right Time: Timing of P application influences both efficiency and residual value. Seasonal applications at planting are generally most effective for soluble sources and highly reactive PRs. In high P-fixing soils, repeated low-dose applications outperform one-off high rates due to reduced fixation losses. Multi-season strategies that combine initial soil P build-up with maintenance applications are rarely implemented but represent a critical frontier for sustainable management.

Right Place: Placement is among the most powerful levers for improving P efficiency under low-input conditions. Banding or spot placement concentrates P in the root zone, reduces soil–fertilizer contact, and enhances early crop uptake. Empirical data from East and Southern Africa indicate yield gains of 15–30% from improved placement alone at low P rates, making this practice especially relevant for resource-constrained farmers.

Short-term response based recommendations often fail to capture the cumulative effects of P depletion and replenishment. Strategic P management recognizes the dual objective of meeting immediate crop demand while gradually rebuilding soil P capital. Regular soil P monitoring is essential, as soil P depletion occurs more rapidly and is less resilient than nitrogen or potassium. Failure to apply P even for a few seasons can rapidly induce severe deficiency, even in soils with historically high P status.

Leveraging cropping systems and legumes

Legumes exhibit a disproportionately strong response to phosphorus due to the central role of P in nodulation and biological nitrogen fixation (Nziguheba et al. 2015). Across SSA, P application to grain legumes commonly results in more than doubling yields, alongside improvements in grain quality and nutritional value. The proportion of responses often exceed those observed in cereals at comparable rates. Beyond direct yield effects, P application to legumes generates substantial residual benefits for subsequent cereal crops. Residual P, combined with enhanced soil nitrogen supply, can significantly increases cereal yields without additional fertilizer input. This amplifying effect positions legumes as strategic entry points for P investment in cereal-based systems.

The slow progress in increasing P use in Africa reflects not only biophysical constraints but also structural socio-economic and policy barriers. High fertilizer prices, weak input distribution systems, limited access to credit, and inadequate advisory services constrain farmer adoption. Gender disparities further influence access to inputs and information.

Policy reforms that support fertilizer affordability, local blending, soil testing services, and integrated advisory platforms are critical for scaling efficient P management practices.

Toward an Integrated Phosphorus 4R Management Framework

The Integrated Phosphorus 4R Management Framework provides a unifying conceptual structure that links soil processes, crop demand, farmer decision-making, and enabling environments into a coherent system for sustainable phosphorus management in Africa (**Fig. 2**).

The framework is anchored in soil P capital, defined by total soil P stocks and their partitioning between labile and stable pools. African soils are characterized by either low total P reserves or strong P fixation, resulting in limited plant-available P despite large total stocks in some cases. Key soil constraints, including P fixation in acidic and highly weathered soils, Ca–P precipitation in calcareous soils, and low buffering capacity in sandy soils, that govern P availability must be considered in designing P investment and management solutions.

At the core of the framework sits the 4R decision space—Right Source, Right Rate, Right Time, and Right Place—depicted as an adaptive management interface rather than a static prescription. Each R interacts dynamically with soil constraints and crop demand:

- **Right Source** decisions are conditioned by soil chemistry (acidic vs calcareous), availability of applied and recycled P from fertilizer, phosphate rock, and organic inputs, as well as labor and mechanization constraints.
- **Right Rate** balances profitability, risk, and sustainability, explicitly distinguishing between response-driven rates and recapitalization rates required to rebuild soil P stocks. Regular soil P assessment is essential to monitor changes and timely adjustment of rates. Rates must be adjusted to crop-specific and system-level P demand. Strategic inclusion of grain legumes, rotations, and residue management pathways enhances both direct P uptake and residual benefits.

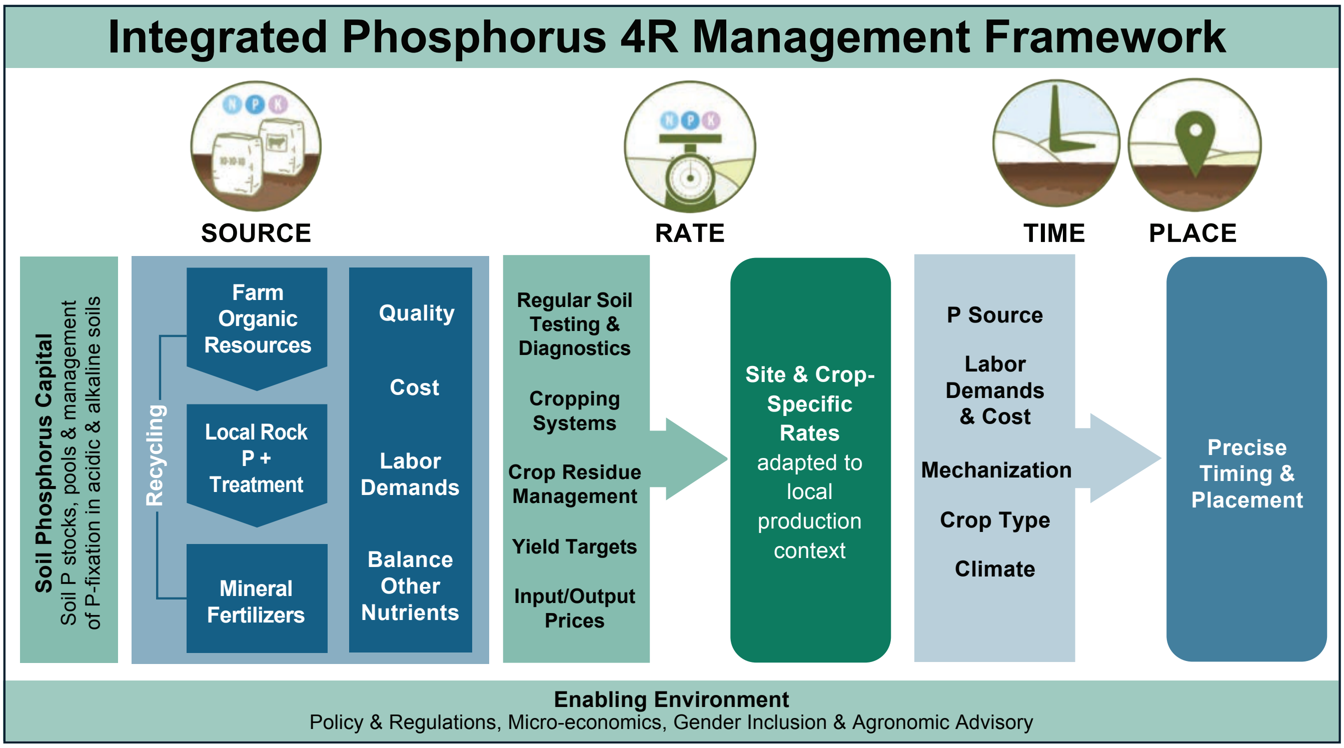

Figure 2. Integrated Phosphorus 4R Management Framework.

- **Right Time** reflects both intra-seasonal timing (e.g., placement at planting) and inter-seasonal strategies that account for residual P effects and fixation dynamics.
- **Right Place** captures the strong influence of placement on P use efficiency under low-input conditions, particularly through banding and spot application. Both time and place are influenced by P sources and rates, as well as labour demands and cost, type of implements or machinery uses, crop type and climatic conditions.

Surrounding the biophysical and management core is the enabling environment, which shapes feasibility and adoption. This includes fertilizer and input markets, pricing and subsidy policies, access to credit, soil testing and diagnostic services, extension and digital advisory platforms, and gender-differentiated access to resources. The framework explicitly situates farmer decision-making within this broader context, acknowledging that optimal 4R solutions are constrained by affordability, risk perception, input and output markets and institutional support.

Conclusions and research priorities

Phosphorus deficiency remains a central constraint to achieving food security and sustainable intensification in Africa. Addressing this challenge requires a shift from blanket recommendations to locally adapted, strategic, and system oriented P management. Integrating 4R principles to optimize short-term agronomic and economic goals with long-term soil P capitalization, cropping system design, and enabling policies is essential for effectively addressing the soil P Challenge in Africa. ■

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EXCEL AFRICA

EXCELLENCE IN AFRICAN CROP NUTRITION RESEARCH & OUTREACH

EXCEL Africa initiative seeks to identify, support, and celebrate outstanding achievements in crop nutrition research and outreach, acknowledging the pivotal role they play in enhancing food security and sustainable agricultural practices.

By spotlighting excellence in this domain, APNI aims to inspire a culture of innovation and collaboration among researchers, agronomists, and other stakeholders to catalyze change and promote effective strategies to address the unique challenges faced by African farmers.

KEY DATES ON OUR 2026 CALENDAR

MARCH

AFRICAN PLANT NUTRITION SCHOLAR AWARD

This award encourages development and success within graduate student programs specializing in the sciences of plant nutrition and management of crop nutrients in Africa. Students in the disciplines of soil science, agronomy, and horticultural science, or tree crop science with a focus on plant nutrition are encouraged to apply.

Funding: Awards of USD $2,000 are available to ten graduate students enrolled in African University.

Eligibility: Candidates must be currently enrolled in a Ph.D. program, or in the second year of a M.Sc., M.Phil. program at the closing date for applications.

Call for applications: March 2026

Application deadline: April 30, 2026

Learn more at: www.apni.net/scholar-apply

MAY

AFRICAN PHOSPHORUS FELLOWSHIP AWARD

This fellowship award supports research programs focused on improving our understanding of phosphorus management in Africa's field or tree crop agro-ecosystems.

Funding: Awards of USD $5,000 are available to five scientists.

Eligibility: Applicants must be full time scientists working at an African NARES (National Agricultural Research and Extension System) institution or university. Applications from scientists in Post Doctorate positions are also eligible for this award. Only applicants who have completed their Ph.D. program will be considered.

Call for applications: May 2026

Application deadline: June 30, 2026

Learn more at: www.apni.net/p-fellowship-apply

JULY

AFRICAN PLANT NUTRITION OUTREACH FELLOWSHIP AWARD

This fellowship award supports education, training and communication programs relevant to improving the use and efficiency of plant nutrients in African agro-ecosystems.

Funding: Awards of USD $5,000 are available to two innovative scientists, extension specialists, or educators in Africa.

Eligibility: Applicants must be full time scientists, extension specialists or educators working at an African NARES (National Agricultural Research and Extension System) institution, university, non-profit organization, or in the private sector to be eligible. Students are not eligible for this award.

Call for applications: July 2026

Application deadline: Sept 30, 2026

Learn more at: www.apni.net/outreach-fellowship-apply

For any additional information about our Awards and Grants Program see www.apni.net/ExcelAfrica

2025 Award and Fellowship Recipients

African Plant Nutrition Scholarships

In 2025, ten students enrolled in advanced science programs were selected for the African Plant Nutrition Scholar Award. Each student received $2,000. This post graduate award strives to encourage the brightest minds focused on the continued advancement crop nutrition and soil health in Africa. Since its establishment in 2020, this intiative has distributed $120,000 to 60 graduate students across the continent. This year's recipients are:

BENIN

Mr. Awouminassi Marcellin ATAKOUN (Doctorate Program)
Kwame Nkrumah University of Science and Technology (KNUST)

AREA OF STUDY: Cattle corralling for improved soil fertility, maize production and for climate change resilience in the Sudano-Savanna area

Mr. ATAKOUN's is examining cattle corralling for improved soil fertility, maize production and for climate change resilience in the Sudano-Savanna area of Benin, West Africa. Cattle corralling is a traditional soil management practice that can contribute to long-term soil carbon sequestration and nutrient enrichment. The study evaluates soil physical and chemical properties and examines maize productivity under current and projected climate conditions using crop simulation models. The objective is to provide a scientific basis for integrating traditional crop-livestock practices into sustainable land use strategies that enhance soil health and resilience to climate variability. The expected impact is to inform climate-smart agricultural policies and promote low-emission farming systems in sub-Saharan Africa.

Awouminassi's future career goal is to become a leading researcher and policy advisor in climate-smart agriculture and sustainable land management across Africa. He aspires to work with international research institutes and regional stakeholders to design, implement, and scale up land use interventions that address both environmental sustainability and food security. He also plans to contribute to academic capacity-building through teaching and mentorship in African universities, while actively engaging in science-policy dialogues to ensure that research outcomes are translated into impactful development actions.

CÔTE D'IVOIRE

Ms. Logbochi Marie Elisabeth ASSOH
(Doctorate Program)
Félix Houphouët-Boigny University

AREA OF STUDY: Optimizing cassava yield and improving its nutritional quality through rational fertilization methods in the forest and pre-forest agroecological zones

Ms. ASSOH is researching the optimization of cassava yield and improving its nutritional quality through rational fertilization methods in the forest and pre-forest agroecological zones of Côte d'Ivoire. Her work aims to define fertilization strategies that can simultaneously enhance agro-nutritional performance, economic profitability, and environmental sustainability of cassava cultivation, based on soil characteristics in the targeted agroecological zones. This research is carried out at the National Center for Agronomic Research (CNRA) in Bouaké, Côte d'Ivoire, and focuses on seven localities selected for their importance in cassava production and their specific agroecological profiles. The main beneficiaries of this research are cassava farmers, who will receive practical recommendations to increase yield and profitability. Researchers and agricultural institutions will also benefit from new scientific insights to refine cassava fertilization strategies. Moreover, companies involved in fertilizer production and distribution may use these findings to develop more suitable formulas aligned with local needs.

She aspires to pursue a career in tropical agronomic research, focusing on the development of sustainable fertilization strategies that contribute to enhancing the nutritional value of staple crops in Africa. Her goal is to contribute meaningfully to the improvement of agricultural systems and food security for vulnerable populations.

ETHIOPIA

Mr. Gebremedhin Chameno CHALITE (Doctorate Program)
Hawassa University

AREA OF STUDY: Unlocking socioecological benefits and indigenous management of agroforestry systems in the Gofa zone of northern Ethiopia

Mr. CHALITE is seeking a better understanding of the influence of indigenous management on plant functional diversity and soil health, including tree-crop interactions. This research has significant expected impact and relevance at local, national, and potentially international levels. It will validate and give recognition to local farmers' knowledge; provide scientific backing for traditional practices and identify areas for improvement; promote practices that combat land degradation, improve soil fertility; fill critical knowledge gaps regarding the socioecological functions of indigenous agroforestry in specific Ethiopian contexts.

Gebremedhin's immediate plan is to contribute to academic discourse and pursue postdoctoral research. His future career plan focuses on sustainable land management, agroforestry and community-based natural resource management in developing countries like Ethiopia, contributing to sustainable development and environmental conservation.

ETHIOPIA *(cont'd)*

Mr. Gemechu Berhanu GERMESSA (Doctorate Program)
Haramaya University

AREA OF STUDY: Productivity of maize and selected soil physical and chemical properties as influenced by application of mineral fertilizers and organic sources under changing climate in west Oromia

Mr. GERMESSA is focused on the evaluation of the effect of integrated climate smart agricultural soil amendment approaches on soil properties, yield, and nutrient use efficiency of maize under changing climate in western Ethiopia. He is assessing how better understanding of farmer practices and spatial variability of key soil properties can help estimate the optimum rate of organic and inorganic fertilizer sources and lime to restore soil health and boost maize yield under changing climate in acidic soils. His research will also use DSSAT crop modeling to simulate maize performance under current and future climate scenarios. Field experimental data collected at three locations for two consecutive seasons will be used for model calibration and validation. This study provides practical information on improving soil health and boost maize yield, possibly improving the incomes of Ethiopian farmers. Moreover, this resilience-oriented strategy has the potential to strengthen Africa's capacity to adapt, enhance food security, and align with sustainable development priorities.

Germessa looks forward to completing his doctorate degree and pursuing a career in higher education, focusing on teaching, research, and community service in my field to make a meaningful contribution.

KENYA

Ms. Chebet ARUSEY (Doctorate Program)
University of Eldoret

AREA OF STUDY: Fate of antibiotic residues and antibiotic-resistant bacteria in livestock manure and their effects on greenhouse gas emissions and nutrient cycling

Ms. ARUSEY is focused on the environmental fate of three commonly used veterinary antibiotics—Oxytetracycline, Enrofloxacin and Tylosin—in livestock manure, and how they affect greenhouse gas (GHG) emissions, microbial communities, and nutrient cycling. The study is structured around three key objectives: to evaluate how these antibiotic residues influence emissions of methane, nitrous oxide, carbon dioxide, and ammonia, as well as their impact on the nutrient quality of manure as a fertilizer; to determine the degradation patterns of these antibiotics and assess their effects on bacterial community structure and functional genes involved in nitrogen and carbon transformations; to examine how antibiotic residues affect soil nutrient dynamics, particularly nitrogen and phosphorus cycling, when manure is applied to soils. The research involves controlled incubations, microcosm studies, and field-scale experiments for sustainable manure management. It integrates GHG measurements, shotgun sequencing, manure and soil analysis, and LC-MS/MS residue detection to examine how antibiotics influence microbial activity and nutrient dynamics. The outcomes inform policy on safe manure use, support nutrient circularity, reduce GHG emissions, and improve the sustainability of integrated crop-livestock farming systems.

Chebet aspires to advance sustainable soil fertility and climate-smart agriculture through research on nutrient cycling, manure management, and microbial interactions. Her goals include improving fertilizer efficiency, influencing policy, mentoring young scientists, and promoting practices that enhance soil health, reduce emissions and antimicrobial resistance, and support resilient, sustainable food production systems.

MOROCCO

Mr. Mbarek EL-GUIRAH (Doctorate Program)
African Sustainable Agriculture Research Institute (ASARI) – Mohammed VI Polytechnic University (UM6P)

AREA OF STUDY: Adaptation of alternative forage crops to salinity and drought stresses in desert conditions of southern Morocco

Mr. EL-GUIRAH is evaluating how alternative forage crops respond to saline and drought conditions prevalent in marginal lands of the Moroccan desert regions, with a special emphasis on identifying crops and practices that can sustainably improve soil fertility while enhancing crop productivity. By exploring tolerant crops, best agricultural management practices, the research is expected to significantly sustain farmer's productivity and profitability, thus supporting sustainable agriculture in Morocco's desertic areas. The research findings could potentially offer viable solutions for managing limited water resources and saline soils, thereby increasing agricultural resilience to challenging conditions.

His career goal is to become an agricultural researcher and consultant specializing in climate-smart agriculture practices. Mbarek aims to contribute to developing practical solutions and advising farming communities on improving crop productivity, enhancing soil health, and adapting agricultural practices to increasingly challenging environmental conditions. Through collaborative research, outreach, and implementation of innovative agricultural techniques, he is willing to make tangible contributions to improving livelihoods and environmental sustainability in regions affected by climate change.

SOUTH AFRICA

Mr. Conrad Wabwire ADDIKAH (Doctorate Program)
University of Pretoria

AREA OF STUDY: Exploring the current and future potential of cassava cultivation

Mr. ADDIKAH is exploring the current and future potential of cassava cultivation in South Africa. Conrad aims to assess the viability of cassava as a resilient crop in the face of climate change. His research will map and synthesise literature on cassava production and utilisation trends, challenges, and opportunities in Southern Africa. Through field trials, Conrad will evaluate the adaptability and performance of various cassava genotypes by analysing genotype and genotype-by-environment interactions. He will also apply the EcoCrop model using CMIP5 and CMIP6 climate projections to assess cassava's current and future suitability across South Africa. Additionally, water use efficiency trials will be conducted on select drought-tolerant, high-yielding genotypes. Two crop models, APSIM-Cassava and DSSAT-CSM MANIHOT, will be calibrated and validated with field data to simulate cassava growth and predict yields under climate scenarios. These tools will also guide the development of climate-smart adaptation strategies. Expected outcomes include identifying stable, high-performing genotypes; developing cassava suitability maps; improving understanding of cassava's water use, and delivering robust, locally adapted crop models. The research will generate practical insights for farmers, policymakers, and breeders to integrate cassava production into South Africa's food systems sustainably.

Upon completing his Ph.D., Conrad plans to pursue a research and teaching career in agronomy, with a focus on climate resilience. He aims to share his expertise through university teaching and targeted training for research institutions, while contributing to global scientific knowledge through impactful publications.

UGANDA

Mr. Donald KAYUZA (Master's Program)
Makerere University

AREA OF STUDY: Effects of lime, biochar, and cattle manure on soil physicochemical properties, yield, and nutrient use efficiencies of lowland rice

Mr. KAYUZA is researching rain-fed lowland rice systems practiced by smallholder farmers in Africa. These rice production systems have a high yield potential, but the actual rice yield is currently low. This is mainly due to declining soil fertility, iron toxicity, and inefficient nutrient utilization. Additionally, alternating wet and dry conditions often shift soil pH and restrict nutrient availability for rice plants. The objective of this study is to increase rice productivity under rain-fed conditions by applying lime and biochar. Specifically, this study evaluates the effects of these treatments on rice yield, nutrient use efficiency, iron uptake, and changes in soil physicochemical properties. The study is conducted in two agroecological zones in Uganda, where cattle manure is used as a locally available nutrient source for integrated soil fertility management. The scope of this study includes both soil and plant responses under rain-fed conditions. The focus is on improving nutrient availability, uptake, and use efficiency in the production of rice. This study is expected to develop cost-effective soil fertility strategies that enhance soil health, support sustainable rice production, and reduce nutrient losses to the environment. These improvements contribute to long-term food security and more resilient farming systems in the region.

Donald aims to become a researcher in the field of soil fertility and sustainable agriculture. He is committed to supporting smallholder farmers through science-based innovations that improve crop productivity and soil management in Sub-Saharan Africa.

GHANA

Mr. Emmanuel BAIDOO (Doctorate Program)
Kwame Nkrumah University of Science and Technology

AREA OF STUDY: Soil carbon sequestration, nutrient characteristics, and greenhouse gas emissions in african dark earths

Mr. BAIDOO is building a resilient agroecosystem in Ghana by improving soil fertility and yield. The objectives driving this research will focus on: 1) quantifying soil nutrient characteristics and grain yield of the African Dark Earth (AfDE) and non-Dark Earths cultivated lands in Ghana; and 2) estimating the carbon footprint of the AfDEs via measurements of greenhouse gas under different fertilizer regimes and establish how they contribute to climate change mitigation. This will be studied across nine different agroecosystems in Ghana. This research will help contribute to knowledge on indigenous innovations of the AfDE as a scientific tool for building climate-smart and resilient agro-ecosystems in Ghana and sub-Saharan Africa. Climatic, socioeconomic, and soil factors impacting carbon footprint and crop yield in AfDE will be established as a pathway to an alternative nature-based solution to food security problems in SSA and Africa. More so, a pathway will be developed towards integrating such indigenous efforts with mineral plant nutrition.

Emmanuel aspires to contribute to building food security, climate resilience, and environmental sustainability across Africa and at the global level as researcher and scientist. He is interested in training earlier career scientists and students in data processing, data analysis, interpretation and bridging the wide gap between the researcher and farmers in Ghana and Africa through seminars and conferences. In the short-term, he wants to develop a useful scientific tool and model for reducing GHG emissions in agricultural land uses with regards to fertilizer application in Ghana.

GHANA

Ms. Nancy Korkor TETTEH (Master's Program)
University of Ghana

AREA OF STUDY: Carbon fractions in soils of agroforestry and monoculture cocoa cropping systems in the semi-deciduous and moist evergreen zones of Ghana

Ms. TETTEH is focused on quantifying and characterizing soil organic carbon fractions to: 1) determine the changes in labile and non-labile carbon fractions of soils (Acrisols) in the Western-north region of Ghana, resulting from differences in cocoa cropping system (agroforestry and monoculture) and agroecological zones (Semi-Deciduous and Moist Evergreen zones), and; 2) compare dissolved organic carbon, soil microbial biomass carbon, particulate organic carbon, and the potassium oxidizable carbon methods of quantifying soil labile carbon pools. This study is expected to contribute significantly to sustainable land management by informing practices that enhance carbon sequestration and soil fertility in tropical agricultural systems.

Looking ahead, Nancy is interested in becoming a leading soil scientist and researcher dedicated to sustainable agriculture, soil carbon management, and climate-smart practices in Sub-Saharan Africa. She intends to pursue a Ph.D. and contribute to evidence-based policy formulation, farmer education, and capacity building. Through research, outreach and collaboration, Nancy aspires to help bridge the gap between science and practice, ensuring improved soil health, food security, and resilience of agricultural systems to climate change.

This scholarship is supported through APNI's continued and valued partnership with Mohammed VI Polytechnic University (UM6P) and OCP Group (OCP S.A.). This initiative strives to encourage the brightest minds to focus on the critical target of continued advancement of the science of crop nutrition across Africa. Applications undergo a rigorous process via the selection committee who consider the full spectrum of academic and personal achievements for each potential recipient.

African Phosphorus Fellowship

This initiative strives to encourage scientific programs directed towards improving our understanding of more efficient and effective phosphorus (P) management in African agro ecosystems. In 2025, five researchers each received awards of $5,000.

NIGERIA

Dr. Adebayo OLOWOAKE (Professor)
Kwara State University

PROJECT: Growth dynamics of cowpea cultivars as influenced by source, rate, and time of phosphorus fertilizer application

Dr. Olowoake's study is expected to determine preferred phosphorus (P) fertilizer sources for optimal growth performance of cowpea cultivars. It will reveal how different sources affect root development, shoot biomass, and nodulation. Results will clarify how early, split, or late application of P influence early establishment, flowering, and pod formation in cowpea. Different cowpea cultivars may respond differently to the source, rate, and timing of P and the study is expected to reveal interactions between cultivar and fertilizer variables.

Dr. Rejoice Ibrahim SOLOMON (Senior Lecturer)
Modibbo Adama University of Technology

PROJECT: Assessment of biomass and phosphorus synergies for maize production and soil carbon enhancement

Dr. Solomon aims to determine how biomass amendments affect soil phosphorus (P) availability, and what benefits come from combining different types of biomasses with P fertilizers including maize growth, yield, soil carbon content, and whether biomass-based amendments can improve the resilience of maize production systems. The work will help our understanding of the long-term effects of biomass + P combinations on soil health, including microbial abundance and organic matter content. Rejoice is also interested in the socio-economic factors currently influencing maize farmers adoption of biomass-based soil amendments.

GHANA

Dr. Ransford Opoku DARKO (Associate Professor)
University of Cape Coast

PROJECT : Optimizing Phosphorus Use Efficiency Through Irrigation Scheduling in High P-Fixing Soils Under Maize-Based Cropping Systems

Dr. Darko is studying optimal phosphorus (P) use efficiency through improved irrigation scheduling in high P-fixing soils under maize-based cropping systems. The study will assess the effects of different irrigation schedules on soil moisture and P availability and evaluate the impact of irrigation timing and frequency on maize growth, yield, and P uptake.

CAMEROON

Dr. Marie Noela Enyoe OLOUGOU (Post-doctoral Fellow)
University of Buea

PROJECT: Harnessing the potential of indigenous phosphate-solubilizing microorganisms for sustainable phosphorus management in Cameroon

Dr. Oloougou's research is aimed at improving phosphorus (P) availability and soybean grain yield. She will be determining the distribution and bioavailability of different P fractions in soils under soybean cultivation, focusing on their dynamics and implications for precision P fertilization. She plans to isolate, identify, and characterize indigenous phosphate-solubilizing microorganisms (PSMs) adapted to local soil conditions and evaluate their potential role in improving P availability in high P-fixing soils. She is interested in evaluating the synergistic effects of native PSMs combined with organic and inorganic P sources on P mobilization, soil fertility and health, soybean nodulation, and yield.

ETHIOPIA

Dr. Ashenafi Woldeselassie TESHALE (Assistant Professor)
Wolaita Sodo University

PROJECT: Effect of nutrient-enriched biochar and irrigation levels on potato yield, phosphorus use efficiency and soil health in Wolaita Sodo, Ethiopia

Dr. Teshale's research aims to evaluate the combined effects of nutrient-enriched biochar and varying irrigation levels on potato productivity, phosphorus (P) use efficiency, and soil health in Wolaita Sodo, Ethiopia, where acidic soils and water scarcity limit crop yields. By addressing P-fixation and moisture stress through biochar application and regulated irrigation, the research seeks to enhance P availability for improved potato growth. The ultimate goal is to develop sustainable, cost-effective practices for smallholder farmers, offering practical solutions for improving P use efficiency and enhance the resilience of smallholder farmers under the changing climate.

African Plant Nutrition Outreach Fellowhip

This award acknowledges innovation in education, training and communication programs relevant to improving the use and efficiency of plant nutrients in African agro ecosystems. In 2025, two scientists each received awards of $5,000.

ETHIOPIA

Dr. Birhanu AGUMAS (Senior Researcher in System Agronomy)
Amhara Agricultural Research Institute

PROJECT: Enhancing nutrient use efficiency and crop yield through data driven decision support tools (DST) outreach, research, and capacity building

Dr. Agumas is working towards strengthened outreach and capacity building for extension agents and district-level agricultural extensionists and promote the dissemination and adoption of 4R-based solutions to address soil fertility decline and enhance agricultural productivity in Ethiopia. He will validate and pilot site-specific fertilizer management tools through the application of data-driven decision support tools (DSTs) tailored to one of the major maize-growing districts. He is aiming at enhanced technical capacity and knowledge amongst key stakeholders—including farmers, extension personnel, and researchers—regarding the effective use of DSTs in the district's agricultural extension.

ZIMBABWE

Dr. Blessing MAGONZIWA (Lecturer)
University of Zimbabwe

PROJECT: Community-based capacity building in soil nutrient analysis and management: A 3-pronged approach

Dr. Magonziwa is seeking to train extension officers on the use of in-field Soil Tool Kit methods for soil analysis and give recommendations for improved soil health management. She will use infield Soil Tool Kit Methods and a Mobile Lab and train farmers on the implications of the results based on their current practices. She wishes to increase engagement with farmers through face-to-face community dialogues on soil health and nutrient management. She also plans to create a virtual WhatsApp platform for the training and engagement of farmers, researchers, and extensionists on improved soil health and nutrient management practices.

Learn more about opportunities available from APNI's EXCEL Africa Initiative at:
https://apni.net/ExcelAfrica

Zinc Fertilization Strategies for Enhanced Rice Production in Tanzania

By Damiano Kwaslema, Tindwa Hamisi, Deodatus Kiriba, James Mutegi, Esther Mugi-Ngenga, and Nyambilila A. Amuri

The study evaluates zinc fertilization strategies to improve rice yield in Tanzania's Kilombero district. Field trials compared Zn sources, rates, and application methods under rain-fed and irrigated conditions. *Soil-applied $ZnSO_4$ and foliar $ZnSO_4$ within a NPKS fertilizer blend were most optimal in terms of yield and in addressing the issues of widespread Zn deficiency and food security.*

A participatory approach enabled researchers and farmers to work together and collect data and observe rice performance under different zinc and microbial fertilizer rates and regimes in Kisawasawa village, Kilombero District, Tanzania.

Rice is one of the most important staple crops in Tanzania, a significant contributor to both food security and livelihood, with about equal amounts of its production destined either for household use or to be marketed for income (TZA-NBS-AASS, 2023). However, achieving optimal rice yields and nutritional quality is a challenge due to prevailing soil nutrient deficiencies. Low productivity measured against an increasing demand are also the main drivers for encroachment of rice farming into protected areas in the Kilombero valley of Tanzania.

The most widely studied and deficient nutrients for rice production are nitrogen (N) and phosphorus (P), which represent two of the three primary nutrients found in most fertilizers. Limited emphasis on supplementation of other required nutrients has resulted to low use efficiency for applied fertilizers and depletion of micronutrients in most soils (Senthilkumar et al., 2021).

Zinc (Zn) deficiency in soils is a widespread problem affecting rice production in the Kilombero valley. Introduction of Zn in fertilizer blends is one of the efforts used to correct this deficiency. However, farmers' have limited access to Zn-enriched fertilizers and knowledge on their proper application. Most of the available fertilizer formulation contain 0.007-4.6 % Zn (AGRA-IFDC-AFAP, 2018), supplying 0.03-9.5 kg Zn/ha based on recommendation of 100 kg N/kg and 40 kg P/ha, and fertilizer grade. It is uncertain as to which fertilizer formulation will supply optimum Zn for a particular location based on soil fertility status, to guide their distribution. Furthermore, studies have highlighted the need for identifying the optimal source, application rate, method, and frequency of Zn application to maximize its effectiveness in improving rice yields (Khampuang et al., 2021). Different Zn sources, such as zinc sulfate ($ZnSO_4$) and zinc oxide (ZnO), and application methods

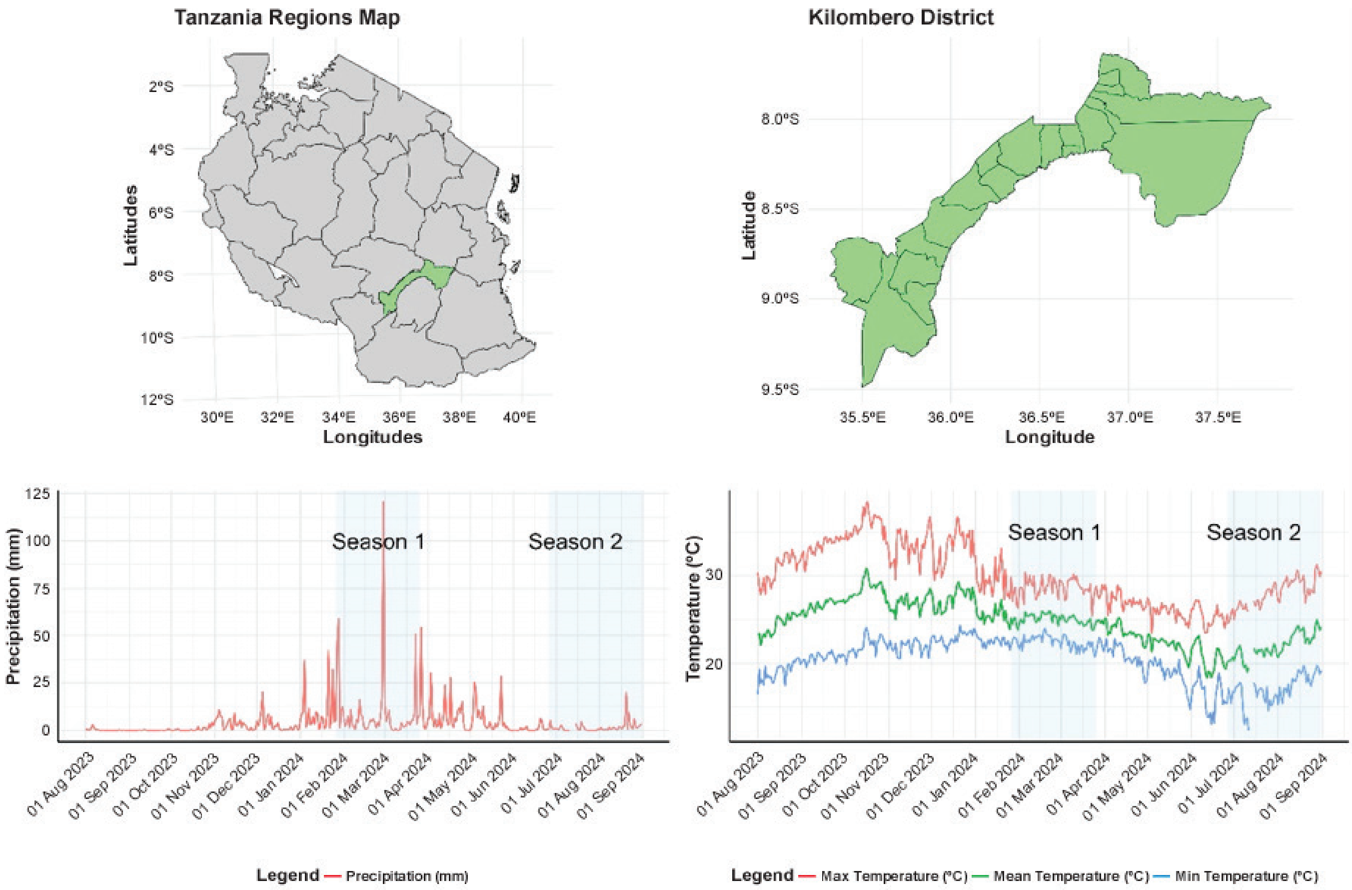

Figure 1. Study area location and weather conditions [daily maximum, minimum, and mean temperatures (°C) and precipitation (mm)] in Kilombero from August 1, 2023, to August 31, 2024. Data were obtained from NASA POWER (Sparks, A. 2024). Shaded regions indicate the two experimental seasons: Season 1 (January 26, 2024, to March 26, 2024) and Season 2 (June 26, 2024, to August 31, 2024).

such as soil or foliar application or root dipping vary in their bioavailability. This can influence Zn uptake and subsequent rice growth, yield and potential to fight hidden hunger. Therefore, addressing Zn deficiency through optimized fertilization strategies is essential for enhancing both the rice yield and yield quality.

The study outlined below sought optimal Zn fertilization strategies for rice grown under irrigated and rain-fed conditions in the Kilombero district. By evaluating different Zn sources, application rates, methods, and frequencies, this research aims to identify practices that can enhance rice production, thereby contributing to improved food security and economic outcomes of farmers. Evidence-based recommendations will allow farmers to optimize Zn use in rice production, ultimately improving yield outcomes and supporting sustainable agricultural development.

Study area description

The field experiments were conducted in the Kisawasawa rain-fed scheme, and the Mkula irrigation scheme (**Fig. 1**). These two represent some of the most prominent rice growing areas in Kilombero district, making it one of the three districts contributing to Morogoro's leading contribution to rice production in Tanzania, with 22% of land under rice production and 17% of rice production in Tanzania (TZA-NBS-AASS, 2023). The Kilombero district falls within a tropical savanna climate. The area has two distinct rainy seasons: a short season from October to December and a longer season from March to May, interspersed with dry spells, with the mean annual rainfall of between 1200-1400 mm. The average temperature ranges from 22-23°C.

Climate condition during study period

Significant climate variability was observed during the two experimental seasons in Kilombero (**Fig. 1**). In season 1 (January 2024-March 2024), temperatures and rainfall were generally favorable for rice growth, with mean temperatures around 25°C. Both the frequency and intensity of rainfall were

Table 1. Description of experimental treatments.

Treatment	Zinc source + Basal fertilizers	Application rate	Zn application method and frequency
T1	Absolute control	-	-
T2	NPKS	-	-
T3	$ZnSO_4$ + NPKS	1 kg Zn/ha	Soil incorporation during transplanting
T4	$ZnSO_4$ + NPKS	2 kg Zn/ha	Soil incorporation during transplanting
T5	$ZnSO_4$ + NPKS	4 kg Zn/ha	Soil incorporation during transplanting
T6	$ZnSO_4$ + NPKS	0.6 kg Zn/ha	Foliar (3 weeks after transplanting)
T7	$ZnSO_4$ + NPKS	0.8 kg Zn/ha	Foliar (3 and 5 weeks after transplanting)
T8	$ZnSO_4$ + NPKS	1 kg Zn/ha	Foliar (2, 3 and 5 weeks after transplanting)
T9	ZnO + NPKS	1% ZnO	Root dipping
T10	ZnO + NPKS	3% ZnO	Root dipping

high, reaching up to 125 mm/day. In contrast, season 2 (June 2024-September 2024) experienced relatively lower temperatures and rainfall during early stages of crop growth, with average minima of less than 15°C, and average maxima of < 35°C.

Farmer field experimental layout

The field experiments were conducted in the farmers' fields where treatments (**Table 1**) were set up by researchers. Participating farmer groups jointly managed the fields and collected data with researchers to facilitate co-learning. Prior to rice planting, soil samples were collected to analyze specific physicochemical properties. Soil samples were collected at 0-20 cm depth and analyzed using standard wet chemistry procedures at the Soil Science Laboratory of the Sokoine University of Agriculture. The rice variety TXD 306 (SARO 5) was used as a test crop. The experiments were laid out in a randomized complete block design with ten treatments and three replications. The fertilizers used were urea (46-0-0), Minjingu NPKS fertilizer and Zn as $ZnSO_4 \cdot H_2O$ and ZnO. The top dress N fertilizer was applied four weeks after planting.

Measurement of plant growth parameters and yield components

As a proxy of evaluating effectiveness of Zn fertilization strategies, we measured plant height, tiller number, grain yields, yield components, and biomass for each plot at maturity as described in Gomez, (2006). Tiller number was counted per plant in single-plant hills, with productive and unproductive tillers separated at harvest. Grain yield was calculated by harvesting grains from selected hills, excluding plots with more than 20% hill reduction due to damage and adjusted to 14% moisture content. The 100-grain weight was measured by counting and weighing 1,000 fully developed grains. Yield components such as panicle number, number of filled grains per panicle, and grain weight were also assessed using standardized sampling and measurement procedures. Low and high farm gate prices were collected for seasons 2022/2023 and 2023/2024 through farmer interviews to calculate gross revenue from rice to determine the financial implications of each treatment. Averaged over both seasons prices ranged between Tsh 800-1,166.67 per kg at Kisawasawa and Tsh 1,066-1,233 per kg at Mkula.

Status of rice growing farms of Mkula and Kisawasawa irrigation schemes

Soil laboratory analysis (**Table 2**) indicate pH ranged from 4.9-5.8 at Mkula, categorizing the soils as moderately acidic. The texture varied from sandy loam in Zone 1 to sandy clay loam in Zones 2, 3 and 4. Zinc concentrations in Mkula ranged from 0.5-1.2 mg/kg, with Zone 2 showing a critically low Zn concentration of 0.5 mg/kg, below the critical threshold of 0.6 mg/kg for rice (Fairhurst et al., 2007). Although Zones 1, 3 and 4 had slightly

Table 2. Soil analysis results on micronutrient status of rice growing farms of Mkula and Kisawasawa irrigation schemes, Kilombero, Tanzania.

Field reference	pH (1:2.5) H_2O	EC, µS/m	Texture	Cu	Zn	Fe	Mn
				mg/kg			
Zone 1 Mkula	5.7	66.4	sandy loam	3.5	1.2	304.4	24.1
Zone 2 Mkula	5.8	100.2	sandy clay loam	3.0	0.5	251.1	2.4
Zone 3 Mkula	4.9	73.8	sandy clay loam	3.3	1.1	317.0	4.4
Zone 4 Mkula	5.4	63.8	sandy clay loam	4.3	0.9	297.9	12.1
Zone 1 Kisawasawa	5.0	123.6	clay loam	3.9	2.1	210.5	29.0
Zone 2 Kisawasawa	5.4	212	sandy clay loam	4.2	1.0	231.9	12.6
Zone 3 Kisawasawa	4.9	69.3	sandy clay loam	2.4	0.7	209.8	21.8
Zone 4 Kisawasawa	4.5	108.8	clay	3.0	1.3	182.3	29.4
Kiberege	5.1	159.3	sandy clay loam	0.9	2.1	182.7	28.3
Maulid Liwindi	5.3	111.7	sandy clay loam	1.5	1.7	278.1	41.6
Ernest Paspanofu	4.9	178.0	sandy loam	0.5	1.8	197.8	43.2

higher Zn concentrations (1.2, 1.1 and 0.9 mg/kg, respectively), they remained in the marginal range, indicating that Zn supplementation is necessary to address potential Zn deficiency across the entire Mkula site. Copper (Cu) concentrations ranged from 3.0-4.3 mg/kg, well above the critical level of 0.1-0.3 mg/kg, indicating sufficient Cu availability. Iron (Fe) concentrations were high across all zones, ranging from 251-317 mg/kg, far exceeding the critical level of 2-5 mg/kg. Manganese (Mn) concentrations varied significantly, with Zone 2 showing a critical deficiency of 2.4 mg/kg, below the threshold of 12-20 mg/kg. In contrast, Zones 1, 3 and 4 had Mn concentrations of 24.1, 4.4 and 12.1 mg/kg, respectively, indicating that while Zone 2 requires Mn supplementation, other zones have sufficient Mn for rice growth.

In Kisawasawa, the pH ranged from 4.5-5.4, indicating acidic conditions. The soil textures were predominantly clay and sandy clay loam. Zinc concentrations ranged from 0.7-2.1 mg/kg, with most zones having Zn concentrations above the critical deficiency threshold, though Zone 3 exhibited marginal Zn status at 0.7 mg/kg. Copper concentrations in Kisawasawa were consistently above the critical deficiency level, ranging from 2.4-4.2 mg/kg. Iron concentrations were similarly high, ranging from 182-231 mg/kg, and Mn concentrations were sufficient across the site, with values ranging from 12.6-43.2 mg/kg.

This analysis suggests that Zn deficiency is a key concern in both Mkula and Kisawasawa irrigation schemes, with specific zones in each village exhibiting marginal to deficient Zn concentrations, given that most farmers rely solely on macronutrient supplementation (Senthilkumar et al., 2021). Zinc supplementation, through either soil or foliar application, is recommended to improve rice productivity, particularly in Zn-deficient areas such as Mkula's Zone 2 and Kisawasawa's Zone 3.

Effect of zinc fertilization strategies on rice growth

The results revealed significant differences among treatments at both Kisawasawa (**Table 3**) and Mkula (**Table 4**). Significant differences due to treatments were observed for biomass accumulation ($p = 0.014$) at Kisawasawa, but not Mkula ($p=0.076$). The number of tillers showed significant differences due to treatments in both Kisawasawa ($p=0.035$) and Mkula ($p=0.030$). In all treatments and in both sites, the zero fertilizer treatment had the lowest of all growth parameters measured, while the fertilized treatments did not differ in growth parameters measured. Therefore, fertilizers applied improved growth of rice, but there were no significant differences between fertilizer types.

The percentage of filled grain did not show significant differences at the Kisawasawa site (p

Table 3. Effect of varying sources, rates and application methods of zinc on rice growth and yield parameters at Kisawasawa, Kilombero, Tanzania.

Treatment	Biomass, g/plant	Plant height, cm	Number of tillers	100 grain weight	Number of filled grain per panicle	Number of panicles per hill	% filled grain
T1	36.10 a	198.4	11.42 e	3.012	46.69	8.417	98.00
T2	52.56 ab	177.2	17.58 abcd	3.358	58.92	7.729	97.74
T3	50.68 ab	109.0	20.33 a	3.252	51.67	7.646	97.64
T4	56.27 ab	108.5	20.42 a	3.209	47.21	8.062	97.49
T5	65.82 b	107.5	18.92 abc	3.348	49.33	8.646	97.46
T6	51.86 ab	105.9	17.25 abcd	3.159	61.18	8.854	97.58
T7	61.65 b	105.9	18.58 abcd	3.476	61.8	7.938	97.55
T8	63.65 b	103.8	19.25 a	3.123	60.99	7.479	98.01
T9	56.79 ab	102.1	19 ab	3.153	45.96	8.458	97.77
T10	50.8 ab	98.4	12.83 bde	3.474	44.79	8.042	96.68
p value	0.014	0.56	0.035	0.837	0.080	0.96	0.747
s.e.d.	6.583	53.66	2.627	0.30	6.907	1.170	0.658

T1 = Absolute control, T2 = NPKS only, T3, T4, and T5 involved soil incorporation of NPKS plus $ZnSO_4$ prior transplanting with rates of 1, 2 and 4 kg Zn ha^{-1}, respectively. T6, T7 and T8 involved soil application of NPKS plus foliar applied $ZnSO_4$ at rates of 0.6 kg Zn ha^{-1} (3rd week from transplanting day), 0.8 kg Zn ha^{-1} (3rd & 5th weeks from transplanting day), and 1 kg Zn ha^{-1} (2nd, 3rd & 5th weeks from transplanting day), respectively. T9 and T10 involved soil application of NPKS plus root dipping of seedlings in 1% and 3% suspensions of ZnO, respectively, for 24 hours prior transplanting.

Table 4. Effect of varying sources, rates and application methods of zinc on rice growth and yield parameters at Mkula, Kilombero, Tanzania.

Treatment	Biomass, g/plant	Plant height, cm	Number of tillers	100 grain weight	Number of filled grain per panicle	Number of panicles per hill	% filled grain
Absolute control	42.51	74.42 a	10.25 a	3.41	53.74	6.73	98.04 a
NPKS	66.22	87.78 bc	14.33 b	3.30	60.31	6.08	98.06 a
NPKS+Soil Zn 1 kg/ha	64.31	82.38 b	15 b	3.34	60.81	6.19	98.16 a
NPKS+Soil Zn 2 kg/ha	62.73	87.36 bc	13.83 b	3.56	47.91	6.69	98.18 a
NPKS+Soil Zn 4 kg/ha	78.83	88.23 bc	14.83 b	3.09	60.16	7.02	98.32 ab
NPKS+Foliar Zn 0.6 kg/ha	66.54	85.63 bc	14.08 b	3.47	74.76	5.94	98.38 ab
NPKS+Foliar Zn 0.8 kg/ha	64.90	89.66 c	16.33 b	3.24	47.47	7.23	98.39 ab
NPKS+Foliar Zn 1.0 kg/ha	63.02	86.11 bc	14.25 b	3.47	53.04	6.25	98.74 b
p value	0.076	0.040	0.030	0.055	0.157	0.56	0.033
s.e.d.	9.075	2.96	1.377	0.131	9.241	0.72	0.184

T1 = Absolute control – no fertilizer applied, T2 = NPKS only, T3, T4, and T5 involved soil incorporation of NPKS plus $ZnSO_4$ prior transplanting with rates of 1, 2 and 4 kg Zn ha^{-1}, respectively. T6, T7 and T8 involved soil application of NPKS plus foliar applied $ZnSO_4$ at rates of 0.6 kg Zn ha^{-1} (3rd week from transplanting day), 0.8 kg Zn ha^{-1} (3rd & 5th weeks from transplanting day), and 1 kg Zn ha^{-1} (2nd, 3rd & 5th weeks from transplanting day), respectively.

= 0.747) but was significant at Mkula (p=0.033) (**Table** 3 and **4**). The highest percentage (98.74%) was recorded in treatment T8 (1 kg Zn/ha, foliar), while the control (T1) and T2 (NPKS only) had slightly lower percentages (98.04% and 98.06%, respectively). Treatments with foliar-applied $ZnSO_4$, such as T6 and T7, also had high percentages of filled grain, further highlighting the effectiveness of foliar Zn application. The effect of Zn fertilization strategies on 100-grain weight showed no significant differences in both sites.

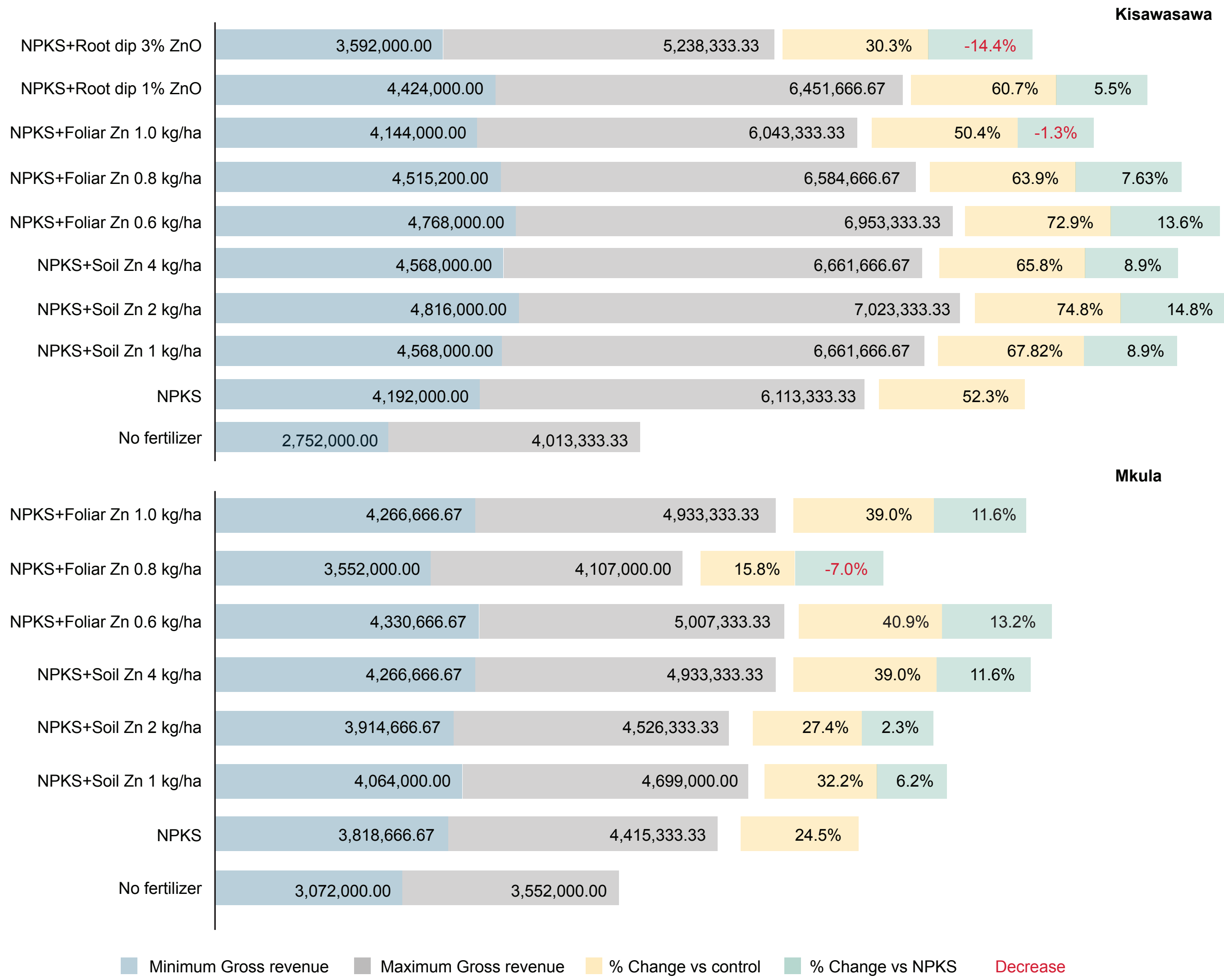

Figure 2. Gross revenue (minimum and maximum) from rice and percent increase due to NPKS and NPKS + Zinc fertilizer in two sites of Kilombero valley, Tanzania. (% change in gross revenue = increase/decrease in gross revenue in a treatments relative to No fertilizer and NPKS alone).

Effect of zinc fertilization strategies on rice grain yield

Zinc fertilization strategies significantly affected grain yield at both experimental sites (**Table 5**). Application of all fertilizers significantly increased yield and gross income by 2-75% over the no fertilizer treatments, while addition of soil and foliar Zn at all rates increased grain yield and gross income by 15% relative to the NPKS (**Fig. 2**). Exceptions included the slight decrease in yield in T8 and T10 at Kisawasawa and T7 at Mkula.

The Kisawasawa site had consistently higher yields across all treatments, with the highest yield of 6.02 t/ha obtained in T4 (soil applied NPKS and soil incorporation of NPKS plus $ZnSO_4$ prior transplanting at 2 kg Zn/ha). The highest yields in Mkula were obtained in T6 (NPKS + foliar applied $ZnSO_4$ at rates of 0.6 kg Zn/ha) (4.06 t/ha), T5 (NPKS + soil applied 4 kg Zn/ha) and T8 (NPKS + seedlings dipping in 1% ZnO), both of which recorded 4 t/ha. These results show site-specific responses of rice to Zn fertilization. Furthermore, root dipping rice seedlings in 3% suspensions of ZnO decreased rice yield in Kisawasawa.

Conclusions

Fertilizer combination that supplies soil applied N, P, K, and S with soil applied $ZnSO_4$ at the rate of 2 kg Zn/ha is a suitable strategy for rain-fed area with acid soil deficient in those nutrients. On the other hand, foliar applied Zn at the rate of 0.6 kg Zn/ha in addition to N, P, K, and S is a suitable strategy in the irrigated rice-growing areas. Use of a high rate of ZnO

Table 5. Yield response of rice treated with varying zinc fertilization strategies in Mkula and Kisawasawa irrigation schemes, Kilombero, Tanzania.

Site	Kisawasawa	Mkula
Treatments	Yield, t/ha	
Absolute control	3.44 c	2.88 a
NPKS	5.24 ab	3.58 ab
NPKS+Soil Zn 1 kg/ha	5.71 ab	3.81 b
NPKS+Soil Zn 2 kg/ha	6.02 a	3.67 ab
NPKS+Soil Zn 4 kg/ha	5.71 ab	4.00 b
NPKS+Foliar Zn 0.6 kg/ha	5.96 a	4.06 b
NPKS+Foliar Zn 0.8 kg/ha	5.644 ab	3.33 ab
NPKS+Foliar Zn 1.0 kg/ha	5.18 ab	4.00 b
NPKS+Root dip 1% ZnO	5.53 ab	nd
NPKS+Root dip 3% ZnO	4.49 bc	nd
p value	0.01	0.08
s.e.d.	0.61	0.37

Absolute control (no fertilizers applied); NPKS=soil applied NPKS only; NPKS+Soil Zn = involved soil incorporation of NPKS plus $ZnSO_4$ prior transplanting with rates of 1, 2 and 4 kg Zn ha^{-1}; NPKS+Foliar Zn = involved soil applied NPKS plus foliar applied $ZnSO_4$ at rates of 0.6 kg Zn ha^{-1} (3rd week from transplanting day), 0.8 kg Zn ha^{-1} (3rd & 5th weeks from transplanting day), and 1 kg Zn ha^{-1} (2nd, 3rd & 5th weeks from transplanting day), respectively; NPKS+Root dip % ZnO = involved soil application of NPKS plus root dipping of seedlings in 1% and 3% suspensions of ZnO, respectively, for 24 hours prior transplanting.

at 3% through seedling root dipping did not suit rice production in Kilombero and may need further research for optimization. Therefore, both soil and foliar applied Zn in the form of $ZnSO_4$ are the best fertilization strategy for rice production in Kilombero district. ■

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ANNUAL PHOTO CONTEST RESULTS

NUTRIENT DEFICIENCY SYMPTOMS IN CROPS

PLANT NUTRITION RESEARCH IN ACTION

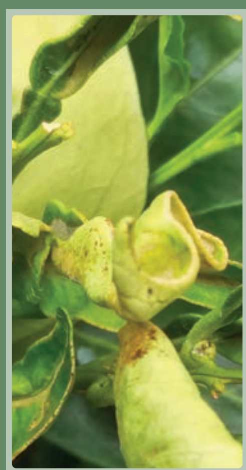
apni.net/photo-contest

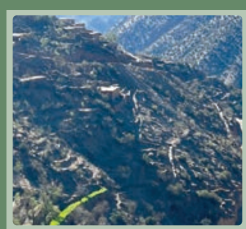
We're excited to announce the results of our annual photo contest! Thank you for the incredible submissions from across Africa. Your participation helps us showcase nutrient deficiency examples and plant nutrition research, raising awareness about healthy soils and crops, and sharing interesting activities and perspectives about agricultural R&D in Africa.

Cash prizes have been awarded to the top photos in each category, and we're pleased to feature additional honorable mentions.

The contest will reopen in early 2026—watch for details in the next issue of Growing Africa, on our website, or follow us on social media for updates.

Thank you for helping us celebrate the great work towards improving nutrient use in Africa!





CROP NUTRIENT DEFICIENCY CATEGORY:

WINNING ENTRY

Calcium Deficiency in Carnation Plants

Mr. Victor Kipkurui
Naivasha, Kenya

Mr. Kipkurui's photos from a field of carnation plants (*Dianthus caryophyllus*) growing in Naivasha, Kenya, provides a clear example of calcium (Ca) deficiency. Victor explains that the symptoms of leaf tip burn are a result of the current prevailing conditions of high relative humidity and heavy rains which hindered plant uptake of calcium even if supplied at regularly adequate rates within fertigation solutions. Since calcium uptake is dependent on a steady transpiration stream, if relative humidity is high the resulting decline in transpiration reduces calcium absorption and limits its concentration in actively growing tissues like leaf tips. Mr. Kipkurui's further explains that mitigation measures involve additional calcium application with foliar sprays and, if grown in a controlled environment, dehumidification using fans during night hours.

CROP NUTRIENT DEFICIENCY CATEGORY:
HONORABLE MENTION

Mr. Abubakar Ahmad Rufa'I
Yakawada Giwa Local Government Area,
Kaduna State, Nigeria

Abubakar shares a photo from a crop of okra growing in his home garden that is showing vivid symptoms of magnesium (Mg) deficiency observed as yellowing between the leaf veins, and leaf curling, initially on older growth.

Mr. Workat Sebnie
Lalibella, Ethiopia

Mr. Sebnie's photo was taken from an experiment studying nitrogen (N) and phosphorus (P) rates in wheat. It clearly illustrates the effects of N deficiency on plant growth in the experiment's N omission control plot.

PLANT NUTRITION RESEARCH CATEGORY:

WINNING ENTRY

Striga Infestation in Maize

Mr. Moses Odur
Mumias West, Kakamega County, Kenya

Mr. Odur took this photo from a smallholder maize farm in Kenya, which shows an active infestation of *Striga hermonthica* (commonly known as purple witchweed) a parasitic plant that significantly reduces maize yields in the region. His ongoing field research links the persistence of Striga to acidic soil conditions (low pH) and plant stress caused by inherent nutrient deficiencies. Moses's team has implemented agricultural liming treatments to correct soil pH and improve nutrient availability. While they have recorded a notable reduction in Striga density, total eradication has not yet been achieved, indicating the need for integrated soil and crop health strategies.

PLANT NUTRITION RESEARCH CATEGORY:

HONORABLE MENTION

Ms. Andrialalao Sophie Raharimalala
Ankilizato, Menabe region, Madagascar

Ms. Raharimalala took this photo from a farmer's field growing common bean, an off-season legume crop in rotation with lowland rice. Andrialalao explains that although farmers in this region may not fully understand the underlying mechanisms of soil fertility improvement, they do recognize the benefits of integrating legumes into their crop rotation. The visible improvement in rice growth and the additional yield obtained after rotating with a leguminous crop encourage them to continue this practice. In addition, the legume grains provide a valuable source of protein and extra income, contributing to improved household nutrition and livelihoods.

Short-term Effects of Legume-based Cropping Systems and Residue Management on Soil Fertility in Malawi

By Peter Mbogo Mfune, Joseph Chimungu, Keston Njira, Patson Nalivata, and Austin T. Phiri

Researchers focused on the short-term effects of legume planting pattern and residue management practices (i.e., incorporation immediately after harvest and mulching) on soil fertility status in contrasting environments and soils in Malawi. *Results revealed substantial increase in soil nitrogen and phosphorus which would eventually improve soil health and reduce mineral fertilizer requirements for subsequent crops.*

Left to Right: Sole cowpea crop, cowpea-pigeon pea intercrop, and pigeon pea immediately after cowpea residue incorporation.

Soil fertility decline has been reported to be one of the major challenges faced by smallholder farmers in Sub-Saharan Africa (SSA) (Zingore et al., 2015). In Malawi, like other SSA countries, high population has put great pressure on agricultural land. This has resulted in the loss of soil fertility due to poor soil management practices such as monocropping coupled with under replenishment of nutrients removed with harvested crop products (Zingore et al., 2015). Although inorganic fertilizers increase crop yields, they continue to be expensive and are often beyond reach for most farmers (World Bank, 1996). Governments try to put measures such as input subsidies in place to increase fertilizer use, but the sustainability of such initiatives is often unpredictable. It is imperative to search for alternative means of enhancing soil fertility that are both sustainable and economic. One such approach is Integrated Soil fertility Management (ISFM), which combines soil fertility management practices that promote use of both organic and inorganic nutrient sources, improved germplasm, and appropriate agronomic practices tailored to local conditions to maximize agronomic use efficiency of all applied nutrients, and improve overall crop productivity (Vanlauwe et al., 2010). One such ISFM practice includes the integration of legumes within the crop production system (Palm et al.,1997).

Leguminous crops have the capacity to increase soil fertility through biological nitrogen fixation (BNF) and subsequent mineralization of below and above ground biomass (Drinkwater et al., 1998). BNF is achieved through the mutualistic relationship between legumes and bacteria, especially rhizobia spp including: *Allorrhizobium, Bradyrhizobium, Rhizobium, Sinorhizobium,* and *Mesorhizobium* (Giller, 2001; Syvia et al., 2005; Berrada and Fikri-Benbrahim, 2014). Soil microorganisms decompose the highly nutrient-rich plant residues that enrich the soil with much-needed N and other essential nutrients. Usually about two-thirds of the N fixed through a legume crop is available for the subsequent growing season. Microorganisms can positively affect physical, chemical, and biological soil properties that are the defining facets of soil health (Stagnaria et al., 2017; Nanganoa et al., 2019; Vasconcelo et al., 2020). Legume crop products also contribute to human and livestock nutrition as low-cost sources of protein, especially to resource poor farmers where meat availability is low (Maposa and Jideani, 2017; Kerr et al., 2007).

In Malawi, traditional legumes include common beans (*Phaseolus vulgaris*), cowpea (*Vigna ungiculata*), soybean (*Glycine max*), groundnut (*Arachis hypogaea*) and pigeon pea (*Cajanus cajan*) grown as either sole crops or as intercrops with cereals like maize (Mhango et al., 2012; Ngwira et al., 2012). Sole legume systems contribute to nutrient inputs primarily through N fixation, while intercropping systems not only enhance land-use efficiency but also foster complementary resource use between species.

Some farmers intercrop legumes with other legumes, a practice commonly called double-up legume (DUL) cropping (ICRISAT/MAL, 2000; Mhango, 2011). The goal of this strategy is to take advantage of two complimentary interactions provided by the legume species (Chikowo et al., 2015). DUL systems significantly raises soil N according to research by Njira et al. (2012), who found that the pigeon pea/groundnut intercropping produced 82.8 kg N/ha compared to 54.1 kg N/ha by pigeon pea or 55.8 kg N/ha by groundnut. According to Njira et al. (2017), a pigeon pea/cowpea intercrop generated 82.9 kg N/ha, which was significantly higher than cowpea (62.5 kg N/ha) or pigeon pea (59.9 kg N/ha) when intercropped with maize, but it was comparable to that of the pigeon pea alone (92.9 kg N/ha). Furthermore, (Kanyama-Phiri et al., 2000; Phiri et al., 2012) reported that farmers in Malawi consistently ranked DUL highly among organic soil fertility enhancement options. To maximize soil fertility benefits under DUL, legume residue management becomes very critical. Residue management plays a key role in sustaining nutrient stocks by recycling organic matter and maintaining soil cover, thereby reducing erosion and nutrient loss (Sanginga and Woomer, 2009).

Therefore, short-term evaluations of these practices are particularly critical to understand immediate impacts on soil fertility parameters such as soil organic carbon (C), available N and P, and soil biological activity. Despite their potential, the relative short-term benefits of these systems remain underexplored in many smallholder contexts. This study investigates the short-term effects of sole legume cropping, legume-legume intercropping, and residue management on soil fertility, providing insights to guide ISFM strategies for sustainable intensification in SSA.

Study site description

The study was carried out at two distinct sites including Chitala agricultural research station within the Chinguluwe extension planning area in the Central region and Bvumbwe agricultural research station under the Dwale extension planning area in the South.

The experiment was a randomized complete block design with all the five treatments replicated three times. Each plot size was 20 x 10 m. The pigeon pea crop was planted at a spacing of 90 cm apart with three seeds per station in both sole and intercropped treatments.

Chitala (Salima district)	**Bvumbwe** (Thyolo district)
• Latitude 13°15′, 40′ south and longitude 43°15′ east. Hot lakeshore district within the low ecological zone (606 m.a.s.l).	• Latitude 15° 55′ south and longitude 35° 04′ east. High-altitude district (1174-1228 m.a.s.l).
• Mean annual temperature of 28°C max and 16°C min. Moderate mean annual rainfall (800 mm) with frequent dry spells.	• Cool weather and high annual rainfall >1300mm accompanied by frequent mist (chiperoni) weather.
• Alfisol soils with black compact non-cracking topsoil. High base saturation and low N and K content but high in calcium (Ca).	• Lixisol soils with acidic red clay.

Table 1. Baseline composite soil characteristics for Bvumbwe and Chitala.

Site	Depth, cm	Sand, %	Silt, %	Clay, %	Class	pH	OC, %	N, %	P, ppm	K, ppm
Bvumbwe	0-20	53	11	42	SC	5.5	0.87	0.07	32.9	0.06
Chitala	0-20	58	8	34	SCL	6.0	0.92	0.07	9.7	0.08

Cowpea in both sole and intercropped treatments was planted at 30 cm apart with three seeds planted per station according to MoAFS (2012). Sorghum seeds were planted at 30 cm (5-7 seeds) per planting station then thinned to two plants after emergence (88,888 plant population). At harvest time all legume biomass from the treatments were incorporated into the soil except in treatment 5 (mulch) in accordance with design.

The crop varieties included: pigeon pea (Mwaiwathu alimi, ICEAP 00557) maturing between 5-6 months with yields up to 2.5 t/ha, cowpea (IT82-E-16) maturing in 2 months with yields up to 3 t/ha, and sorghum (Pilira 5).

All good agronomic practices were applied across treatments during the whole growing season. The field was deeply ploughed by tractor to minimize the effect of hardpans on root penetration. Hand hoe ridging was used to effectively achieve the recommended 75 cm ridge spacing. Planting was done in late December at both sites after receiving their effective rainfall. Manual weeding was used at both sites to make sure that the trials are free of weeds. Scouting of pests, especially leaf eaters and sap suckers, was done every two weeks and pests were treated as needed. At harvest, all the biomasses were cut and incorporated into the soil between the ridges. Soil sampling was done 10 weeks after biomass incorporation to determine fixed and mineralized nutrients.

Baseline soil characterization

Table 1 provides the soil baseline data at the two trial sites for the season 2021-2022 before legume planting. At Chitala, the soil texture was sandy clay loam (SCL). The Bvumbwe soil was sandy clay (SC). Soil pH was 6.0 and 5.5 for Chitala and Bvumbwe, respectively. Both sites had very low levels of N (<0.08%). Chitala had low levels of P (9-18 ppm range) while Bvumbwe had adequate P (25-33 ppm range) according to threshold values.

Effect of legume cropping system on soil nitrogen and phosphorus

Table 2 shows soil N and P concentrations after legume harvesting at both trial sites. At Bvumbwe, low levels of N (0.08-0.12% range) were found for the pigeon pea system while the sorghum system had very low (<0.08%) N levels. No significant differences were found between cowpea cropping and pigeon pea + cowpea (biomass not incorporated) systems, which both had medium N levels (0.12-0.2% range). The system with pigeon pea + cowpea biomass incorporated had high levels of N (0.20-0.3%). Soil P also differed across treatments at Bvumbwe although all had very high P levels (>34 ppm). The pigeon pea + cowpea (biomass incorporated) system had the highest P levels (52.2 ppm).

At Chitala, significant differences in soil N and P were also obtained amongst the cropping systems. Sole sorghum cropping had very low N levels (<0.08%) compared to the other treatments which were slightly higher (0.08-0.12% range). Pigeon pea cropping had higher levels of N (0.11%) compared to the other cropping systems. Significant differences were also obtained in soil P across the treatments although all were categorized as low (9-18 ppm range). The

Table 2. Soil nitrogen and phosphorus after legume cropping system at Bvumbwe and Chitala trial sites.

		Bvumbwe		Chitala	
Treatment	Depth	N, %	P, ppm	N, %	P, ppm
Sorghum (incorp)	0-20	0.06	42.7	0.04	15.2
Pigeon Pea (PP) (incorp)	0-20	0.11	44.4	0.11	15.2
Cowpea (CP) (incorp)	0-20	0.19	45.1	0.09	14.2
PP + CP (incorp)	0-20	0.28	52.2	0.09	15.5
PP + CP (not incorp)	0-20	0.20	43.2	0.10	15.6
Mean		0.13	51.9	0.09	14.6
% CV		17.8	18.3	26	12.4
F. Prob		0.04	0.63	0.01	0.66
SED		0.03	-	0.02	-

Table 3. Effect of cropping system on soil nitrogen buildup.

Treatment	Depth, cm	Bvumbwe Initial N	Final N	N buildup	N change	Chitala Initial N	Final N	N buildup	N change
		----------------- % ----------------				----------------- % ------------------			
Sorghum (incorp)	0-20	0.07	0.06	-0.01	-14.1	0.07	0.04	-0.03	-42.9
Pigeon Pea (PP) (incorp)	0-20	0.07	0.11	0.04	57.1	0.07	0.11	0.04	57.1
Cowpea (CP) (incorp)	0-20	0.07	0.19	0.12	171.4	0.07	0.09	0.02	28.6
PP + CP (incorp)	0-20	0.07	0.28	0.21	300	0.07	0.09	0.02	28.6
PP + CP (not incorp)	0-20	0.07	0.20	0.13	185.7	0.07	0.1	0.03	42.9

pigeon pea+cowpea (PP+CP) treatment (biomass not incorporated) had the highest P levels (15.6 ppm).

Soil nitrogen and phosphorus build-up

Table 3 shows the overall effect of legume cropping system on N buildup at both sites. Results from Bvumbwe indicate that PP+CP biomass incorporated had the greatest positive buildup in N levels (0.21%) representing a 300% increase over baseline samples. The sole sorghum system had the lowest levels (0.06%) representing a 14.1% decline in N. No significant differences in N levels were observed between sole cowpea (0.19%) and PP+CP biomass not incorporated (0.20%) representing respective increases of 171.4 % and 185.7%. The difference in N buildup between the two PP+CP systems (incorporated vs. not incorporated) demonstrated the impact of residue management.

At Chitala, sole pigeon pea had the highest N buildup (0.11%) though not statistically different to PP+CP biomass incorporated (0.09%) and pigeon pea biomass not incorporated (0.10%) representing increases of 57.1%, 28.6%, and 42.9%, respectively. Like Bvumbwe, sole sorghum grown at Chitala had the lowest levels of N (0.04%), representing a decline of -42.9%.

Table 4 below indicates the effect of legume cropping systems on P buildup at both sites. Significantly higher P buildup (19.3 ppm) was recorded under the PP+CP (biomass incorporated) system at Bvumbwe. Phosphorus buildup at Chitala was generally lower, PP+CP biomass not incorporated (5.92 ppm) had the highest P buildup to PP+CP biomass incorporated (5.82 ppm) representing a 61.1% and 60.1% change respectively. Insignificant differences in P change were observed with other cropping system at both sites but sole sorghum had the lowest change (29.8%) at Bvumbwe while sole cowpea was the lowest (46.6%) at Chitala.

Significantly higher N and P buildup in legume inclusive systems signify the positive short-term effects this cropping system had on major soil fertility defining parameters. These increases under DUL treatments, where residues were incorporated in the soil immediately after harvesting, clarify the significance of residue management in legume cropping system. These results support the hypothesis that residue management in either sole legume or

Table 4. Effect of cropping system on soil nitrogen buildup.

Treatment	Depth, cm	Bvumbwe Initial N	Final N	P buildup	P change	Chitala Initial P	Final P	P buildup	P change
		------------- ppm -------------			%	------------- ppm -------------			%
Sorghum (incorp)	0-20	32.89	42.7	9.81	29.8	9.68	15.2	5.52	57.0
Pigeon pea (PP) (incorp)	0-20	32.89	44.4	11.51	34.9	9.68	15.2	5.52	57.0
Cowpea (CP) (incorp)	0-20	32.89	45.1	12.21	37.1	9.68	14.2	4.52	46.6
PP + CP (incorp)	0-20	32.89	52.2	19.31	58.7	9.68	15.5	5.82	60.1
PP + CP (not incorp)	0-20	32.89	43.2	10.31	31.3	9.68	15.6	5.92	61.1

DUL systems affects soil fertility differently under different environments. Pigeon pea + cowpea where biomass was incorporated had a higher N and P contribution at the Bvumbwe site, while at Chitala sole pigeon pea contributed higher N while PP+CP biomass not incorporated registered the highest P levels.

Baseline soil N showed low levels of this nutrient at both sites. This gave a good standpoint for this study as initial amounts of N in the soil affect subsequent N fixation. Such an understanding agrees with Havlin et al., 2005 who reported that excess nitrite in the soil reduces the activity of nitrogenase thereby reducing N fixation.

However, other differences between sites are suggested to have affected the performance of different cropping systems tested in this study as the same treatments performed differently across sites. This agrees with the findings of Giller, 2001; Mozamadi et al., 2012 who reported that growth, nodulation and BNF of legumes are affected by many factors which include soil temperature, soil pH, essential macro and micronutrients, presence of essential microbial symbionts, and the cropping system practiced. It is therefore important to consider differences in environmental conditions when practicing legume-based cropping system. Acidic and moderately acidic soil pH observed at both sites did not have an apparent affect on availability and abundance of microbes effecting nutrient buildup in the soil. A pH between 5.5-7.0 is ideal for enhancing soil nutrient availability to crops as it creates a good environment for microbes to thrive (Hamza, 2008).

At both sites legume cropping systems positively affected N and P buildup, which affirms the effectiveness of this novel system towards soil improvement. These findings agree with Olufowote and Barnes-McConnel (2002) who reported that when legumes like cowpea are included in a cropping system as either sole or intercrop components, they help to improve fertility status of degraded soils.

The highest N buildup of up to 300% at Bvumbwe in PP+CP (biomass incorporated) can be attributed to combined biomass decomposition and N fixation from both legumes in addition to adequate moisture in the soil, which favors effective decomposition of crop residues. These results agree with the findings of Phiri et al., 2024 who also found that PP+CP increased N and P availability in the soil due to combined effect of the two legumes when compared to growing as sole crops. Lower N and P buildup under non-incorporated (mulched) treatments could be because of dry conditions within the topsoil. The significance of residue incorporation observed in this study agrees with the findings of Bakht et al., 2009 and Shafi et al., 2007 who also reported significant N and P increase in the soil due to legume residue incorporation.

Vigorous pigeon pea growth observed in the field, coupled with a longer duration in the field compared to cowpea, promotes higher N and P buildup in the soil under sole pigeon pea cropping at Chitala as compared to the other treatments studied. This prompted accumulation of more above and below ground biomass, which released more N and P during their decomposition. It was further suggested that the more N and P buildup under sole pigeon pea, as opposed to an intercrop, at Chitala was due to reduced inter-specific competition for light, nutrients, and moisture. Such findings in this study agree with those of Njira et al., 2017 who reported a higher N fixation using the modified N-difference method in sole pigeon pea as compared to a PP+CP intercrop. However, such findings do not agree with this study's results at Bvumbwe where pigeon pea-cowpea intercropping had higher N buildup compared to sole pigeon pea. This discrepancy is attributed to poor field performance of pigeon pea due to differences in environmental conditions. Negative N buildup under farmers practice (sole sorghum) was attributed to nutrient mining. Slightly lower P buildup under sole cowpea at Chitala was attributed to poor field performance of the crop. Continuous cropping results into mining of available nutrients in the soil thereby rendering the soil being poorer. Such understanding agrees with the findings of Ahmad et al., 2013 who reported that mono-cropping system negatively affects soil physical, chemical, and biological properties.

Conclusions

Double-up legume cropping systems played a significant role in soil nutrient buildup as significant N and P was built under this system compared to other cropping systems. However, environmental conditions including soil types and climate greatly contributed to the effect of these double-up cropping systems. It is imperative to consider site differences when employing different legume cropping systems. The study further explained that nutrient buildup under double-up legume cropping systems is highly intensified with residue incorporation. Farmers are therefore encouraged to adopt this technology to revitalize their soils by increasing nutrients buildup and overall soil health which will eventually reduce the requirement of inorganic fertilizers. ■

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Nitrogen Dynamics under Cowpea–Pigeon Pea Intercropping and Residue Management in Malawi's Drought Prone Areas

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Soil nitrogen depletion remains a critical barrier to sustainable crop production in Malawi's drought-prone smallholder farming systems. This study investigated the influence of cowpea–pigeon pea intercropping and residue management on soil nitrogen dynamics. Results show strengthened nitrogen cycling through biological nitrogen fixation, improved residue quality, and increased residue biomass. This integrated approach provides a climate-smart pathway to restore soil fertility and enhance the resilience and productivity of smallholder farming systems in Malawi's drought-affected regions.

Sustainable intensification of agriculture is increasingly critical in sub-Saharan Africa (SSA), where soil degradation, declining productivity, and climate variability threaten food security and farmer livelihoods (Ahmed et al., 2022). In Malawi, soil fertility decline is primarily driven by continuous monocropping, residue burning, erosion, and the diversion of crop residues for livestock feed, leading to severe nutrient depletion (Mwale et al., 2011; Ngwira et al., 2012a; Raj et al., 2022). These challenges, compounded by recurrent droughts and floods, reduce crop productivity, increase reliance on costly synthetic fertilizers, and weaken the resilience of smallholder farming systems (Sharma et al., 2025; Sosola et al., 2022).

Addressing these challenges require integrated approaches that enhance soil fertility while building resilience to climatic stress. Legume-based intercropping and crop residue incorporation have emerged as sustainable strategies for improving soil health and nutrient use efficiency in smallholder systems. Legumes such as cowpea (*Vigna unguiculata*) and pigeon pea (*Cajanus cajan*) play a vital role in biological nitrogen fixation (BNF), improving nutrient cycling, and promoting synergistic interactions that enhance land productivity and resource use efficiency (Ngwira et al., 2012b; Drinkwater et al., 1998; Giller, 2001). When residues are incorporated into the soil, they further improve soil structure, stimulate microbial activity, and increase soil organic matter, thereby reducing fertilizer dependence and mitigating greenhouse gas emissions (Lal, 2006; Begum et al., 2022; Baloch et al., 2025).

Nitrogen (N) plays a central role in agroecosystem productivity, regulating organic matter decomposition, mineralization, and immobilization processes that determine soil fertility and plant nutrient availability (Koch and Sessitsch, 2024). Incorporation of crop residues tightens N cycling by enhancing microbial efficiency and soil N retention, thereby sustaining soil fertility over time (Breza and Grandy, 2025). The type of residue incorporated strongly influences microbial behaviour and N transformation. Legume residues, characterized by low carbon-to-nitrogen (C:N) ratios, decompose more rapidly and release N more efficiently than high C:N residues, thereby stimulating microbial mineralization and improving nutrient availability (Palm et al., 2001; Toleikiene et al., 2024).

Legume–legume intercropping systems, such as cowpea–pigeon pea combinations, are particularly relevant for improving N dynamics in low-input smallholder farming systems. Nitrogen is often a limiting nutrient in these systems, and intercropping legumes provides additional biological N inputs through symbiotic fixation, reducing the need for synthetic fertilizers (Melese et al., 2025; Kebede, 2021). Furthermore, incorporating legume residues enhances microbial biomass and nutrient cycling efficiency, improving plant N uptake and sustaining soil fertility over time (Kumar et al., 2025; Sharma et al., 2025). The complementary rooting structures and microbial associations between cowpea and pigeon pea promote efficient N use and recycling within the soil system (Kokkini et al., 2025).

Despite these benefits, many smallholder farmers in Malawi still rely on monocropping and unsustainable residue management, partly due to limited awareness of the long-term advantages of legume-based systems (Chikowu et al., 2015). Given the increasing frequency of droughts in Malawi's semi-arid regions, understanding how cowpea–pigeon pea intercropping and residue incorporation affect soil N dynamics is essential. This study, therefore, investigates the effects of cowpea–pigeon pea intercropping and residue incorporation on soil N forms—ammonium (NH_4^+), nitrate (NO_3^-), and total N (TN). The objective is to identify sustainable residue and cropping strategies that enhance N availability, reduce N fertilizer dependence, and promote resilient, productive smallholder systems in Malawi's drought-prone areas.

Table 1. Description of experimental treatments and residue management practices.

Cropping system	Residue management	Soil depth, cm
Sorghum monocrop	Above ground biomass removed after harvest	0–20, 20–40
Pigeon pea monocrop	Above ground biomass incorporated; stems excluded	0–20, 20–40
Cowpea monocrop	Above ground biomass incorporated	0–20, 20–40
Cowpea–pigeon pea intercrop	Above ground biomass incorporated; pigeon pea stems excluded	0–20, 20–40
Cowpea–pigeon pea intercrop (residue removed)	Above ground biomass removed after harvest	0–20, 20–40

Study site description

This research was conducted in two distinct locations in Malawi; Chinguluwe EPA located in the central lakeshore district of Salima, and Lunzu EPA situated in the hot, dry, and low-rainfall area of Blantyre in the southern region. Salima District sits at an elevation of 510 meters above sea level and receives an average annual rainfall of approximately 976 mm, with a unimodal distribution. In contrast, Blantyre District has a higher elevation of 1,039 meters above sea level and experiences a mean annual rainfall of 1,122 mm. These sites were chosen due to their distinct agricultural and environmental characteristics, including recurrent dry spells, degraded soils, and low fertility, all of which contribute to reduced crop yields. The cropping history of these areas highlights challenges with staple cereals such as maize and certain legumes, making them particularly suitable for evaluating drought-tolerant crops like pigeon pea, sorghum, millet, and cowpea.

Field experiments were conducted during the 2022/23 and 2023/24 cropping seasons. Treatments were arranged in a randomized complete block design with three replications. Five cropping systems were evaluated: (i) sole sorghum, (ii) sole pigeon pea, (iii) sole cowpea, (iv) cowpea–pigeon pea intercrop, and (v) cowpea–pigeon pea intercrop with residue removal (control). Soil sampling was superimposed on the same plots in the second season in a factorial arrangement with two soil depths (0–20 cm and 20–40 cm).

Residue management varied across treatments. In sole sorghum and the control intercrop, all above ground biomass was removed after harvest. In sole cowpea, sole pigeon pea, and intercrop plots, residues were incorporated into the soil, except pigeon pea stems, which were excluded due to their resistance to decomposition.

Above ground biomass was measured at harvest, and representative samples of cowpea and pigeon pea residues were collected to assess quality prior to incorporation. Samples were oven-dried, ground (<0.5 mm), and analyzed for N and carbon (C). Carbon-to-nitrogen (C:N) ratios were calculated to evaluate residue decomposition potential (Palm et al., 2001). Nutrient uptake was estimated as the product of total above ground dry matter and nutrient concentration.

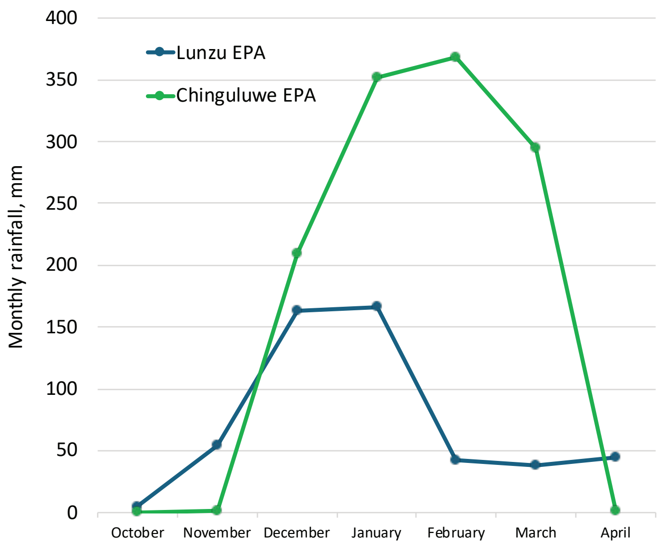

Figure 1. Monthly rainfall amounts (mm) during the 2023/24 growing season for Chinguluwe and Lunzu EPA sites.

Soil samples were collected from each plot using an auger at depths of 0–20 cm and 20–40 cm. Composite samples were obtained from three random positions per plot. Sampling was carried out at three stages: (i) immediately after harvest and before residue incorporation, (ii) six months after incorporation, and (iii) at three-week intervals up to nine weeks after planting sorghum in the following season.

Monthly rainfall at Chinguluwe and Lunzu EPAs

Monthly rainfall patterns at Chinguluwe and Lunzu EPAs during the 2023/24 cropping season showed distinct differences in distribution and intensity (**Fig. 1**). At Chinguluwe, rainfall was minimal in October and November, sharply increasing in December and peaking at approximately 370 mm in January and February, indicative of a short, intense rainy season. However, rainfall declined rapidly by April, potentially constraining late-season nutrient mineralization in the latter months and increasing nutrient leaching risks between January and February. In contrast, Lunzu experienced a more gradual rainfall rise from October, peaking moderately around 160–170 mm in December–January, and declining slowly through February and March, with a minor resurgence in April. This extended, moderate rainfall pattern likely facilitated gradual residue decomposition and steady nutrient mineralization, reducing leaching risks and promoting better synchronization between nutrient availability and crop uptake.

Baseline soil characteristics

Baseline soil analyses revealed variability in texture, pH, organic carbon (OC), and N across sites (**Table 2**). Lunzu soils were sandy clay loam (SCL) with slightly to moderately acidic pH (5.0–6.0) and low OC (0.50–0.74%) and N (0.04–0.06%). Chinguluwe soils ranged from SCL to sandy clay (SC), with neutral to slightly alkaline pH (6.0–7.3) and more variable OC (0.25–0.92%) and N (0.02–0.08%). These findings suggest that both sites have limited fertility, requiring organic or inorganic amendments to improve SOC and nutrient availability.

Residue nitrogen composition and biomass production

Crop residue quality and biomass differed significantly among cropping systems (**Table 3**). Cowpea residues consistently had higher N content and narrower C:N ratios compared to pigeon pea, indicating faster decomposition and nutrient release. For example, at Chinguluwe, sole cowpea residues

Table 2. Baseline soil fertility characteristics at mother on-farm trial at Chinguluwe EPA.

Site	Depth	Sand %	Silt %	Clay %	Texture class	pH	OC %	N %
Chinguluwe EPA 1	0-20	68	13	19	SCL	7.2	0.25	0.02
	20-40	67	14	19	SCL	7.3	0.46	0.04
Chinguluwe EPA 2	0-20	58	8	34	SCL	6	0.92	0.08
	20-40	56	8	36	SC	6.4	0.79	0.07
Lunzu EPA 1	0-20	66	10	24	SCL	6	0.55	0.05
	20-40	50	20	30	SCL	5.8	0.50	0.04
Lunzu EPA 2	0-20	60	10	30	SCL	5	0.69	0.06
	20-40	58	10	32	SCL	5.9	0.74	0.06

Table 3. Effect of cropping system on residue nitrogen composition and biomass production under cowpea–pigeon pea intercropping.

Cropping system	Residue N, kg/ha	Residue N, %	Residue C, %	C:N ratio	Residue biomass, kg/ha
Chinguluwe					
Sole Cowpea	18.40	2.48	37.82	15.25	3,952
Sole Pigeon Pea	11.88	2.03	43.67	21.51	4,020
Pigeon Pea (PP+CP)	6.95	2.94	46.61	15.85	4,730
Pigeon Pea (PP+CP) Check	11.68	2.22	43.44	19.57	3,257
Cowpea (PP+CP)	17.57	2.87	38.02	13.25	3,159
Cowpea (PP+CP) Check	15.68	2.12	40.04	18.89	4,730
Lunzu EPA					
Sole Cowpea	19.55	2.34	36.43	15.57	3,780
Sole Pigeon Pea	12.35	2.11	42.55	20.17	4,301
Pigeon Pea (PP+CP)	10.37	2.46	46.49	18.90	4,397
Pigeon Pea (PP+CP) Check	12.02	2.30	45.13	19.62	4,081
Cowpea (PP+CP)	16.05	2.23	38.66	17.34	2,772
Cowpea (PP+CP) Check	14.22	2.14	38.03	17.77	2,650

"Check" refers to plots without residue incorporation; Sites represent two drought-prone regions: Chinguluwe and Lunzu EPA.

contained 2.48% N with a biomass yield of 3,952 kg/ha. Sole pigeon pea had 2.03% N with a yield of 4,020 kg/ha and a wider C:N ratio. Intercropping (PP+CP) enhanced residue quality for both species, with cowpea residues showing 2.87% N and a C:N ratio of 13.25, while pigeon pea residues contained 2.94% N and a C:N ratio of 15.85. Intercropped pigeon pea produced the most biomass (4,730 kg/ha at Chinguluwe and 4,397 kg/ha at Lunzu), indicating strong potential for SOC build-up and nutrient cycling.

Residue incorporation and soil ammonium

Soil ammonium concentrations were significantly influenced by cropping system and soil depth (**Table 4**). The PP+CP intercrop with residue incorporation recorded the highest soil profile ammonium at both sites (i.e., mean values calculated across both soil depths: Chinguluwe: 40.15 mg/kg; Lunzu: 26.34 mg/kg). Sole cowpea and sole pigeon pea with residues also maintained elevated ammonium, but systems with residue removal, especially sole sorghum, had the lowest levels (Chinguluwe: 18.68 mg/kg; Lunzu: 12.95 mg/kg). Ammonium concentrations were consistently higher within the 0–20 cm soil layer compared to the 20–40 cm, reflecting surface accumulation.

Temporal distribution of soil ammonium

Temporal monitoring revealed that residue incorporation led to a gradual increase in ammonium, peaking six months after incorporation (**Fig. 2**). For instance, the PP+CP intercrop at Lunza EPA increased from 22.93 mg/kg pre-incorporation to a peak of 36.35 mg/kg (25.59 to 60.2 ppm at Chinguluwe). Following this, ammonium levels declined slowly but remained above initial concentrations, indicating sustained N release. Systems without residue incorporation showed minimal increases.

Residue incorporation and soil nitrate

Residue incorporation also significantly enhanced soil nitrate levels (**Table 5**). The PP+CP intercrop with residues recorded the highest nitrate concentrations at both sites (Chinguluwe: 12.97 mg/kg; Lunzu: 10.57 mg/kg), whereas the same system without residue incorporation had lower levels (Chinguluwe: 10.62 mg/kg; Lunzu: 8.99 mg/kg). Sole sorghum consistently showed the lowest nitrate levels, reflecting

Table 4. Effects of cropping system and their residue incorporation on soil ammonium.

	Chinguluwe EPA		Lunzu EPA	
	Soil ammonium, mg/kg			
Cropping system	0-20 cm	20-40 cm	0-20 cm	20-40 cm
PP+CP with residues incorporated	43.76	36.54	29.12	23.55
PP+CP with residue removal	31.87	26.92	22.76	18.96
Sole CP with residues incorporated	40.54	33.2	26.95	21.75
Sole PP with residues incorporated	38.03	31.13	26.61	21.8
Sole sorghum with residue removal	20.69	16.68	14.62	11.27
Mean (Soil depth)	34.97	28.89	24.01	19.46
LSD (Soil depth)		1.74		1.11
LSD (Cropping system)		2.76		1.76

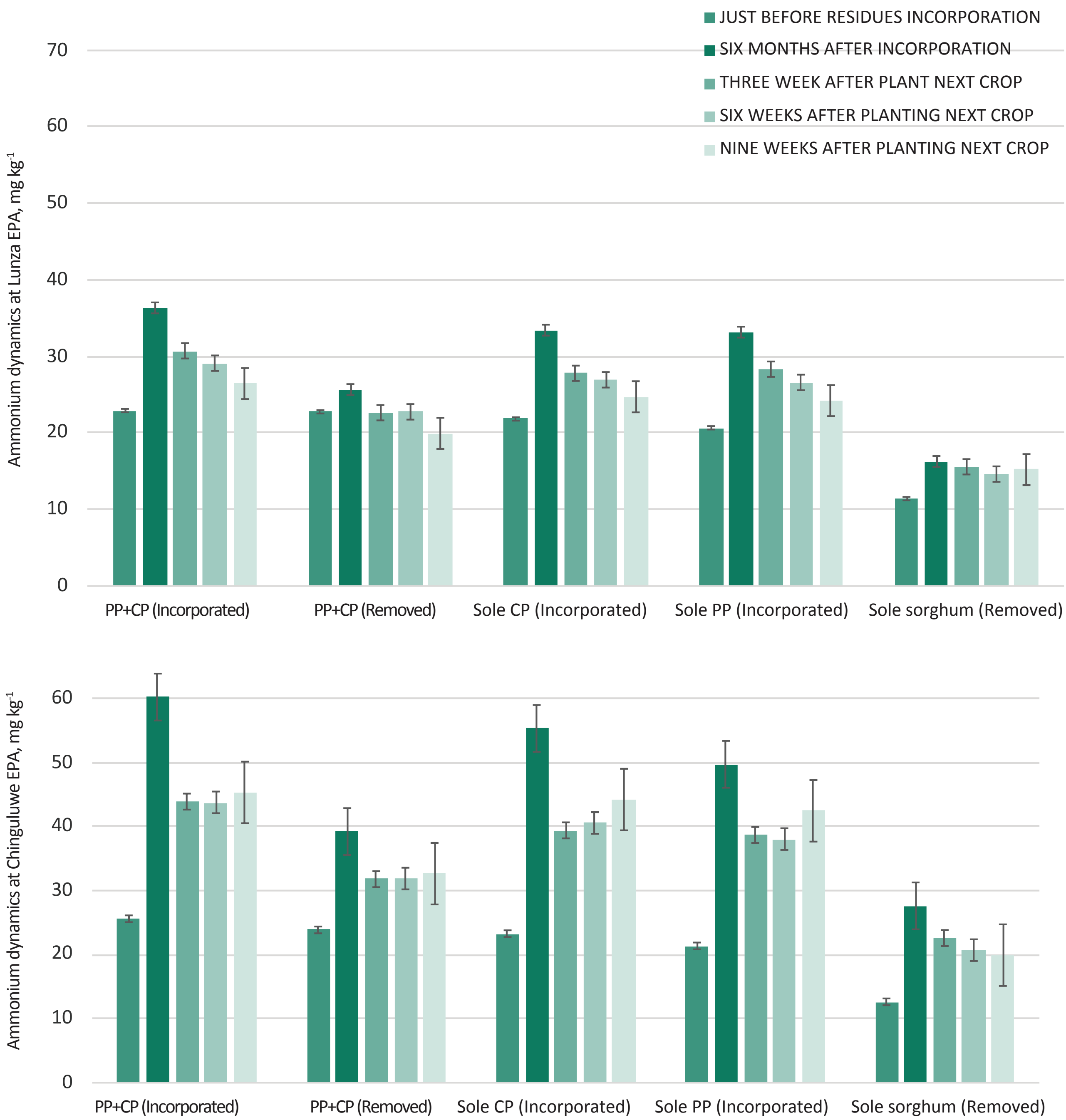

Figure 2. Temporal ammonium dynamics at (top) Lunza and (bottom) Chinguluwe EPAs.

limited contribution to soil N. Nitrate concentrations were higher at 0–20 cm than 20–40 cm, with a significant interaction between soil depth and cropping system, highlighting depth-dependent effects of residue management.

Temporal nitrate dynamics

Over time, nitrate peaked six months after residue incorporation (Chinguluwe: 18.65 mg/kg; Lunzu: 13.60 mg/kg) and declined gradually during subsequent

Table 5. Effects of cropping system and their residues management on soil nitrate.

	Chinguluwe EPA		Lunzu EPA	
	Soil nitrate, mg/kg			
Cropping system	0-20 cm	20-40 cm	0-20 cm	20-40 cm
PP+CP with residues incorp	14.50	11.43	11.78	9.36
PP+CP with residue removal	11.64	9.60	9.88	8.10
Sole CP with residues incorp	13.27	10.94	10.92	8.91
Sole PP with residues incorp	13.01	10.54	10.95	8.66
Sole sorghum with residue removal	9.22	7.92	8.14	6.74
Mean (Soil depth)	12.33	10.08	10.34	8.35
LSD (Soil depth)		0.278		0.168
LSD (Cropping system)		0.439		0.267

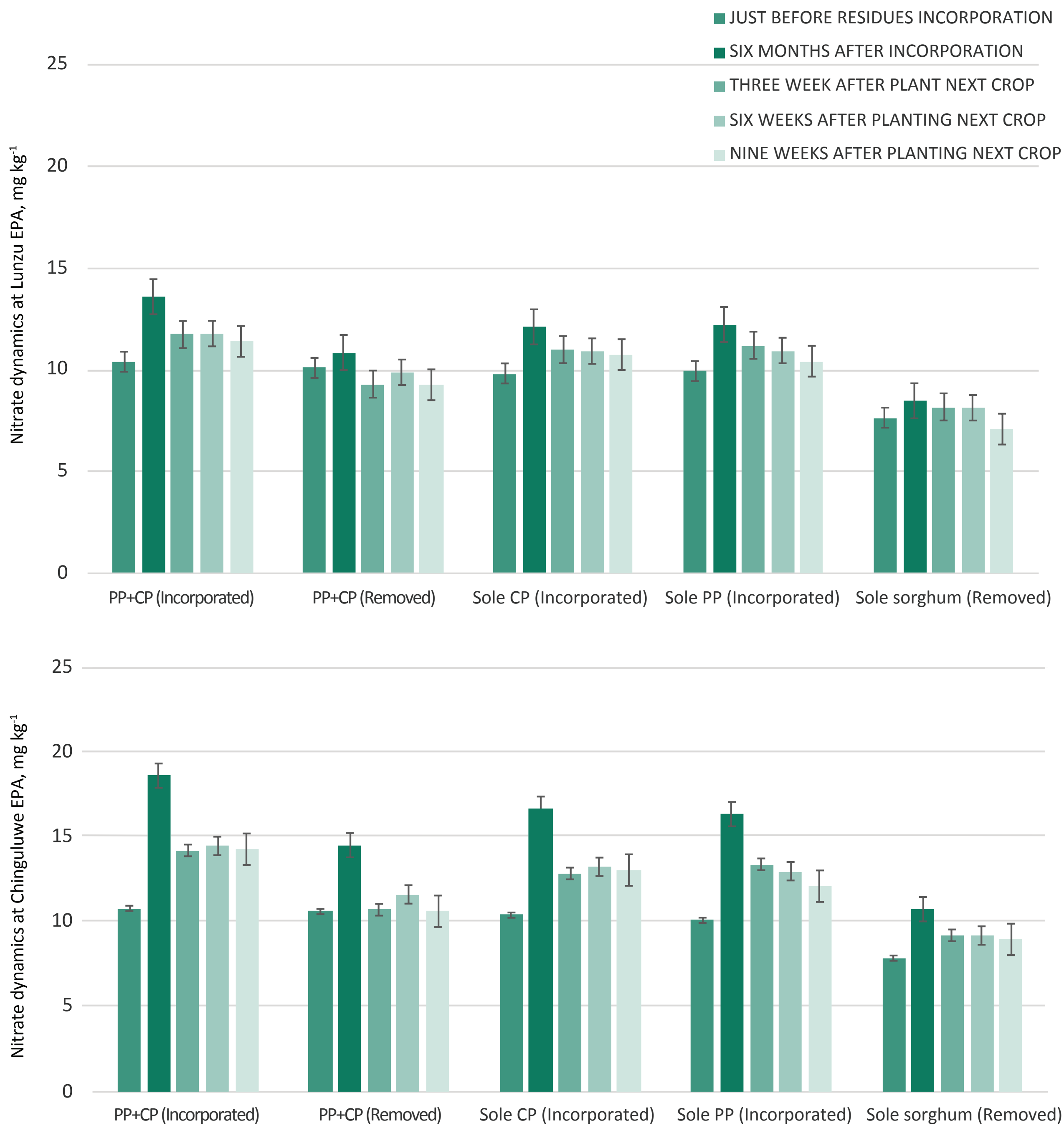

Figure 3. Temporal nitrate dynamics at (top) Lunzu and (bottom) Chinguluwe EPAs.

crop growth (**Fig. 3**). Residue-incorporated systems maintained nitrate above pre-incorporation levels, whereas systems with residue removal exhibited persistently lower nitrate, emphasizing the role of incorporating high N organic matter sources in sustaining soil N availability.

Residue incorporation and total nitrogen

Cropping system, residue management, and soil depth significantly influenced total nitrogen (TN) (**Table 6**). The PP+CP intercrop with residue incorporation consistently recorded the highest TN across both sites (Chinguluwe: 0.306% at 0–20 cm, 0.203% at 20–40 cm; Lunzu: 0.288% and 0.173%, respectively), followed by sole cowpea and sole pigeon pea with residues. Residue removal systems, including sole sorghum, showed the lowest TN, with values declining over time (e.g., PP+CP residue removal: Chinguluwe 0.111% at 0–20 cm). Total N was significantly higher at 0–20 cm compared to 20–40 cm, confirming the importance of surface residues in maintaining N content.

Table 6. Effects of cropping system total soil nitrogen (%) at Chinguluwe EPA and Lunzu EPA.

Cropping system	Chinguluwe EPA		Lunzu EPA	
	Total soil nitrogen, %			
	0-20 cm	20-40 cm	0-20 cm	20-40 cm
PP+CP with residues incorporated	0.306	0.203	0.288	0.173
PP+CP with residue removal	0.111	0.076	0.110	0.073
Sole CP with residues incorporated	0.286	0.176	0.258	0.150
Sole PP with residues incorporated	0.276	0.183	0.265	0.153
Sole sorghum with residue removal	0.083	0.045	0.076	0.036
LSD (Soil depth)		0.010		0.011
LSD (Cropping system)		0.016		0.018

Intercropping, residue incorporation and soil nitrogen dynamics

The results indicate that legume-based intercropping, particularly when coupled with residue incorporation, markedly improves soil N pools. Incorporation of legume residues with low C:N ratios accelerated mineralization and elevated ammonium concentrations, especially in pigeon pea–cowpea systems, where the combined effects of BNF and residue quality enhanced nutrient release (Fuchs et al., 2024; Njira et al., 2017). These findings highlight the pivotal role of residue quality in regulating N cycling (Yan et al., 2020).

Residue incorporation also significantly increased nitrate concentrations compared with residue removal, demonstrating the contribution of decomposed N-rich organic residues to soil fertility (Palm et al., 2001). Nitrate stratification in the 0–20 cm surface layer corresponded with zones of intense microbial and root activity. Vertical stratification concentrated microbial transformations in the top layer (0–20 cm), with nitrate accumulation linked to microbial hotspots (Zhang et al., 2024). Similarly, ammonium and nitrate retention peaked in the top layer (0–20 cm), consistent with enhanced microbial activity and root density under deep subsoiling (Gu et al., 2025). Notably, nitrate and ammonium levels peaked six months after residue incorporation, followed by declines due to plant uptake, leaching, and denitrification (Chen et al., 2014).

Increases in TN further confirm the benefits of intercropping with residue incorporation. Gains are mainly driven by BNF and microbial decomposition, supporting the use of residue incorporation as a sustainable long-term fertility strategy (Abbasi et al., 2015a). Conversely, residue removal led to stagnation or declines in TN, underscoring N-rich residues as vital nutrient inputs in resource-limited systems (Coulibaly et al., 2020).

Residue chemistry strongly influenced decomposition patterns. Legume residues, characterized by low C:N ratios and high N content, decomposed rapidly, leading to faster mineralization (Nicolardot et al., 2001; Palm et al., 2001; Nyabami et al., 2023). Cowpea residues exemplified this. Microbial activity is most efficient when residues approach a 24:1 C:N ratio. High C:N inputs induce immobilization as microbes scavenge soil N, whereas low C:N residues promote mineralization through surplus N release (Gaudel et al., 2024; USDA NRCS, 2011; Mittal, 2011). Incorporating high-quality residues, such as cowpea and pigeon pea, increased TN by stimulating microbial turnover and decomposition (Abbasi et al., 2015b). The positive effects of residue incorporation were amplified in intercropping systems. Legume-based intercrops enriched rhizosphere ammonium and nitrate through BNF and microbial stimulation, thereby improving N availability in such low-input systems (Mokgethoa, 2024). Intercropping also raised soil TN, ammonium, and nitrate concentrations by 14.5% compared to monocropping, while enhancing microbial diversity, (Zhang et al., 2024; Bichel et al., 2017). These outcomes validate intercropping as a sustainable intensification strategy that enhances root-zone utilization and strengthens soil fertility and resilience (Qiu et al., 2025). Residue incorporation consistently outperformed residue removal, with reports of mineral N increasing up to 1.23-fold (Bakht et al., 2009) and TN improving the concentration to between 0.066–0.098% across the 0–20 cm soil layer (Pu et al., 2019). Such improvements extend beyond immediate nutrient cycling, contributing to long-term soil chemical enhancement (Coulibaly et al., 2020).

Overall, the evidence demonstrates that integrating residue incorporation into legume-based intercropping systems improves N cycling via synergistic effects of BNF, residue quality, and microbial processes. This combined approach not only enhances short-term nutrient availability but also builds long-term fertility and resilience, making it a promising strategy for sustainable intensification in smallholder farming systems.

Recommendations

1. **Promote Legume–Legume Intercropping Systems** - Smallholder farmers should be encouraged to adopt cowpea–pigeon pea intercropping as a practical and sustainable strategy for improving N cycling and soil fertility. This system enhances BNF, increases residue N content, and contributes organic matter inputs, thereby improving soil structure, water retention, and nutrient availability.

2. **Encourage Residue Retention and Incorporation** - Residue incorporation should be prioritized over removal or burning, as it ensures continuous N release, enriches soil organic matter, and supports long-term nutrient accumulation. Extension services should provide training on appropriate methods and timing of residue incorporation to maximize N mineralization and soil improvement.

3. **Integrate Intercropping and Residue Management into Climate-Smart Agriculture (CSA) Strategies** - Policymakers and agricultural development programs should embed legume-based intercropping and residue management within Malawi's national CSA framework. This integration will strengthen soil fertility, reduce dependence on inorganic fertilizers, and enhance resilience to drought and land degradation.

4. **Support Research and Long-Term Monitoring** - Further research is needed to assess the long-term effects of legume–legume intercropping and residue incorporation on soil N dynamics, organic C accumulation, and yield sustainability under diverse climatic and soil conditions. Expanding on-farm participatory trials will help refine and adapt intercropping models to local contexts.

Summary

This study demonstrates that cowpea–pigeon pea intercropping, when combined with residue incorporation, is an effective and climate-smart strategy for enhancing N dynamics and improving soil fertility in Malawi's drought-prone smallholder farming systems. The results revealed that intercropping significantly improved residue quality, while increased residue quantity contributed greater biomass and long-term N stabilization. Legume–legume intercropping enhances BNF, residue N enrichment, and soil nutrient cycling efficiency, ultimately leading to improved soil fertility and crop productivity.

Furthermore, the study established that residue incorporation plays a pivotal role in sustaining N availability by promoting gradual mineralization and reducing nutrient losses. Systems that retained and incorporated residues exhibited markedly higher soil ammonium, nitrate, and total N levels compared to residue removal systems. This highlights the importance of maintaining organic matter inputs to support nutrient release, stimulate microbial activity, and restore long-term soil fertility.

Overall, the findings underscore that cowpea–pigeon pea intercropping with residue incorporation offers a low-cost, sustainable, and scalable pathway for rebuilding soil N stocks, enhancing productivity, and strengthening climate resilience in Malawi's smallholder systems. By reducing dependence on synthetic fertilizers, improving N use efficiency, and sustaining soil fertility, this integrated approach provides a practical solution for advancing agricultural sustainability and ensuring food security in drought-affected regions. ■

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When Less is More: Optimizing Fertilizer Use under Water Deficit to Enhance Olive Tree Productivity and Resilience

By Rachid Razouk, Lahcen Hssaini, Yassine Bouslihim and Hakim Boulal

Failing to adjust fertilization may worsen the impact of water stress. *A Moroccan olive study reveals that reasonable reductions in NPK supply under deficit irrigation can sustain high yield levels, fruit physical quality, and olive oil composition. The oil produced under these conditions was richer in health-promoting compounds thus boosting long-term value. The key for growers facing climate change is finding a sustainable balance that enhances tree resilience without severely compromising yield and oil quality.*

Sampling 10-year-old experimental olive orchard, Saiss region, Morocco.

The interaction between plant mineral nutrition and water availability is one of the most critical determinants of crop productivity under changing climatic conditions. Nutrient uptake, transport, and assimilation is altered under water deficit, and nutrient imbalances may, in turn, exacerbate the physiological effects of water stress. Managing these two factors in isolation is therefore insufficient. Their combined optimization is essential for maintaining plant productivity and stability.

Recent studies highlight that well-calibrated nutrient management under moderate water stress can enhance root efficiency, sustain photosynthetic activity, and improve crop quality (Bhattacharya., 2021). Striking this balance, between conserving water and ensuring adequate nutrient supply, represents a key strategy for building plant resilience. Controlled field trials that explore this equilibrium are vital to guide growers toward more sustainable and resource-efficient production systems capable of maintaining yield and quality under climate uncertainty.

Building on this scientific premise, the Olive-FertiClim project was launched as a collaborative initiative between the African Plant Nutrition Institute (APNI) and the National Institute for Agricultural Research (INRA-Morocco). By examining the interplay between water and nutrition, the study sought to define an optimal balance that boosts the tree's resilience, enhances oil quality and value, and provides a sustainable and profitable path forward for Moroccan growers.

Olive was selected as the target crop for this research since it represents a strategic agricultural sector and the heart of Morocco's agricultural landscape, a vital source of livelihood, culture, and rural stability. But today, growers face a complex squeeze from global changes. Climate change is intensifying water scarcity, making every drop of irrigation water more precious than ever (Tanasijevic et al., 2014). At the same time, there remains a knowledge gap on how to properly manage agricultural practices, particularly fertilization strategies under drought conditions, to sustain productivity and quality. Fertilizer efficiency is directly tied to water availability (Erel et al., 2008). Too little water, and the tree cannot absorb the nutrients growers have paid for. Too much irrigation, and those same expensive nutrients can leach away from the roots, wasting money and potentially harming the environment. These intertwined issues pose a direct threat to the resilience of olive growers (Gucci and Caruso, 2011). Addressing them requires practical, field-tested strategies to rationalize fertilizer use, improve water–nutrient interactions, and sustain the production of high-quality, sustainably produced olive oil. In this context, the present study was undertaken to explore practical pathways for optimizing NPK fertilization under different deficit irrigation regimes, thereby contributing to the development of more resilient and resource-efficient olive production systems.

Study description

Conducted over two consecutive growing seasons in Morocco's fertile Saiss region, the experiment was carried out in a 10-year-old private olive orchard planted with the country's predominant olive cultivar, 'Picholine Marocaine'. The orchard was established at a density of 285 trees ha^{-1} (7 × 5 m spacing) on a low-organic-matter soil (0.8%), with moderate levels of available phosphorus (P) (19.9 ppm) and potassium (K) (132 ppm). The study employed a crisscross factorial design arranged in three replicated blocks (**Fig. 1**), to evaluate the combined effects of three different resource management strategies.

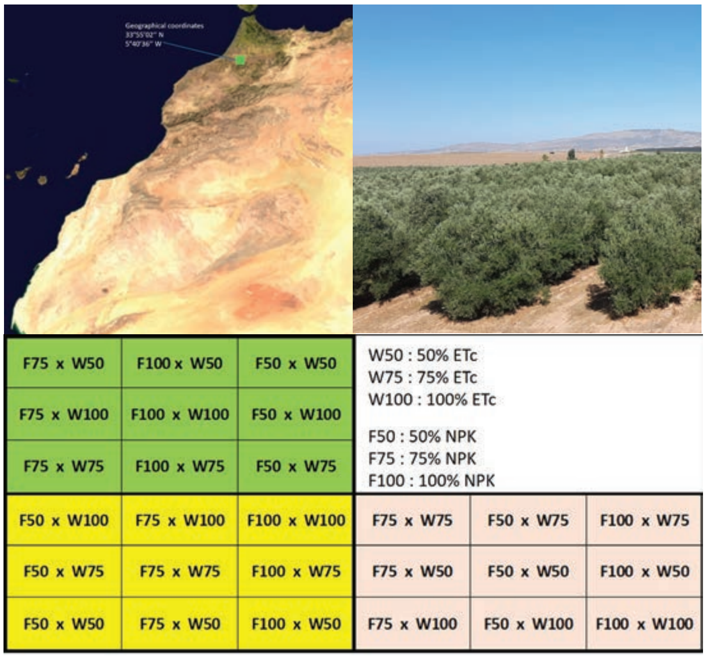

Figure 1. Geographical location of the experimental site and graphical representation of the experimental design showing fertilization (F) and irrigation (W) treatments.

Water Levels: Three irrigation regimes were applied: full irrigation supplying 100% of the crop evapotranspiration (ETc), moderate deficit irrigation at 75% ETc, and severe water stress a 50% ETc.

Fertilizer Levels: Each water level was combined with three distinct NPK fertilization plans. The recommended NPK rates were first calculated for a fully irrigated orchard (100% ETc) targeting a yield of 10 t ha^{-1}, based on soil analysis. Relative to this reference, the treatments consisted of a low dose (50% of the recommended needs), a medium dose (75%), and a high dose (100%).

Throughout the study, the effects of these nine treatment combinations, each replicated three times, were assessed on vegetative growth, yield components, physiological traits indicative of the tree's water and nutritional status, alongside the biochemical characteristics of the olive oil.

Agronomic and physiological responses

The study first quantified the effects of varying irrigation and fertilization levels on key agronomic and physiological parameters. A multivariate analysis of variance (MANOVA) revealed that water level, NPK fertilization rate, and their interaction had statistically significant effects across the range of measured variables. Water availability emerged as the dominant factor influencing productivity, while fertilization showed limited effects, and some variables were significantly affected by their interaction (**Table 1**).

Table 1. MANOVA significance levels for irrigation, fertilization, and their interaction on agro-physiological traits and olive-oil biochemical attributes.

	Irrigation (W)	Fertilization (F)	W x F
Yield and fruit characteristics			
Fruit yield (t ha^{-1})	**	ns	ns
Oil yield (m^3 ha^{-1})	*	ns	ns
Fruit weight (g)	**	*	ns
Oil content (%)	ns	ns	ns
Pulp moisture (%)	**	ns	*
Vegetative growth			
Shoot length (cm Lm^{-1})	ns	ns	ns
Leaf area (cm^2)	ns	ns	ns
Leaf density (mg cm^{-2})	ns	ns	ns
Leaf physiological traits			
Chlorophyll index I (%)	ns	ns	ns
Relative water (%)	ns	ns	ns
gs (mol m^{-2} s^{-1})	***	ns	ns
Cuticular wax (mg g^{-1})	ns	ns	*
Proline (mg g^{-1})	ns	ns	ns
Glycine (mg g^{-1})	ns	ns	***
Soluble sugars (mg g^{-1})	ns	ns	**
Leaf nutrient contents			
Leaf N (%)	***	ns	***
Leaf P (%)	**	ns	ns
Leaf K (%)	***	*	ns
Oil biochemical attributes			
TPC (mg GAE/100 g oil)	***	***	*
TFC (mg CE/100 g oil)	***	**	*
DPPH (%)	**	*	ns
Carotenoid (mg/100 g oil)	***	**	*

***highly significant ($p < 0.001$), **significant ($p < 0.01$), *marginally significant ($p < 0.05$), nsnot significant ($p \geq 0.05$)

Water availability exerted a significant influence on the main yield components. Fruit yield ($p = 0.002$), oil yield ($p = 0.017$), and individual fruit weight ($p = 0.008$) all increased with higher irrigation levels, confirming that water is a key limiting factor for productivity in this olive system. The significant effect on oil yield was primarily driven by the increase in fruit yield, as fruit oil content showed no detectable response. However, NPK fertilization alone had a statistically significant effect only on fruit weight among the yield components ($p = 0.028$), suggesting that nutrient supply influenced the partitioning of assimilates at the fruit level rather than total yield. This finding implies that the effect of fertilization on olive productivity may manifest progressively over the long term, whereas the influence of irrigation on yield was already evident from the first two years of experiment.

According to the ANOVA results, the patterns observed for fruit yield, oil yield, and fruit weight further confirm the dominant influence of irrigation and the modulating role of fertilization (**Fig. 2**). The highest fruit yields were obtained under full irrigation (100% ETc) and moderate water deficit (75% ETc), which performed similarly, with no significant effect of fertilization. Under severe deficit (50% ETc), increasing NPK fertilization to 75% or 100% led to a marked decline in yield, yet productivity could be restored to levels comparable with the 75% ETc regime by reducing fertilization to 50%. A similar trend was observed for fruit weight, except that lowering fertilization at 50% ETc did not improve fruit size, while under full irrigation, higher NPK inputs clearly enhanced it. No significant differences were observed for oil yield, likely because marginal increases in fruit oil content under water deficit compensated for lower fruit production. These findings suggest that the practice of applying full-rate nutrient inputs along with deficit irrigation may exacerbate yield losses.

Vegetative growth parameters, including shoot length, leaf area, and leaf density, were generally less responsive to both irrigation and fertilization. No significant effects were observed for these traits, suggesting that the vegetative growth of 10-year-old trees may be less sensitive to short-term variations in water and nutrient supply. These findings indicate that while water and nutrient management are crucial for fruit development and quality, they exert a comparatively limited immediate effect on canopy growth metrics within the timeframe of this two-season study.

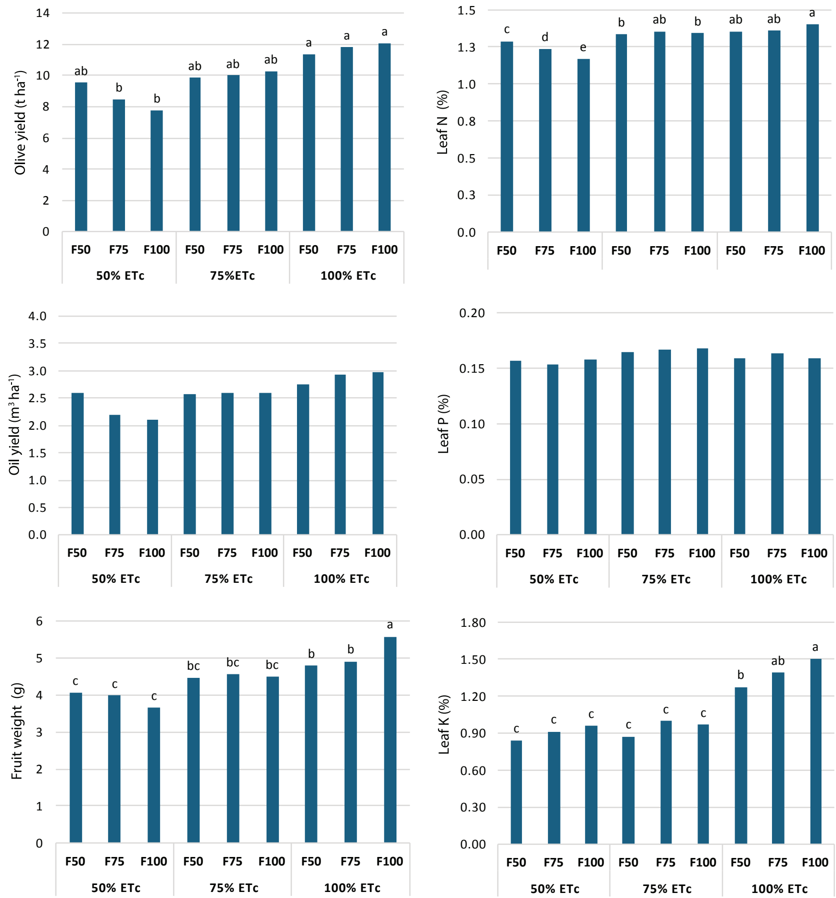

Figure 2. Variation in fruit yield, oil yield, fruit weight, and leaf N, P and K contents in response to the 'Irrigation × Fertilization' treatments.

The ANOVA results further clarify the combined influence of irrigation and fertilization on leaf nutrient concentrations (**Fig. 2**). Leaf N content showed a marked decline under severe water deficit (50% ETc), particularly at higher NPK levels, confirming that nutrient uptake efficiency decreases when water becomes limiting. This reduction likely reflects restricted root activity and possible salt accumulation in the rhizosphere under stress conditions (Brito et al., 2019). Similarly, leaf K was significantly reduced under both moderate (75% ETc) and severe (50% ETc) deficit irrigation. In contrast, leaf P remained statistically unaffected by either factor, suggesting a more stable internal regulation or sufficient baseline availability in the soil. These findings highlight that maintaining full-rate fertilization under water stress can hinder N absorption and disrupt ionic balance, which may, in turn, explain the limited responses observed in yield components.

In contrast, leaf physiological traits displayed diverse responses. Stomatal conductance (gs) was strongly influenced by irrigation ($p < 0.001$), reflecting the trees' immediate response to water availability. Meanwhile, parameters such as cuticular wax content ($p = 0.029$), leaf glycine ($p < 0.001$), and soluble sugar content ($p = 0.005$) were significantly affected by the interaction between irrigation and fertilization, demonstrating that the physiological adaptation of leaves to water stress is modulated by nutrient supply.

Leaf nutrient concentrations were primarily influenced by irrigation levels and their interaction with fertilization. Leaf nitrogen (N) content was significantly affected by irrigation ($p < 0.001$) and the 'irrigation × fertilization' interaction ($p < 0.001$), while leaf P responded only to irrigation ($p = 0.003$) and K was significantly influenced by both irrigation ($p < 0.001$) and fertilization ($p = 0.019$). These results indicate that nutrient uptake and accumulation in leaves are closely tied to water availability, and that fertilization can further modulate nutrient status when considered in combination with irrigation, emphasizing the importance of integrated water–nutrient management for optimal tree performance.

Overall, the findings underscore the predominant role of water availability in shaping olive productivity. Under full irrigation, balanced NPK fertilization appears to enhance the tree's nutritional status, improving fruit weight and potentially supporting long-term stability of both fruit and oil yields. In contrast, under water deficit, the weak fertilization response and absence of significant improvements in yield components indicate that applying full-rate NPK is neither efficient nor agronomically justified. Nutrient management should therefore be aligned with water availability, avoiding excessive input under stress conditions. A moderate fertilization regime, tailored to reduced irrigation, would likely improve nutrient use efficiency, maintain physiological balance, and optimize resource use without compromising sustainability.

Impact on olive oil's biochemical profile and quality markers

This study supports the view that the interplay between controlled water deficits and tailored nutrient applications is a key driver of olive oil quality (Servili et al., 2004). MANOVA results confirmed that irrigation (W), fertilization (F), and their interaction (W×F) significantly influenced the oil's biochemical

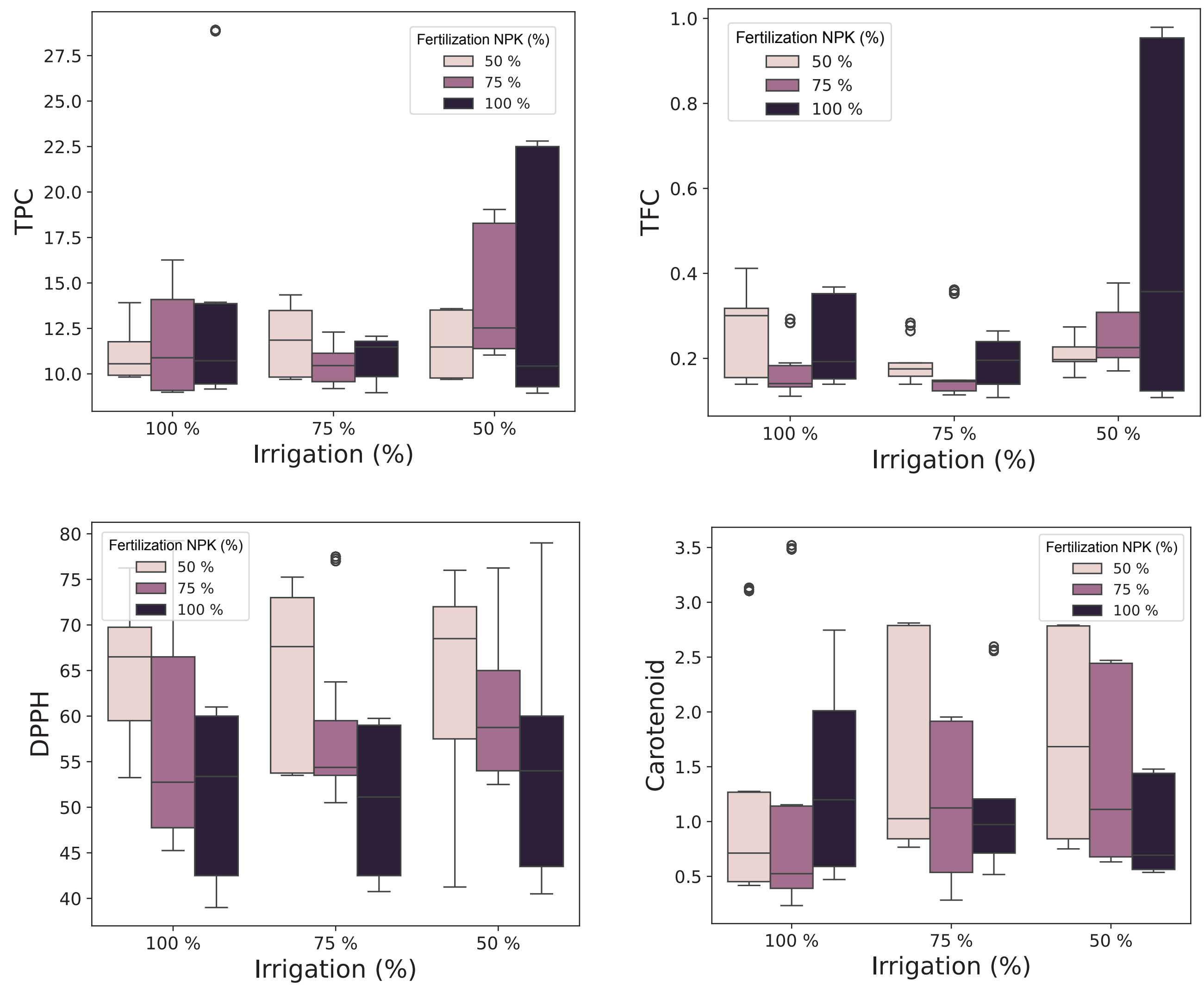

Figure 3. Biochemical attributes of olive oil under different irrigation and fertilization regimes. TPC: Total Phenolic Content, TFC: Total Flavonoid Content. DPPH: antioxidant activity essay using 2,2-diphenyl-1-picrylhydrazyl radicals.

profile (**Table 1**). This was particularly evident in the upregulation of high-value secondary metabolites; for both Total Phenolic Content (TPC) and Total Flavonoid Content (TFC), the combination of severe water stress (50% ETc) and balanced-to-high fertilization (75-100% NPK) produced the highest concentrations (**Fig. 3**), with statistically significant interaction effects (W×F: $p \leq 0.040$) driving increases of up to 30%. However, the study also revealed a more complex metabolic response, where the interplay for other quality markers was different. Maximum antioxidant activity (DPPH) and carotenoid content were achieved with a contrary combination: severe water stress (50% ETc) paired with minimal fertilization (50% NPK).

These divergent biochemical shifts were corroborated at a molecular level using Mid-Fourier Transform Infrared (FTIR) spectroscopy. This analysis provided a chemical fingerprint of the oil based on the raw spectra (**Fig. 4a**). These complex spectra were then quantified by measuring the total integrated spectral area—a measure of the abundance of key chemical bonds associated with oil quality. As shown in **Fig. 4b**, this analysis revealed a clear interaction where increasing fertilization, combined with adequate water, maximized this molecular quality marker. The main effects plot (**Fig. 4c**) further clarified that while lower irrigation tended to decrease the area, higher fertilization strongly increased it, reinforcing the importance of their combined management. This molecular evidence validates the observed quality improvements, confirming that the specific interplay between water and nutrient levels—not just stress alone—is a key mechanism for producing a biochemically superior final product.

Summary

This research clarifies a critical dichotomy between agronomic strategies that maximize yield and those that

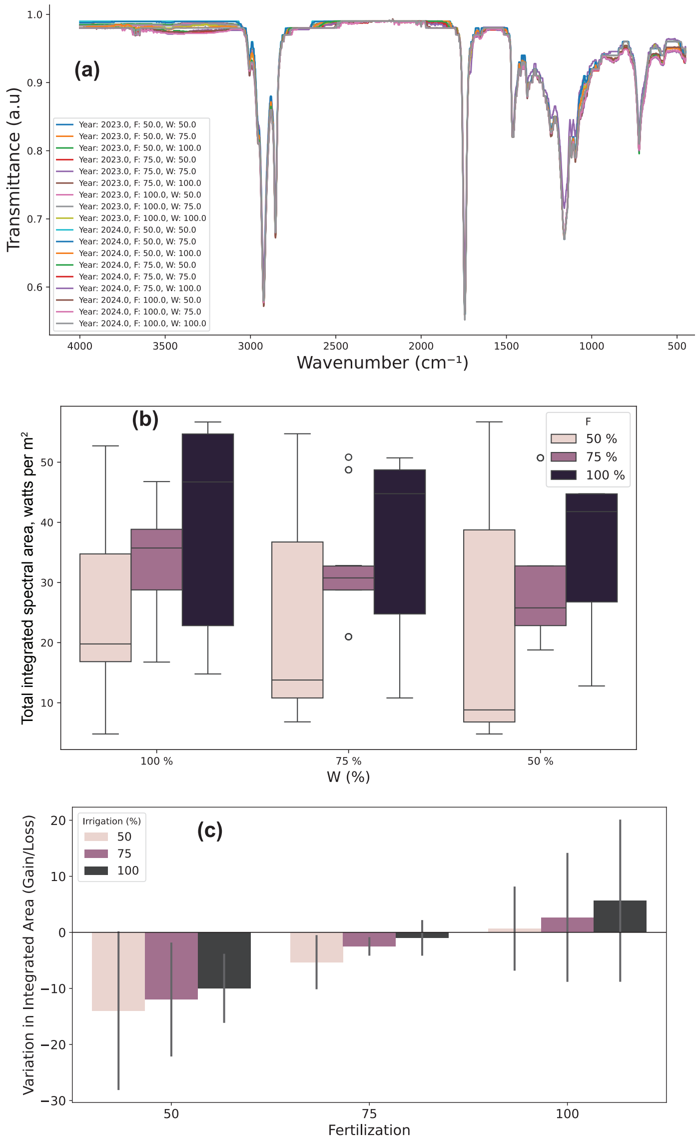

Figure 4. Molecular Confirmation of Oil Quality via FTIR. (a) Raw FTIR spectra for all treatment combinations, providing a chemical fingerprint of the oil. (b) The primary analysis showing the effect of fertilization (F) and irrigation (W) on the integrated spectral area. A larger area indicates a greater abundance of key chemical bonds linked to higher quality. The data reveals a strong positive trend with increasing fertilization, modulated by water availability. (c) Bar chart showing the main effects (gain/loss) of each factor, isolating the strong positive influence of high fertilization on the oil's molecular structure.

optimize the biochemical quality of olive oil. While severe water stress (50% ETc) is the most potent driver for accumulating high-value bioactive compounds like phenols, it poses quantifiable risks to long-term orchard viability and yield stability. The data clearly shows that growers must navigate a trade-off between maximizing oil quality and maintaining tree health. Therefore, the study identifies moderate deficit irrigation (75% ETc) combined with balanced fertilization (75% NPK) as the optimal, sustainable compromise for the 'Picholine Marocaine' cultivar under these conditions. Under more severe water limitation (50% ETc), imposed by restricted water availability, the study further suggests reducing NPK fertilization to 50% to sustain the best possible yield performance and overall tree function under such stressful conditions. These scientifically validated regimes effectively mitigate the severe yield penalties and vegetative decline associated with more extreme stress, while simultaneously securing a significant enhancement in phenolic content, a key driver of market value and consumer preference. This data-driven approach offers a practical and resilient strategy for olive growers, enabling them to enhance product value and build climate resilience by aligning sustainable resource management with economic profitability. However, it is important to emphasize that the experimental values reported here are not direct recommendations for farmers but rather indicative trends suggesting the need to reduce fertilization under water deficit, a level that remains to be confirmed over the long term. ■

Acknowledgement

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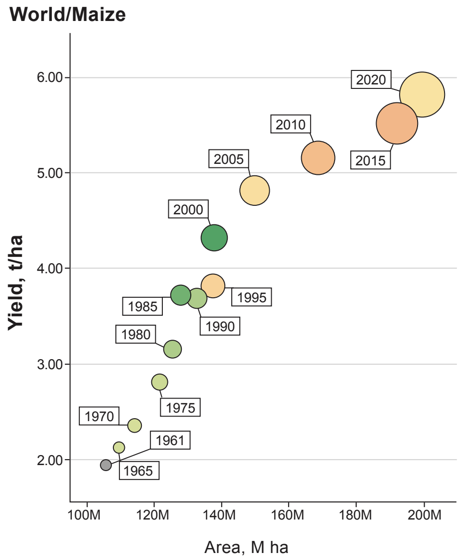
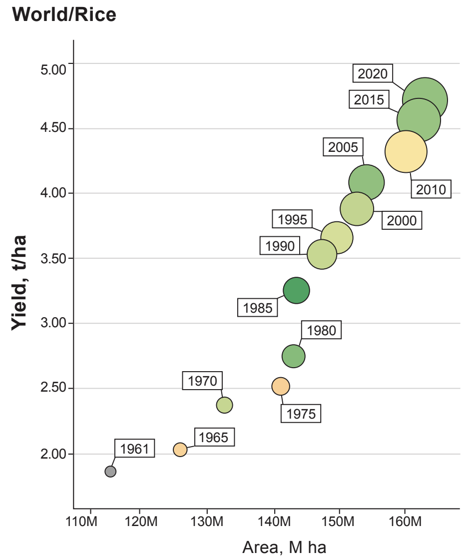
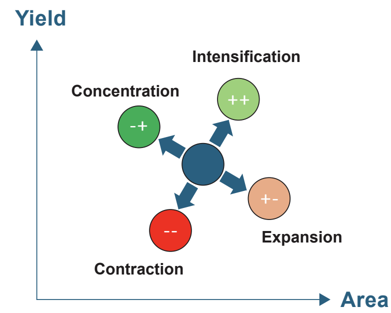
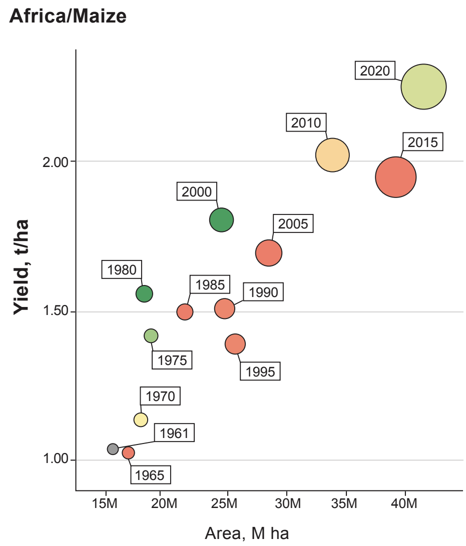
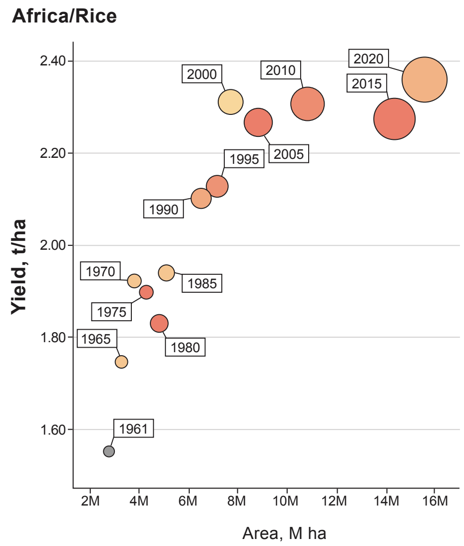
Agricultural Development in Maize and Rice: Yield-Area Dynamics, Agronomic Strategies, and 4R Nutrient Management Opportunities











The **size** of the bubble indicates annual production.

The **colour** of the bubble indicates the degree of **intensification** or **extensification** in the five year period leading to it.

GrowthCharts

FAOStat Data

*The diagram divides trends into four quadrants: Top Right (Light Green): Yield growth and area expansion (intensification with expansion). Top Left (Darker Green): Yield growth and area contraction (intensification with land sparing). Bottom Right (Lighter Red): Yield decline/stagnation and area expansion (extensification). Bottom Left (Darker Red): Yield decline and area contraction (contraction). **World Maize:** Early years (1961–1990) fall in the top-right quadrant (yield and area growth), shifting to the bottom-right (slower yield growth, area expansion) in 2005–2020. **Africa Maize:** Early years (1961–1990) are in the bottom-right quadrant (area expansion, yield stagnation), shifting toward the top-right (yield and area growth) in 2010–2020. **World Rice:** Most years are in the top-right quadrant, reflecting balanced intensification and moderate area growth. **Africa Rice:** Remains in the bottom-right quadrant (area expansion, limited yield growth) throughout.*

The diagram shows that intensification (green quadrants) dominates World Rice and early World Maize, while extensification (red quadrants) is prominent in Africa Rice and recent World Maize. Contraction (bottom-left) and land sparing (top-left) are not strongly evident.

Four pathways of agricultural change. Agricultural systems grow and evolve in different ways depending on pressures such as population demand, input availability, land resources, and climate conditions. Four key strategies describe these shifts:

1. **Intensification** – Increasing crop yield per hectare using more or better inputs (e.g., fertilizer, improved seeds, mechanization);
2. **Extensification** – Expanding the total cultivated area, often into marginal lands or new regions;
3. **Concentration** – Focusing agricultural production in fewer regions or larger farms to achieve economies of scale, and
4. **Contraction** – Reducing cultivated area due to land degradation, urbanization, or shifts to other land uses like conservation.

These strategies don't occur in isolation; they often overlap and shift over time. The bubble charts for maize and rice production across the World and Africa (1961–2020) reflect how these strategies play out. Each chart plots average yield (t/ha) against average area (million ha), with bubble size showing production and color indicating recent development patterns (green = intensification, red/orange = extensification). A quadrant diagram helps place each trend in the broader conceptual framework.

Region/Crop	Trend	Interpretation
World/Maize	Early years show clear intensification (1960–1990), with yield growing from 2 to 4 t/ha. From 2005–2020, yield growth slows while area expands to 200M ha – a shift toward extensification.	Technological improvements drove early gains (hybrids, fertilizer, irrigation). As productivity gains plateau, expansion into new areas (e.g., Brazil, Eastern Europe) compensates. This may threaten forest and savannah ecosystems.
World/Rice	Continuous intensification from 2 to 4.5 t/ha, with only modest area increases (110 M to 160 M ha).	Reflects heavy investment in improved varieties (e.g., IRRI's Green Revolution), irrigation, and input use. Limited land availability forced productivity gains through intensification.
Africa/Maize	Historically extensive: area grew from 15 M to 40 M ha; yield rose slowly from 1.0 to 2.0 t/ha. Since 2010, green bubbles appear, signs of intensification.	This turning point suggests adoption of better seeds and fertilizers. However, challenges remain including poor access to inputs, weak extension systems, and climate variability.
Africa/Rice	Yield rose modestly (1.6 to 2.4 t/ha), but area exploded from 2 M to 16 M ha – a clear case of extensification.	Expansion without matching productivity gains raises alarms. Rainfed and upland systems dominate, often with limited input use or irrigation. Risk of land degradation and nutrient depletion is high.

Region/Crop	Agronomic Focus	Crop Nutrition Challenges
World/Maize	Fine-tuning high-input systems; shifting to sustainable intensification.	Risks of nutrient oversupply in intensive systems; nutrient mining in extensive frontier zones.
World/Rice	Maintaining high yield while managing water and input efficiency.	High NPK demand; potential for nutrient leaching or runoff in flooded systems. Micronutrient imbalances (e.g., Zn, Fe) common.
Africa/Maize	Expanding use of improved seeds, site-specific nutrient management.	Widespread N and P deficiencies; low organic matter; limited fertilizer access and affordability.
Africa/Rice	Need for irrigation development, resilient varieties, and integrated practices.	Poor fertilizer use efficiency; soil acidification; expansion into low-fertility or degraded soils.

Region/Crop	How the 4Rs Can Help Farmers
World/Maize	Use fertilizer types that match crop needs (Right Source). Apply the right amount, avoid too much or too little (Right Rate). Add fertilizer when the crop can use it best (Right Time). Place it near the roots, not scattered across the field (Right Place).
World/Rice	Include small nutrients like zinc in fertilizer blends. Use small doses several times instead of one big dose. Deep place fertilizers to reduce loss in wet soils. Combine chemical fertilizers with organic matter (e.g., manure).
Africa/Maize	Choose blended fertilizers and local organic inputs suited to local soils. Use microdosing when and where proven effective, small, cost-effective applications. Apply around rainfall and early growth stages. Place fertilizer close to seeds to increase effect.
Africa/Rice	Choose blended fertilizers and local organic inputs suited to local soils. Adapt fertilizer types for rainfed vs. irrigated rice. Research with farmers on how and when to apply fertilizer. Fertilize at planting and before flowering. Deep place or target fertilizer to avoid loss in runoff.

Observed Trends in Maize and Rice Production

The above Tables summarize key patterns observed in the maize and rice production data from 1961–2020, including the agronomic implications.

Agronomic and Crop Nutrition Implications: Understanding the agronomic meaning behind these patterns is essential for guiding future action. Where yield gains stall and land expands, agronomic efficiency suffers. Where intensification dominates, soil health and input use must be managed carefully to avoid long-term decline.

The Role of 4R Nutrient Stewardship: The 4R Nutrient Stewardship Framework, Right Source, Right Rate, Right Time, and Right Place, offers a proven, flexible approach to managing fertilizer use efficiently and sustainably. The Table below outlines how the 4Rs can help improve productivity and sustainability for maize and rice in both global and African contexts:

Comparative Highlights

Rice (Global vs. Africa)

Global rice systems have matured through decades of research, irrigation and intensive management, delivering reliable productivity from the same land base. The chart displays consistent yield growth (from 2.0 to 4.5 t/ha) and moderate area expansion (from 110 M to 160 M ha) over 1961–2020, with mostly green bubbles indicating sustained intensification. 1961–2020 (Intensification): Rice production has primarily increased through yield improvements (e.g., from 2.0 t/ha in 1961 to 4.5 t/ha in 2020), with a smaller increase in area (110M to 160M ha). The persistent green bubbles suggest a focus on boosting productivity per hectare, likely due to land and water constraints in rice-growing regions (e.g., Asia). While the area grew modestly, the dominant strategy has been intensification, reflecting efforts to meet rising food demand without vastly expanding farmland. This focus on intensification highlights the need to maximize output in regions with limited land availability. However, it may strain resources like water and soil, necessitating sustainable practices to maintain long-term productivity.

African rice systems are still reliant on land expansion. Productivity remains low due to minimal irrigation, input use, and support infrastructure. Africa must move beyond area expansion toward sustainable intensification. Better seed-fertilizer combinations, and 4R-based training can accelerate this transition. The chart shows moderate yield growth (from 1.6 to 2.4 t/ha) and significant area expansion (from 2M to 16M ha) over 1961–2020, with red bubbles in recent years indicating persistent extensification. 1961–2020 (Extensification): Rice production has relied heavily on expanding cultivated area (2M to 16M ha), with yields increasing only modestly (1.6 to 2.4 t/ha). Red bubbles suggest that output growth has come from bringing more land into cultivation rather than boosting productivity, possibly due to barriers like limited irrigation or technology adoption. Persistent Extensification (2010–2020): Unlike maize, rice continues to prioritize area expansion over yield gains, reflecting challenges in intensifying production for this water-intensive crop. This reliance on extensification raises sustainability concerns, such as land degradation or deforestation. Promoting sustainable intensification, e.g., through improved water management or high-yielding varieties, could help balance production and environmental goals.

Maize (Global vs Africa)

Global maize began with heavy intensification, but recent shifts to extensification show signs of ecological strain. The chart shows a steady increase in both yield (from 2.0 to 6.0 t/ha) and area (from 100 M to 200 M ha) between 1961 and 2020. Early years (1961–1990) feature green bubbles, indicating intensification, while later years (2005–2020) show orange bubbles, signaling a shift to extensification. 1961–1990 (Intensification): During this period, maize production grew primarily through higher yields (e.g., from 2.0 t/ha in 1961 to 4.0 t/ha in 1990), with moderate area expansion (100 M to 140 M ha). This suggests technological advancements, such as improved seeds, fertilizers, and irrigation, drove productivity gains, aligning with intensification. 2005–2020 (Extensification): In recent decades, yield growth slowed (reaching 6.0 t/ha by 2020), while the area expanded significantly (to 200M ha). The shift to orange bubbles indicates that production increases relied more on cultivating additional land rather than further boosting yields, reflecting extensification. This may stem from yield improvements hitting a plateau or new land becoming available. Implications: The transition from intensification to extensification suggests that early productivity gains were technology-driven, but recent growth has leaned on land expansion, potentially raising environmental concerns like deforestation or habitat loss.

Africa's maize sector is showing early success in intensifying, a promising trend, if supported by access to appropriate technologies and inputs. Africa is at a crucial inflection point. 4R strategies can help smallholders improve yields and protect soil resources, especially under increasing climate stress. The chart shows slow yield growth (from 1.0 to 2.0 t/ha) and significant area expansion (from 15 M to 40 M ha) over 1961–2020. Early years (1961–1990) feature yellow to red bubbles (extensification), while recent years (2010–2020) show yellow to green bubbles, indicating a shift toward intensification. 1961–1990 (Extensification): Initially, maize production grew through area expansion (15 M to 30 M ha), with yields stagnating at 1.0–1.5 t/ha. Red bubbles suggest that output increased by cultivating more land rather than improving productivity, possibly due to limited access to technology or infrastructure. 2010–2020 (Shift to Intensification): In recent years, yields rose to 2.0 t/ha, while area growth slowed (35 M to 40 M ha). The shift to green bubbles indicates a focus on improving productivity, likely through better farming practices, seeds, or fertilizers, reflecting efforts to enhance food security. The move toward intensification is a positive step for sustainable agriculture in Africa, reducing reliance on land expansion. However, challenges like input access and climate variability may limit further progress.

Toward Smarter, More Sustainable Growth

Maize and rice exhibit distinct trajectories. World Maize shifted from intensification to extensification, reflecting a move from technology-driven gains to land-based growth. World Rice has maintained intensification, likely due to land constraints in key regions. These differences highlight how crop biology, growing conditions, and socio-economic factors shape agricultural strategies. The graphs illustrate more than just maize and rice data, they highlight development pathways, agronomic trade-offs, and future priorities. They underscore that: Intensification must now focus on sustainability, especially for systems nearing ecological limits. Extensification, still common in Africa, can no longer be the primary growth model. It risks soil degradation, biodiversity loss, and declining marginal returns. 4R Nutrient Stewardship presents a powerful, adaptable solution: helping farmers grow more with less, use fertilizers wisely, and protect their land. Across contexts, smart nutrition strategies grounded in local conditions can make agriculture more productive, profitable, and sustainable. In the face of growing food demand, changing climate, and limited land, the 4Rs offer a clear roadmap to feed the future, without exhausting it. In Africa, both maize and rice historically leaned on extensification, but maize is now shifting toward intensification, possibly due to its status as a staple crop and targeted investments. ■

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GrowthCharts ***GrowthCharts briefly explores perspectives on key issues, concepts and needs related to the development of African agriculture. For more visit: www.apni.net/GrowthCharts***

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#Maize #Coted'Ivoire #4RNutrientStewardship #BMPs #APNI #METFPA #OCP #sharegrowingafrica

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