

Soil Fertility Status and Nutrient Interrelationships in Alkaline, Sandy Soils of the Maknossa Agriculture Project, southwest Libya: Implications for Cereal and Fodder Production

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Abstract

Sandy, alkaline soils under center-pivot irrigation are increasingly relied upon to expand cereal and fodder production in arid regions, yet their capacity to supply phosphorus (P) and micronutrients is poorly characterized at the farm scale. This study assessed soil fertility status and nutrient interrelationships across 20 georeferenced topsoil samples (0–20 cm) collected from center-pivot fields at the Maknossa Agriculture Project, Wadi Utba, Fezzan, Libya, an area cultivated with wheat, barley, and fodder crops. Soils were analyzed for pH, electrical conductivity (EC), and macro- and micronutrients using standard extraction procedures (Olsen-P, 1 M ammonium nitrate for exchangeable cations, 0.05 M EDTA for micronutrients) with inductively coupled plasma analysis. Descriptive statistics, Nutrient Index (NI) and Soil Fertility Index (SFI) classification, Spearman correlation, and principal component analysis (PCA) were used to characterize fertility status and its underlying drivers. Soils were consistently alkaline (mean pH 8.10 ± 0.14) with excessive calcium (2304.6 ± 347.98 ppm) but only marginal available phosphorus (11.55 ± 4.38 ppm). Soil pH correlated negatively with both available P ($r_s = -0.776$, $p < 0.001$) and Zn ($r_s = -0.763$, $p < 0.001$). Three principal components explained 79.0% of total variance, representing an alkalinity axis (pH, Ca, K), a trace-metal/salinity axis (Cu, Mn, Na), and a mixed nitrogen–carbonate axis. Despite these constraints, the SFI classified 70% of samples as having High overall fertility and the remaining 30% as Moderate, indicating that productive potential is present but chemically constrained. An operational phosphorus fertigation model incorporating a pH-scaled alkaline-fixation correction factor is proposed to guide site-specific triple superphosphate (TSP) application, replacing an earlier, methodologically flawed version of the model. These findings support a shift from broadcast phosphorus application toward acidified fertigation and foliar micronutrient management at this and comparable arid, calcareous, center-pivot sites.

Keywords: arid soils; phosphorus fixation; nutrient index; soil fertility index; principal component analysis; fertility management

ملخص

التربة الرملية القلوية التي تُروى بنظام الري المحوري أصبحت تعتمد بشكل متزايد للتوسع في إنتاج الحبوب والأعلاف في المناطق الجافة، إلا أن قدرتها على توفير الفوسفور والعناصر الغذائية الدقيقة لا تزال غير موصوفة بدقة. هدفت هذه الدراسة إلى تقييم حالة خصوبة التربة والعلاقات المتبادلة بين العناصر الغذائية في 20 عينة من التربة السطحية (2-30 سم)، جمعت من 20 حقل من مجموع 25 دائرة زراعية في مشروع مكنوسة الزراعي، ويتم زراعة القمح والشعير والخبث والحمضيات ومحاصيل الأعلاف. تم تحليل التربة من حيث درجة الحموضة، والتوصيل الكهربائي، والعناصر الغذائية الكبرى والصغرى باستخدام إجراءات استخلاص قياسية (أولسن-بي، نترات الأمونيوم 1 مولار للأيونات الموجبة القابلة للتبادل، EDTA 0.05 مولار للعناصر الغذائية الدقيقة باستخدام جهاز تحليل البلازما المقترنة حثيًا ICP). استُخدمت الإحصاءات الوصفية، ومؤشر المغذيات (NI)، ومؤشر خصوبة التربة (SFI)، ومعامل ارتباط سبيرمان، وتحليل المكونات الرئيسية (PCA) لتوصيف حالة الخصوبة والعوامل المؤثرة فيها. كانت التربة قلوية باستمرار (متوسط الرقم الهيدروجيني 8.10 ± 0.14) مع فوسفور متاح هامشياً (11.55 ± 4.38 ppm). Soil pH correlated negatively with both available P ($r_s = -0.776$, $p < 0.001$) and Zn ($r_s = -0.763$, $p < 0.001$). Three principal components explained 79.0% of total variance, representing an alkalinity axis (pH, Ca, K), a trace-metal/salinity axis (Cu, Mn, Na), and a mixed nitrogen–carbonate axis. Despite these constraints, the SFI classified 70% of samples as having High overall fertility and the remaining 30% as Moderate, indicating that productive potential is present but chemically constrained. An operational phosphorus fertigation model incorporating a pH-scaled alkaline-fixation correction factor is proposed to guide site-specific triple superphosphate (TSP) application, replacing an earlier, methodologically flawed version of the model. These findings support a shift from broadcast phosphorus application toward acidified fertigation and foliar micronutrient management at this and comparable arid, calcareous, center-pivot sites.

مع وفرة في الكالسيوم (347.98 ± 2304.6 جزء في المليون) ولكن بكمية ضئيلة من الفوسفور المتاح (4.38 ± 11.55 جزء في المليون). اوجد ان ارتباط الرقم الهيدروجيني للتربة عكسياً بكل من الفوسفور المتاح ($r_s = -0.776, p < 0.001$)، والزنك ($r_s = -0.763, p < 0.001$)، فسُرت ثلاث مكونات رئيسية 79.0% من التباين الكلي، ممثلةً محور القلوية (الرقم الهيدروجيني، الكالسيوم، البوتاسيوم)، ومحور العناصر النزرة/الملوحة (النحاس، المنغنيز، الصوديوم)، ومحور مختلط للنيتروجين والكربونات. على الرغم من هذه القيود، صُنّف مؤشر خصوبة التربة 70% (SFI) من العينات على أنها ذات خصوبة عالية، والنسبة المتبقية (30%) على أنها ذات خصوبة متوسطة، وبإمكانها ان تكون منتجة، ولكنها مقيدة كيميائياً. يُقترح نموذج تشغيلي لتسميد الفوسفور بالري، يتضمن عامل تصحيح لتثبيت القلوية، لتوجيه تطبيق سماد السوبر فوسفات الثلاثي (TSP) في مواقع محددة، ليحل محل نسخة سابقة من النموذج تعاني من عيوب منهجية. تدعم هذه النتائج التحول من تطبيق الفوسفور بشكل عشوائي إلى التسميد الحمضي بالري وإدارة المغذيات الدقيقة الورقية في هذا الموقع والمواقع المماثلة الجافة والجيرية التي تعتمد على الري المحوري.

الكلمات المفتاحية: التربة الجافة؛ تثبيت الفوسفور؛ مؤشر المغذيات؛ مؤشر خصوبة التربة؛ تحليل المكونات الرئيسية؛ إدارة الخصوبة

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Introduction

Global expansion of cereal and fodder production into arid and semi-arid marginal land has intensified interest in the fertility management of sandy, calcareous soils under mechanized irrigation. Center-pivot systems are widely used to bring such land into production because they allow precise water delivery across large, otherwise unfarmable areas, but the same soils that make pivot irrigation attractive coarse-textured, low in organic matter, and high in free calcium carbonate also constrain nutrient availability in ways that are easy to overlook when fertilizer programs are based on total nutrient content rather than plant-available fractions.

Alkalinity is the central agronomic challenge in these environments. In calcareous soils, phosphorus reacts with calcium and magnesium to form increasingly insoluble calcium phosphate and hydroxyapatite phases as pH rises, so that a large share of applied mineral phosphorus is effectively removed from the plant-available pool (Adnan et al., 2025). The same high-pH, high-carbonate conditions widely suppress zinc availability, and zinc deficiency is now recognized as one of the most common micronutrient constraints on wheat production in calcareous soils worldwide (Kalayci et al., 1999). Because total soil-nutrient content can appear adequate even when the plant-available fraction is severely limited, this pattern is sometimes described as a form of "hidden hunger" in otherwise mineral-rich arid soils.

Robust diagnosis of this problem requires more than single-nutrient soil tests. Classical approaches such as the Nutrient Index (Parker et al., 1951) classify each nutrient into low, medium, or high fertility bands relative to established critical levels, offering a simple field-interpretable summary. More recent work has combined these indices with multivariate statistical tools most commonly principal component analysis (PCA) to identify the underlying chemical "systems" driving fertility variation across a landscape, an approach that has been applied successfully in arid environments ranging from the Nile Delta (Shokr et al., 2025) to the Tambo Valley of coastal Peru (Poma-Chamana et al., 2025). These studies consistently find that alkalinity- and salinity-related components, rather than any single deficient nutrient, explain the majority of variance in soil fertility across arid, irrigated landscapes.

The Maknossa Agriculture Project is a center-pivot development in the Wadi Otba area of the Fezzan region of southwestern Libya, growing wheat, barley, and fodder crops (primarily alfalfa) across a cluster of pivot-irrigated fields on deep, sandy, calcareous soils. As with many

recently developed arid farming systems, fertilizer programs at the site have historically been guided by total nutrient testing without an integrated, multivariate diagnostic framework, and a preliminary internal assessment of the site identified a methodological problem in its own fertilizer recommendation model: an aggregate summary statistic (the sample minimum) had been mistakenly carried through the calculation as if it were an individual soil sample, generating an operationally meaningless phosphorus recommendation. Correcting this error, and more fundamentally, building a phosphorus recommendation model that explicitly accounts for alkaline fixation rather than treating soil-test phosphorus as directly equivalent to fertilizer requirement, motivated the present analysis.

This study therefore had four objectives: (1) to characterize the current status of macro- and micronutrients across 20 soil samples from the Maknossa center-pivot fields; (2) to classify overall fertility status using Nutrient Index and Soil Fertility Index approaches; (3) to identify the statistical and multivariate relationships between soil pH, electrical conductivity, and nutrient availability; and (4) to develop and apply a corrected, pH-scaled phosphorus fertilization recommendation model that accounts for alkaline fixation, replacing the earlier flawed calculation.

Materials and Methods

Study Area and Research Design

This study adopted a cross-sectional, site-characterization design to assess soil physico-chemical properties, quantify the status of extractable macro- and micronutrients, and generate actionable, site-specific nutrient management recommendations for the Maknossa Agriculture Project. The Project is located at latitude 26.4170 North and longitude 13.5620 East, south of the city of Sabha, southwestern Libya, at a distance of (150 km). The total area of the project is (5306) hectares for growing grains under the circular center pivot irrigation system, distributed over (73) fields, with the area of the fields ranging between 40-60 hectares. The site is representative of arid, sandy, calcareous landscapes brought into cultivated with wheat, barley, and fodder (primarily alfalfa) under a shared irrigation and management regime. A cross-sectional design was chosen because the primary aims were to describe current fertility status and examine the statistical relationships between soil pH, electrical conductivity (EC), and nutrient availability across the pivot fields, rather than to track temporal change; capturing all samples within a single campaign also reduces confounding from seasonal fluctuations in soil moisture and mineralization, improving comparability across sampling locations.

Twenty georeferenced, composite topsoil samples (2–30 cm, the primary rooting zone for wheat, barley, and alfalfa and the standard depth for developing fertilizer recommendations in agronomic practice) were collected from center-pivot fields distributed across the project area, identified in the accompanying site map by pivot number. Each composite sample combined several subsamples from within the sampled field, homogenized prior to laboratory analysis.

Laboratory Analysis

In the laboratory, all soil samples were air-dried at room temperature, gently crushed, and passed through a 2 mm sieve prior to analysis. Soil pH and EC were determined in a 1:2.5 soil: water suspension using a calibrated pH meter and conductivity meter, respectively, following internationally accepted protocols for agronomic soil testing.

Available phosphorus (P) was determined using the Olsen extraction, which employs 0.5 M sodium bicarbonate at pH 8.5 to mobilize phosphate from carbonate-rich, neutral-to-alkaline soils (Olsen et al., 1954). The Olsen method was selected because it is the most appropriate test for soils with pH values at or above neutrality, where acid extractants tend to underestimate plant-available P and where the NaHCO_3 extractant's action in depressing dissolved calcium helps release Ca-bound phosphate that would otherwise be missed.

Exchangeable potassium (K), magnesium (Mg), calcium (Ca), and molybdenum (Mo) were extracted using 1 M ammonium nitrate (NH_4NO_3), a neutral salt solution widely used to displace weakly adsorbed and exchangeable cations without extensively dissolving primary minerals, providing a realistic estimate of the readily available pool that can contribute to crop uptake over a growing season (Stuanes et al., 1984).

Micronutrients copper (Cu), iron (Fe), zinc (Zn), and manganese (Mn) were extracted with 0.05 M ethylenediaminetetraacetic acid (EDTA) disodium salt, a chelating agent that complexes metal cations and releases them from exchange sites and organic complexes into solution. EDTA-based extraction is a long-established method for estimating the plant-available fraction of trace metals across a wide range of soils, including near-neutral and calcareous soils where these micronutrients are prone to precipitation (Lindsay & Norvell, 1969), and it underlies the same equilibrium chemistry used in the related DTPA soil test subsequently developed for Zn, Fe, Mn, and Cu (Lindsay & Norvell, 1978).

Total carbonate (CaCO_3) was determined by acid-neutralization titration. All extracts were analyzed using inductively coupled plasma (ICP) optical emission spectrometry, which allows simultaneous determination of multiple elements in a single run with high precision, improved throughput, and consistent internal calibration across macro- and micronutrients an important consideration when constructing composite indices and multivariate models from a modest number of samples.

Quality assurance followed standard laboratory practice, including method blanks, duplicate samples, and calibration checks at regular intervals during each analytical batch.

Data Processing and Statistical Analysis

Descriptive statistics (mean, standard deviation, minimum, and maximum) were computed for all physico-chemical and nutrient variables using the full, cleaned dataset of 20 samples (Table 1). A Nutrient Index (NI) approach (Parker et al., 1951) was used to classify each nutrient into Low, Medium, or High fertility bands based on established critical thresholds; a per-sample Soil Fertility Index (SFI) was then computed as the mean classification score (Low = 1, Medium = 2, High = 3) across nine key nutrients (N, P, K, Ca, Mg, Fe, Mn, Zn, Cu), banded into Low (< 1.67), Moderate (1.67–2.33), and High (> 2.33) overall fertility classes.

Spearman rank correlation coefficients were calculated between soil pH and EC and each nutrient, appropriate given the modest sample size and non-normal distribution of several variables, to test the hypothesis that pH- and salinity-mediated processes govern nutrient availability at this site. Principal component analysis (PCA) was applied to thirteen standardized physico-chemical variables (pH, EC, Ca, Mg, K, N, P, Fe, Mn, Zn, Cu, CaCO_3 , Na) to identify the latent factors underlying fertility variation, following the general multivariate framework used in comparable arid-soil fertility assessments (Poma-Chamana et

al., 2025; Shokr et al., 2025). All statistical analyses were performed in Python (pandas, SciPy, scikit-learn).

Phosphorus Fertigation Model with Alkaline Fixation Correction

An operational phosphorus recommendation was developed to translate each sample's Olsen-P value into a fertigation-ready triple superphosphate (TSP, 46% P₂O₅) requirement. In earlier versions of this analysis, an aggregate summary statistic (the dataset minimum) was inadvertently carried through the recommendation calculation as though it were an individual field sample, generating a fertilizer recommendation (52.4 kg/ha TSP) that corresponded to no real, identifiable location. That error has been corrected in the present analysis: the operational recommendation is now computed only for the 20 real, identified soil samples, and any descriptive statistic (mean, minimum, maximum) is reported separately as a summary of that per-sample table, never as a stand-in for a sample itself (see Results and Supplementary Table S1).

A second, more fundamental limitation of the earlier model was addressed at the same time: the original calculation treated the phosphorus deficit relative to a sufficiency threshold as directly equivalent to the fertilizer-P requirement, with no adjustment for the fact that a large share of applied phosphorus in alkaline, calcareous soil is fixed as insoluble calcium phosphate before it becomes available to the crop (Adnan et al., 2025). The revised model therefore incorporates an explicit, pH-scaled P-availability reduction (fixation) factor. For each sample, the phosphorus deficit was calculated as the difference between a sufficiency threshold of 15 ppm Olsen-P (a commonly used critical level for wheat and barley) and the measured soil-test P value, floored at zero. This deficit was converted to an elemental phosphorus requirement using a soil-mass factor of 2.6 kg element per hectare per ppm deficit (2–30 cm depth, bulk density 1.3 Mg m⁻³), then to P₂O₅ using the standard 2.29 conversion factor. This base P₂O₅ requirement was then multiplied by a fixation factor scaled to each sample's own pH: 1.3× at pH 7.5–7.9, 1.6× at pH 8.0–8.2, and 1.8× at pH ≥ 8.3, reflecting the progressively greater proportion of applied P expected to precipitate as calcium phosphate at higher pH (Adnan et al., 2025). The corrected P₂O₅ requirement was finally converted to kg TSP per hectare by dividing by the 46% P₂O₅ content of TSP.

This fixation factor is a literature-consistent heuristic rather than a value empirically calibrated against crop response at this specific site, and this limitation is addressed explicitly in the Discussion.

Results

Descriptive Soil Fertility Status

Across the 20 sampled fields, soils were consistently alkaline, with pH ranging narrowly from 7.90 to 8.40 (mean 8.10 ± 0.14) and no sample falling below neutrality. Calcium was excessive at every site (mean 2304.60 ± 347.98 ppm), while available phosphorus was low to marginal (mean 11.55 ± 4.38 ppm, range 5.0–23.0 ppm), sitting close to or below the 15-ppm sufficiency threshold used for wheat and barley in this analysis. Electrical conductivity was generally low but showed a wide range (0.52–3.52 dS/m), indicating localized salinity accumulation at a small number of pivot fields rather than a uniform site-wide constraint. Full descriptive statistics for all measured parameters are given in Table 1.

Table 1. Descriptive statistics for physico-chemical properties and macro- and micronutrient concentrations across 20 soil samples from the Maknossa Agriculture Project.

Parameter	Mean	SD	Minimum	Maximum
pH	8.10	0.14	7.90	8.40
EC (dS/m)	1.04	0.78	0.52	3.52
CEC (meq/100g)	5.83	0.99	3.60	7.50
Ca (ppm)	2304.60	347.98	1519.0	2954.0
Mg (ppm)	150.35	35.04	83.0	221.0
K (ppm)	262.20	85.01	90.0	403.0
N (ppm)	288.55	165.37	83.0	568.0
P (ppm)	11.55	4.38	5.0	23.0
Fe (ppm)	22.45	18.85	2.0	57.0
Mn (ppm)	66.10	21.84	37.0	115.0
Zn (ppm)	1.92	1.05	0.6	3.9
Cu (ppm)	1.01	0.41	0.4	1.9
B (ppm)	1.73	1.53	0.9	7.6
Mo (ppm)	0.28	0.06	0.2	0.4
S (ppm)	38.35	43.81	8.0	142.0
Na (ppm)	82.25	20.15	51.0	140.0
CaCO ₃ (%)	2.35	2.81	0.0	9.0

Nutrient Index Classification

Nutrient Index classification (Table 2) confirmed phosphorus as the most consistently limiting macronutrient: 35% of samples fell in the Low class and only 5% in the High class, the weakest overall profile of any nutrient assessed. By contrast, calcium, magnesium, manganese, copper, and boron were classified as High in most samples, consistent with the site's alkaline, calcareous character. Iron showed a notably bimodal pattern (35% Low, 55% High), suggesting spatial heterogeneity in redox conditions or organic matter distribution across the pivot fields rather than a uniform micronutrient constraint.

Table 2. Nutrient Index (NI) classification of soil samples (percentage of samples in each fertility class, n = 20).

Nutrient	Low (%)	Medium (%)	High (%)
N	15	45	40
P	35	60	5
K	10	50	40
Ca	0	15	85
Mg	0	25	75
Fe	35	10	55
Mn	0	0	100
Zn	0	25	75
Cu	0	10	90
B	0	20	80

Soil Fertility Index

The composite Soil Fertility Index (SFI), which integrates classification scores across nine key nutrients per sample, placed 70% of samples in the High overall fertility class and the remaining 30% in the Moderate class, with no sample classified as Low. This indicates that, notwithstanding the phosphorus and localized iron constraints identified above, the site's aggregate nutrient status is fundamentally sound; the practical challenge lies in the availability

of specific nutrients chiefly phosphorus and, by extension, zinc rather than in an overall nutrient deficit.

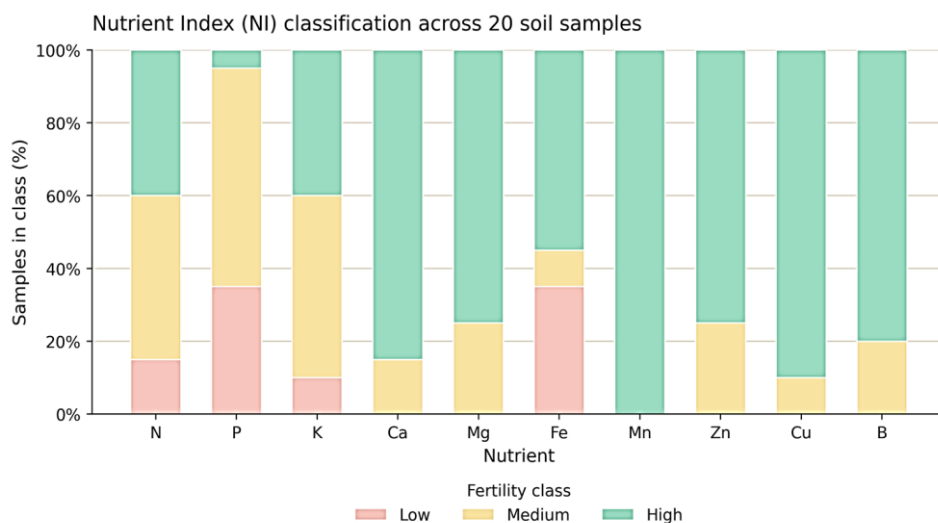


Figure 1. Nutrient Index (NI) classification of ten macro- and micronutrients across 20 soil samples from the Maknossa Agriculture Project.

Correlations Between Soil Reaction and Nutrient Availability

Spearman correlation confirmed strong, statistically significant associations between soil pH and nutrient availability (Table 3; full correlation matrix in Figure 2). Phosphorus showed the strongest negative association with pH of any nutrient tested ($r_s = -0.776$, $p < 0.001$), followed closely by zinc ($r_s = -0.763$, $p < 0.001$), consistent with the well-established antagonism between soil alkalinity and the availability of both nutrients in calcareous soils (Adnan et al., 2025; Kalayci et al., 1999). Calcium, magnesium, sulfur, and sodium all correlated positively with pH, reflecting the shared geochemical origin of alkalinity and base-cation accumulation at this site. Electrical conductivity correlated strongly with both sulfur and sodium, consistent with localized secondary salinization at a subset of pivot fields rather than a site-wide process.

Table 3. Selected statistically significant Spearman correlations between soil pH, electrical conductivity (EC), and nutrient concentrations ($n = 20$).

Soil property	Nutrient	Spearman's rho	p-value
pH	N	-0.505	0.023
pH	P	-0.776	<0.001
pH	Ca	0.610	0.004
pH	Mg	0.503	0.024
pH	Zn	-0.763	<0.001
pH	S	0.704	<0.001
pH	Na	0.580	0.007
EC	S	0.688	<0.001
EC	Na	0.597	0.006

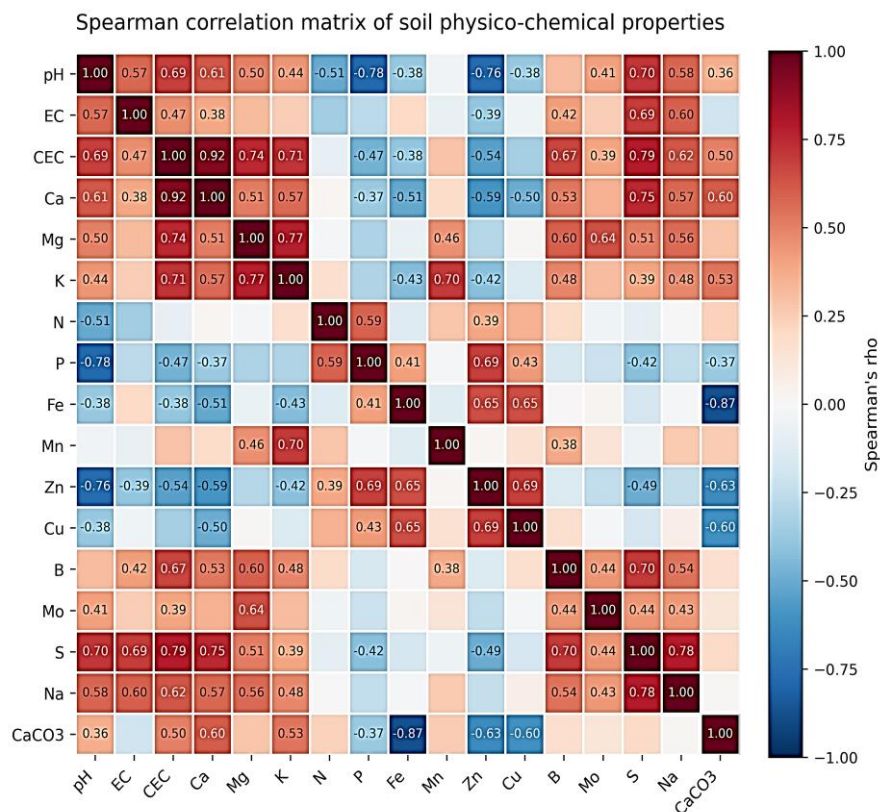


Figure 2. Spearman correlation matrix of soil physico-chemical properties across 20 samples from the Maknossa Agriculture Project.

Principal Component Analysis

Principal component analysis of thirteen standardized physico-chemical variables produced three components with eigenvalues supporting retention, together explaining 79.0% of total variance. The first component (PC1, 37.1% of variance) was dominated by positive loadings for calcium, potassium, pH, magnesium, and carbonate, and negative loadings for zinc, phosphorus, and iron, and is interpreted as an alkalinity axis directly reflecting the pH-driven antagonism between base-cation accumulation and micronutrient/phosphorus availability described above. The second component (PC2, 22.8% of variance) was dominated by copper, manganese, sodium, magnesium, and iron, representing a combined trace-metal and secondary-salinity axis. The third component (PC3, 19.1% of variance) loaded most strongly on electrical conductivity, nitrogen, and carbonate, and is best interpreted as a mixed nutrient-management/carbonate axis rather than a single clean process. Sample scores on the first two components (Figure 3) show a broad spread along the alkalinity axis, with several high-pH, high-carbonate samples (e.g., 67, 68, 84) clearly separated from lower-pH, higher-phosphorus samples (e.g., 14, 23, 74).

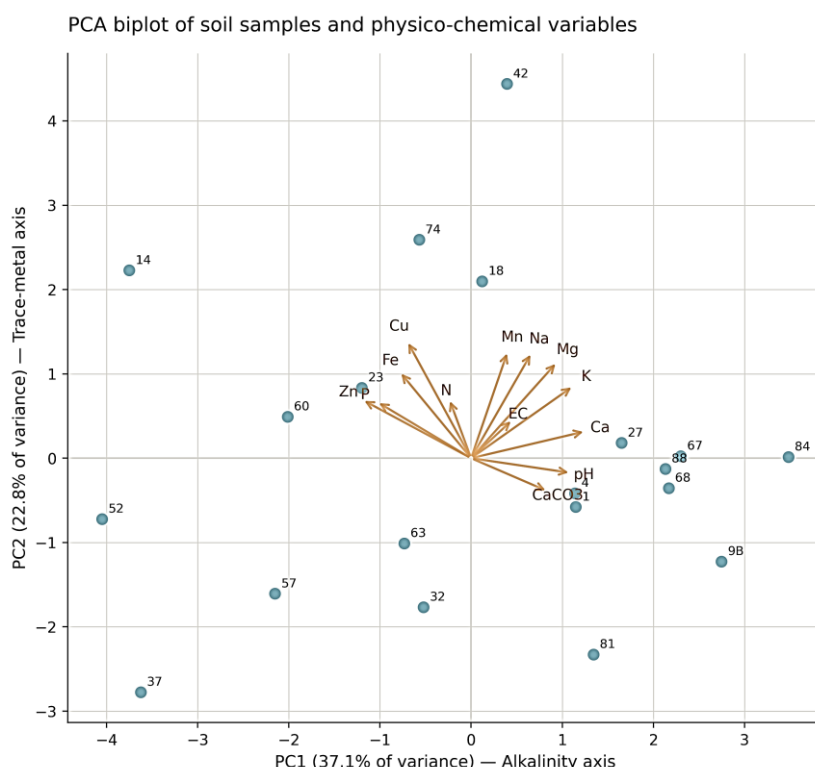


Figure 3. Principal component analysis (PCA) biplot of 20 soil samples and thirteen physico-chemical variables.

Corrected Phosphorus Fertigation Recommendation

Applying the corrected, pH-scaled phosphorus fertigation model (see Materials and Methods) to the 20 reals, identified soil samples, four samples (20%; fields 14, 52, 60, and 74) already met or exceeded the 15-ppm Olsen-P sufficiency threshold and required no supplemental phosphorus. The remaining 16 samples required a corrected triple superphosphate (TSP) application ranging from 20.7 to 233.0 kg/ha. Across all 20 samples, the mean recommended TSP application was 86.0 ± 70.9 kg/ha (median 64.7 kg/ha; interquartile range 36.2–129.5 kg/ha). This range and central tendency are reported here strictly as descriptive statistics of the per-sample recommendations; no aggregate statistic (mean, minimum, or maximum) is itself treated as a fertilizer recommendation for an actual field, correcting the earlier version of this model in which the dataset minimum was mistakenly applied as though it were a real sample, yielding an erroneous, unattributable recommendation of 52.4 kg/ha TSP. The complete, sample-level recommendation table is provided in Supplementary Table S1.

Discussion

The results confirm that alkalinity, rather than any absolute shortage of soil minerals, is the primary constraint on fertility at the Maknossa site. Every sample fell within a narrow, strongly alkaline pH band, and calcium was excessive throughout, consistent with the well-documented chemistry of calcareous arid soils in which phosphorus and several micronutrients are progressively fixed into insoluble forms as pH rises (Adnan et al., 2025). The strength of the pH–phosphorus and pH–zinc correlations observed here ($r_s = -0.776$ and -0.763 , respectively) closely mirrors findings from other calcareous, wheat-growing systems, where the same antagonism between soil alkalinity and phosphorus/zinc availability has repeatedly been identified as the central agronomic bottleneck (Kalayci et al., 1999).

The PCA results reinforce this interpretation while adding useful nuance. Rather than a single deficient nutrient, three semi-independent chemical systems an alkalinity axis, a trace-metal/salinity axis, and a mixed nitrogen–carbonate axis jointly account for the majority (79.0%) of variance in soil chemistry across the site. This pattern is broadly consistent with multivariate fertility assessments from other arid, irrigated landscapes, where alkalinity- and salinity-related components similarly dominate the first two or three principal components (Poma-Chamana et al., 2025; Shokr et al., 2025). Practically, this means that a fertility management program built around a single amendment (for example, phosphorus fertilizer alone) is unlikely to be sufficient; interventions need to address pH and localized salinity in parallel with nutrient supplementation.

The relatively favorable Soil Fertility Index result 70% of samples classified as High overall fertility, with the remainder Moderate and non-Low might at first appear to sit in tension with the marginal phosphorus status and strong pH-driven antagonisms described above. The two findings are not actually in conflict: the SFI is a composite index averaged across nine nutrients, most of which (Ca, Mg, Mn, Cu, B) are abundant at this site, so a single constrained nutrient such as phosphorus is diluted within the composite score. This is precisely the situation the Nutrient Index breakdown by individual nutrient (Table 2) is designed to reveal, and underscores why a composite fertility index should always be interpreted alongside, rather than instead of, nutrient-specific classification.

The corrected phosphorus fertigation model directly addresses a methodological problem identified in the previous version of this analysis, in which the phosphorus deficit relative to a sufficiency threshold was treated as numerically equivalent to the fertilizer-P requirement, with no allowance for the substantial share of applied phosphorus that is fixed into unavailable forms in alkaline, calcareous soil before it can be taken up by the crop. By scaling the fertilizer correction to each sample's own measured pH, the revised model produces markedly higher recommended TSP rates for the site's most alkaline fields (up to 233.0 kg/ha at pH 8.4) than a naive deficit-based calculation would suggest, consistent with published findings that phosphorus fertilizer requirements in calcareous soils rise substantially with increasing lime and pH (Adnan et al., 2025). The earlier error in which the dataset minimum was carried through the calculation as though it were an actual field sample producing an unattributable, operationally meaningless 52.4 kg/ha recommendation has been eliminated; the corrected model computes and reports recommendations only for real, identified soil samples, with descriptive statistics reported separately and explicitly labeled as such.

Limitations

Several limitations should be considered when applying these findings. First, the pH-scaled fixation factor (1.3–1.8×) is a literature-consistent heuristic rather than a coefficient empirically calibrated against crop response trials at this specific site; validating and refining this factor against actual yield and tissue-nutrient response to fertigation at Maknossa would substantially strengthen the operational model. Second, the dataset comprises 20 samples from a single sampling campaign, which is adequate for a site-level diagnostic snapshot but limits the ability to characterize seasonal variability or to support strong spatial generalization across the full pivot-irrigated area. Third, sampling design details (exact coordinates, replication, and timing relative to the cropping calendar) were not fully documented in the source materials, which somewhat constrains formal assessment of spatial dependence. Finally, the Soil Fertility Index,

like any composite indicator, can obscure a specific single-nutrient constraint; it should continue to be reported alongside, not in place of, nutrient-specific Nutrient Index classification.

Conclusion

Soils at the Maknossa Agriculture Project are alkaline and calcium-rich throughout, with phosphorus and, to a lesser extent, zinc availability constrained by pH-driven fixation rather than by any absolute shortage of soil minerals. Three principal components alkalinity, trace-metal/salinity, and a mixed nitrogen–carbonate axis jointly explain most of the fertility variation across the site's center-pivot fields. A corrected, pH-scaled phosphorus fertigation model, which explicitly accounts for alkaline fixation and is applied only to real, identified soil samples, provides a more defensible basis for site-specific triple superphosphate recommendations than the uncorrected model used previously. These findings support a shift toward acidified fertigation, foliar zinc and boron supplementation, and continued monitoring of localized salinity, as the most promising near-term management responses at this and comparable arid, calcareous sites.

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Conflict of Interest

The author declares that there are no conflicts of interest.

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Supplementary Material

Table S1. Sample-Level Phosphorus Fertilization Recommendations

The table below reports the corrected, pH-scaled phosphorus fertilization recommendation for each of the 20 reals, identified soil samples individually. No aggregate or summary statistic (mean, minimum, or maximum) is included as a row in this table; the mean, standard deviation, median, and interquartile range of the TSP recommendation across all 20 samples are reported in the Results section (Corrected Phosphorus Fertilization Recommendation) as descriptive statistics only and should not be applied as a fertilizer recommendation for any individual field.

Table S1. Sample-level phosphorus deficit, fixation factor, and corrected triple superphosphate (TSP) recommendation for all 20 soil samples.

Field / sample	Soil-test P (ppm)	pH	P deficit (ppm)	Fixation factor	Corrected P ₂ O ₅ (kg/ha)	TSP (kg/ha)
1	13.0	8.0	2.0	1.6	19.1	41.4
4	12.0	8.1	3.0	1.6	28.6	62.1
9B	7.0	8.2	8.0	1.6	76.2	165.7
14	23.0	7.9	0.0	1.3	0.0	0.0
18	11.0	8.1	4.0	1.6	38.1	82.8
23	11.0	7.9	4.0	1.3	31.0	67.3
27	12.0	8.1	3.0	1.6	28.6	62.1
32	14.0	8.1	1.0	1.6	9.5	20.7
37	12.0	7.9	3.0	1.3	23.2	50.5
42	12.0	8.1	3.0	1.6	28.6	62.1
52	18.0	8.0	0.0	1.6	0.0	0.0
57	9.0	8.1	6.0	1.6	57.2	124.3
60	16.0	8.0	0.0	1.6	0.0	0.0
63	9.0	8.1	6.0	1.6	57.2	124.3
67	5.0	8.4	10.0	1.8	107.2	233.0
68	6.0	8.4	9.0	1.8	96.5	209.7
74	16.0	8.1	0.0	1.6	0.0	0.0
81	7.0	8.2	8.0	1.6	76.2	165.7
84	8.0	8.2	7.0	1.6	66.7	145.0
88	10.0	8.2	5.0	1.6	47.6	103.5