JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(11), 64–76
https://doi.org/10.12911/22998993/225255
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.05.27
Accepted: 2026.09.15
Published: 2026.10.01

Engineering sulfate potassium nutrient pathways as a nature-based solution for productivity recovery and externality mitigation in degraded humid-tropical ultisol agroecosystems

Susilawati[1*], M. Umar Harun[2], Marlina[2], Marieska Verawaty[3], Kelvin Rizky Aryaduta Sembiring[2], Suwandi[4], Rahmat Hidayatulah[2]

[1] Department of Agroecotechnology, Faculty of Agriculture, Universitas Sriwijaya, South Sumatra 30662, Indonesia
[2] Department of Agronomy, Faculty of Agriculture, Universitas Sriwijaya, South Sumatra 30662, Indonesia
[3] Department of Biology, Faculty of Maths and Natural Science, Universitas Sriwijaya, South Sumatra 30662, Indonesia
[4] Department of Plant Protection, Faculty of Agriculture, Universitas Sriwijaya, South Sumatra 30662, Indonesia
* Corresponding author's e-mail: susilawati@fp.unsri.ac.id

ABSTRACT

Humid-tropical ultisols supporting smallholder horticulture in Southeast Asia are widely recognised as degraded agroecosystems whose biogeochemical functioning has been disrupted by accelerated cation leaching, sulfur depletion following reduced atmospheric S deposition, and decades of chloride-loaded fertilisation. From an ecological engineering perspective, restoring the productive capacity of these soils requires interventions that simultaneously address nutrient cycling, soil-microbiome connectivity, and avoidance of off-site externalities, rather than yield optimisation alone. This study evaluated potassium sulfate (K_2SO_4) as an ecologically engineered substitute for potassium chloride (KCl) in a degraded humid-tropical ultisol of Indralaya Selatan, Ogan Ilir, South Sumatra, Indonesia, using shallot (*Allium cepa* var. *aggregatum* L.) as a sentinel crop. A randomised complete block design with four K_2SO_4 doses (0, 60, 90, 120 kg ha^{-1}) and three replications (n = 12) was implemented across an eight-week growing season. Fourteen plant-level state variables describing canopy, photosynthetic and harvest-organ traits were monitored and combined with site-level inputs to estimate avoided chloride load and net sulfate input to the agroecosystem. Multivariate ordination (PCA, 63.1% cumulative variance) positioned the 90 kg ha^{-1} treatment in the high-functioning quadrant aligned with bulb dry weight, shoot dry weight, bulb volume and chlorophyll, while supraoptimal dosing (120 kg ha^{-1}) shifted system state back toward control, consistent with the self-organising response expected of ecologically engineered nutrient pathways. Pearson connectivity analysis revealed a coherent yield-component cluster (bulb diameter–bulb dry weight, r =.909, p <.01) interpretable as a functional ecological module mediated by K^+-driven turgor and S-dependent structural integrity. An OLS model (R^2 =.827) is proposed as a non-destructive ecological monitoring tool for in-field state assessment. Substitution of K_2SO_4 at 90 kg ha^{-1} for an equivalent K-rate of KCl avoided an estimated ~32 kg Cl^- ha^{-1} season^{-1} entering the rooting zone and added ~16 kg S ha^{-1} to the soil S pool, quantifying a tangible nature-based-solution benefit. The findings advance an ecologically engineered nutrient-pathway framework chloride-free, dual K–S supply, dose-bounded by ecosystem self-organisation, and coupled to non-destructive monitoring for the restoration of productive function in degraded humid-tropical ultisol agroecosystems.

Keywords: degraded ultisol restoration, chloride externality avoidance, agroecosystem self-organisation, tropical smallholder agroecology.

INTRODUCTION

Shallot (*Allium cepa var. aggregatum* L.) is a globally significant Allium crop and a strategic horticultural commodity across Southeast Asia, where it serves simultaneously as a daily culinary staple, a source of bioactive organosulfur compounds (allicin, quercetin, flavonols) of recognised nutraceutical value, and a major source of cash income for smallholder farming households (FAO, 2024; Sagar et al., 2022). Indonesia ranks among the world's leading shallot producers, with national output exceeding 1.87 million tonnes harvested from approximately 104,000 hectares (FAO, 2024). The crop's strategic position in the Indonesian food system is reinforced by its short growing cycle (≈ 60–70 days), its compatibility with the smallholder land-tenure structure that characterises upland horticulture, and its consistent year-round market demand (Muarif et al., 2022; Tiemann and Sabine, 2023). Despite this strategic importance, however, Indonesia's national average productivity of approximately 9.4 t ha^{-1} remains substantially below the genetic yield potential of 20–25 t ha^{-1} achievable under optimised nutrient and soil management (FAO, 2024; Susanti et al., 2024). This persistent productivity gap constrains both national food-system resilience and the livelihood security of the smallholder households that produce the bulk of the national crop, underscoring the need for nutrient-management strategies that can recover productive function while remaining feasible at the smallholder scale.

The productivity gap described above is most acutely expressed in the humid-tropical ultisol landscapes of Sumatra, which dominate the upland geography of Indonesia's principal shallot-producing provinces and exhibit the classical signatures of an ecologically degraded soil: acidic reaction, low cation exchange capacity, accelerated leaching of base cations under > 2,000 mm annual rainfall, kaolinite-dominated clay fixation of potassium, and progressive depletion of soil organic matter and sulfur pools (Chen et al., 2024; Hasanuzzaman et al., 2018; Susanti et al., 2024). When such soils are placed under intensive horticultural cropping, their depleted biogeochemical state is further pressured by chloride-loaded conventional fertilisation predominantly potassium chloride (KCl) which compounds salinisation risk, suppresses sulfur-dependent secondary metabolism in Allium crops, and exports reactive chloride loads downward into shallow groundwater under the prevailing high-rainfall regime (Hartono et al., 2023; Wilmer et al., 2022). The conventional response incremental adjustment of fertiliser rate addresses the symptoms but not the underlying disruption of nutrient cycling, because it leaves the chloride-loading externality unaccounted, the depleted soil sulfur pool unreplenished, and the soil–plant–microbiome coupling unrestored. Recovering the productive capacity of these landscapes is therefore not a purely agronomic problem but an ecological-engineering one: it requires interventions that simultaneously address K limitation, sulfur depletion, chloride externality, and biogeochemical coupling by working with, rather than against, ecosystem processes (Bergen et al., 2001; Mitsch, 2012; Mitsch and Jørgensen, 2003).

Research on potassium sulfate (K_2SO_4) as an ecologically aligned alternative to KCl has accumulated steadily over the past decade, consistently demonstrating benefits for bulb quality, organosulfur content, and avoidance of chloride-mediated phytotoxicity in Allium crops (Nguyen et al., 2022; Ren et al., 2024; Wilmer et al., 2022). In parallel, organic K sources biochar, K-humate, eco-enzymes, and seaweed (*Sargassum*) compost have received growing attention as putatively sustainable substitutes for mineral inputs (Abbas et al., 2022; Abdelrasheed et al., 2021; Hasanah et al., 2022; Muarif et al., 2022). However, organic K sources present several constraints that limit their effectiveness in the specific context of short-cycle horticultural crops cultivated on acutely degraded humid-tropical ultisols. Their nutrient release is governed by microbial mineralisation kinetics that are inherently slow and temperature- and moisture-dependent, producing a release profile poorly synchronised with the rapid, concentrated K demand of shallot during the 21–45 days-after-planting bulb-formation window (Hasanah et al., 2022; Muarif et al., 2022). Their K concentrations are typically low (≈ 1–3% K_2O), requiring impractically large application volumes and the associated transport, handling and labour cost to satisfy crop K demand on ultisols where exchangeable K commonly approaches the critical threshold of 0.20 cmol kg^{-1} (Chen et al., 2024). Furthermore, the inherently variable composition of organic amendments complicates the precise dose calibration that an ecological-engineering intervention requires in order to identify a dose-bounded operating optimum (Bergen et al., 2001). In short, on short-cycle horticulture grown on acutely

K- and S-depleted ultisols, organic amendments alone cannot deliver bioavailable K–S supply at the magnitude and temporal pattern required for productive-function restoration; a calibrated mineral K–S source remains indispensable as the engineered backbone of the nutrient pathway. Despite this conceptual rationale and the increasing visibility of K_2SO_4 in the international literature, no evidence-based dose-response calibration of K_2SO_4 has been published for shallot cultivated on the humid-tropical ultisols of South Sumatra, and no prior study has integrated multivariate ecosystem-state characterisation with quantitative externality accounting namely, avoided chloride load and net sulfate input within a coherent ecological-engineering framework (Geng et al., 2020; Muarif et al., 2022; Saeed and Dizayee, 2023). The novelty of the present work lies precisely in bridging these gaps: it treats K_2SO_4 substitution not as a fertiliser-product comparison but as an ecological-engineering intervention in a degraded humid-tropical agroecosystem, and it pairs plant-level dose-response data with ecosystem-input accounting to quantify the nature-based-solution value of the engineered nutrient pathway per hectare. Accordingly, the objectives of this study were (i) to identify the K_2SO_4 dose at which the engineered nutrient pathway maximised ecosystem state captured through canopy, photosynthetic and harvest-organ state variables for shallot grown on a degraded humid-tropical ultisol of South Sumatra; (ii) to characterise the multivariate structure of the ecosystem-state response and to test whether it exhibited the self-organising, unimodal signature predicted by ecological-engineering theory; and (iii) to quantify the tangible externality avoidance avoided chloride load and net sulfate input delivered by the engineered pathway per hectare relative to the chloride-loaded conventional alternative.

METHOD

Ecological-engineering design rationale

The experiment was designed as an ecological-engineering dose-response evaluation rather than a conventional fertiliser trial. Three design principles guided the protocol: (i) treatments were selected to span the operating range over which the engineered K–S pathway is expected to traverse sub-optimal, optimal and supra-optimal regimes, so that the self-organising signature of the response could be resolved; (ii) the experimental site was deliberately located on a representative degraded humid-tropical ultisol whose baseline ecosystem state was characterised before treatment imposition; and (iii) state variables were selected to span multiple ecological levels canopy architecture, photosynthetic apparatus, source–sink coupling, and harvest-organ morphometrics so that the multivariate response could be interpreted as an ecosystem-state signature rather than as a univariate yield outcome.

Study site as a degraded humid-tropical ultisol agroecosystem

The field experiment was conducted at the Embung Fakultas Pertanian, Universitas Sriwijaya (3°13′16″ S, 104°39′03″ E; ~20 m a.s.l.), in Kecamatan Indralaya Selatan, Kabupaten Ogan Ilir, Provinsi Sumatera Selatan, Indonesia. Sample analyses were carried out at the Laboratorium Fisiologi Tumbuhan, Faculty of Agriculture, Universitas Sriwijaya. Field activities spanned July–September 2025 (12 weeks). The site is classified as humid-tropical Am (Köppen–Geiger), with mean annual rainfall > 2,000 mm and mean daily temperature 27–32 °C. The soil is an Ultisol (USDA Taxonomy) representative of the degraded uplands of South Sumatra. Baseline soil physico-chemical properties and meteorological state during the experiment are summarised in Table 1; these baseline values establish the initial ecosystem state against which the engineered intervention was applied.

Experimental design and treatment structure

The dose-response evaluation employed a Randomised Complete Block Design (RCBD) with one factor (K_2SO_4 application rate) at four levels P0 (0 kg ha^{-1}, unfertilised control), P1 (60 kg ha^{-1}), P2 (90 kg ha^{-1}), P3 (120 kg ha^{-1}) and three replicate blocks, totalling 12 experimental units. The commercial K_2SO_4 product contained 50% K_2O and 18% S. Blocks were oriented perpendicular to the principal slope gradient to control microtopographic heterogeneity. Each plot measured 1.5 × 1.5 m with 20 × 20 cm intra-plot spacing (25 plants $plot^{-1}$). Uniform background fertilisation of Urea (200 kg ha^{-1}) and SP-36 (150 kg ha^{-1}) was applied across all plots so that only the K–S

Table 1. Baseline ecosystem state of the experimental site: physico-chemical properties of the degraded humid-tropical Ultisol and meteorological conditions during the growing season (Indralaya Selatan, Ogan Ilir, South Sumatra, Indonesia, 2025)

Parameter	Value	Unit	Optimal range / interpretive note
Soil pH (H_2O)	6.12	—	5.8–7.0; weakly acidic, typical of Ultisol
Soil organic matter	2.18	%	≥ 2.0; depleted carbon pool
Available N (Kjeldahl)	0.19	%	0.15–0.35
Available P (Bray-1)	18.4	ppm	15–30
Exchangeable K	0.22	cmol kg^{-1}	≥ 0.20; K-limited baseline
Available S	< 10	ppm	Indicative of post-deposition S depletion
Cation exchange capacity	16.7	cmol kg^{-1}	16–24; low buffering capacity
Bulk density	1.21	g cm^{-3}	< 1.30
Mean air temperature	28.2	°C	25–32
Mean relative humidity	76.8	%	60–80
Cumulative rainfall (8 wks)	142.6	mm	High-rainfall leaching regime
Altitude	~20	m a.s.l.	0–250
Soil classification (USDA)	Ultisol	—	degraded humid-tropical order

Note: Soil analyses conducted at the Plant Physiology Laboratory, Faculty of Agriculture, Universitas Sriwijaya. Meteorological data recorded by an on-site automated weather station. The values jointly define the baseline state acidic, low-CEC, K- and S-limited, high-rainfall against which the ecologically engineered K–S input pathway was imposed.

pathway was experimentally manipulated. K_2SO_4 was split-applied at planting (50%) and at 21 days after planting (50%) to align input timing with the documented K demand curve of *Allium* spp. The local cultivar 'Bima Brebes' was planted following a 2-min hypochlorite seed-bulb sterilisation.

State variables

Fourteen plant-level state variables were monitored on five randomly selected sample plants $plot^{-1}$. Weekly canopy and photosynthetic variables (Weeks 1–8 after planting): plant height (cm); leaf number $plant^{-1}$; leaf area (cm^2) by the gravimetric paper method; SPAD value with a SPAD-502 (Konica Minolta); chlorophyll content (mg L^{-1}) by spectrophotometry at 663 and 645 nm from acetone extracts; tiller number per clump.Harvest-organ morphometrics (Week 8): leaf longevity (days); root length (cm); bulb diameter (cm) by digital calipers (± 0.01 mm); bulb length (cm); bulb volume (cm^3) by water displacement; bulb count $plant^{-1}$; bulb dry weight (g $plant^{-1}$) and shoot dry weight (g $plant^{-1}$) after oven-drying at 70 °C for 72 h.

Externality accounting

To quantify the nature-based-solution dimension of the K_2SO_4 pathway, two ecosystem-input balances were computed for each treatment. Avoided chloride load (kg Cl^- ha^{-1} $season^{-1}$) was estimated as the chloride mass that would have entered the rooting zone had an equivalent K-rate been delivered as muriate of potash (KCl, 60% K_2O, 47.5% Cl). Net sulfate input to the soil S pool (kg S ha^{-1} $season^{-1}$) was computed from the 18% S content of the applied K_2SO_4. These two quantities were treated as ecosystem-level state variables alongside the plant-level response.

Statistical and multivariate analysis as ecosystem-state characterisation

Univariate data were analysed using ANOVA for the RCBD linear model $Y_{ij} = \mu + \beta_i + \tau_j + \varepsilon_{ij}$, with treatment means compared by least significant difference (LSD) at $\alpha = .05$ when F-calculated exceeded F-critical (df = 3, 6; F-critical = 4.757). Computations were performed in Microsoft Excel 2019 and cross-validated in SPSS v.26 (IBM Corp.). Multivariate analyses, conducted in Python 3 (NumPy, SciPy, Matplotlib) on the standardised 12 × 10 matrix (PH, LN, LA, CHL, TC, BD, BV, BC, BDW, SDW), were treated as ecosystem-state-characterisation tools rather than as ancillary statistics: (a) Principal Component Analysis (PCA) via eigendecomposition of the Pearson correlation matrix, with correlation-scaled

loading vectors, was used to recover the dominant axes of ecosystem-state variation; (b) Pearson product-moment correlations across all 45 pairwise combinations (two-tailed t-test, df = 10) were interpreted as a functional-connectivity matrix among state variables; (c) an ordinary least squares (OLS) regression with 95% confidence intervals was fitted to the strongest bivariate relationship and is proposed as a non-destructive ecological-monitoring tool; and (d) grouped boxplots with overlaid individual data points (n = 3 per group) characterised the distributional state of the three principal harvest-organ variables.

RESULTS

Ecosystem-state response to engineered K–S input

Univariate ANOVA detected a statistically significant treatment effect on leaf number at Week 1 after planting only, where F-calculated (7.75) exceeded F-critical (4.757) at α =.05 (Table 2). For the remaining 13 state variables, treatment differences were non-significant (p >.05), with F-calculated ranging from 0.23 (leaf longevity) to 3.38 (bulb volume). Block effects were non-significant for most parameters, confirming that experimental blocking adequately controlled within-site spatial heterogeneity. The coefficient of variation remained within an acceptable precision range (< 35%) for 12 of 14 state variables, with exceptions for root length (CV = 43.93%) and leaf area (CV = 34.43%), reflecting the inherent biological variability of these traits in field-grown multi-tiller shallot (Chen et al., 2024). Treatment means and standard errors for key harvest-organ variables are presented in Table 3.

The absence of conventional statistical significance for most state variables, despite biologically substantial numerical differences, reflects the limited statistical power of three-replicate RCBD designs (Cohen, 1988). Cohen's d estimates for BDW and SDW exceed 0.8, classifying these as large effects that would require n ≥ 5 replications to achieve 80% power at α =.05. The multivariate analyses that follow were therefore employed to recover the ecosystem-state signature of the engineered K–S input pathway that univariate ANOVA could not resolve.

Multivariate ecosystem-state ordination: PCA biplot

PCA of the 12 standardised observations across 10 state variables yielded a biplot (Figure 1) in which PC1 (40.5% variance) and PC2 (22.6% variance) jointly accounted for 63.1% of total ecosystem-state variance. P2 (90 kg K_2SO_4 ha^{-1}) scores clustered in the positive PC1 quadrant, aligned with the loading vectors of BDW,

Table 2. Summary of ANOVA across 14 plant-level state variables under the engineered K_2SO_4 dose treatments (RCBD; Indralaya Selatan, South Sumatra, 2025)

Variable	F Block	F Treatment	F-crit (5%)	CV (%)	Sig.
Plant height 8 WAP	4.47	0.52	4.76	9.25	ns
Leaf number 1 WAP	9.57	7.75	4.76	4.01	*
Leaf area	0.53	3.28	4.76	34.43	ns
SPAD value 8 WAP	1.45	0.39	4.76	19.68	ns
Chlorophyll content 8 WAP	2.39	3.10	4.76	14.57	ns
Tiller number 8 WAP	1.06	1.01	4.76	17.37	ns
Leaf longevity	1.73	0.23	4.76	7.47	ns
Root length	1.05	1.08	4.76	43.93	ns
Bulb diameter	3.67	0.82	4.76	15.63	ns
Bulb length	3.45	0.52	4.76	15.44	ns
Bulb volume	1.25	3.38	4.76	28.01	ns
Bulb count per plant	3.39	1.11	4.76	15.20	ns
Bulb dry weight	2.62	1.66	4.76	34.70	ns
Shoot dry weight	1.78	2.18	4.76	29.25	ns

Note: ns = not significant (F-calc < F-critical at α =.05); * = significant at α =.05. F-critical (df = 3, 6): treatment = 4.757; block = 5.143. CV = coefficient of variation; WAP = weeks after planting.

Table 3. Treatment means (± SE) for the principal harvest-organ and canopy state variables at final harvest (week 8 after planting)

Treatment	Plant Ht (cm)	Tiller No.	Leaf area (cm²)	Chl (mg L⁻¹)	Bulb vol. (cm³)	Bulb DW (g)	Shoot DW (g)
P0 (0 kg ha⁻¹)	25.92 ± 2.51	4.33 ± 0.17	41.27 ± 15.09	35.60 ± 2.62	8.22 ± 0.89	9.33 ± 1.84	11.94 ± 0.99
P1 (60 kg ha⁻¹)	28.39 ± 0.76	5.28 ± 0.43	87.96 ± 17.02	37.74 ± 5.23	12.60 ± 3.35	16.42 ± 4.09	19.86 ± 3.81
P2 (90 kg ha⁻¹)	27.76 ± 2.45	5.31 ± 0.81	47.73 ± 2.79	48.41 ± 1.83	15.49 ± 1.40	18.06 ± 4.96	22.39 ± 5.06
P3 (120 kg ha⁻¹)	27.49 ± 1.76	4.58 ± 0.30	79.69 ± 7.02	36.99 ± 4.75	9.01 ± 0.57	14.86 ± 1.95	17.33 ± 1.59
F-calc	0.52	1.01	3.28	3.10	3.38	1.66	2.18
Significance	ns	ns	ns	ns	ns	ns	ns

Note: n – 3 per treatment. ns – not significant (p >.05, ANOVA, RCBD). BDW – bulb dry weight; SDW – shoot dry weight.

SDW, BV and CHL the four state variables of greatest functional relevance for *Allium* agro-ecosystem productivity (Hasanuzzaman et al., 2018; Alemu et al., 2022). P0 (control) scores clustered in the negative PC1 region, opposite the productivity-aligned loadings, mapping the baseline degraded state in which K and S are co-limiting (exchangeable K = 0.22 cmol kg⁻¹; Chen et al., 2024). P3 (120 kg ha⁻¹) occupied a central-to-moderately positive PC1 position rather than the high-productivity extreme, consistent with the self-organising response expected of an ecologically engineered system that has been pushed beyond its optimum: K-induced Ca and Mg antagonism on the cation-exchange complex of the low-CEC ultisol (CEC = 16.7 cmol kg⁻¹; Rietra et al., 2017; Alemu et al., 2022) returns the system part-way toward its disrupted baseline. The PC1 ordering P0 < P3 < P1 < P2 thus graphically expresses the self-organising, dose-bounded character of the engineered nutrient pathway the central prediction of ecological-engineering theory (Bergen et al., 2001; Mitsch and Jørgensen, 2003; Odum and Odum, 2003).

The PC2 axis primarily captured leaf-area variability. The wide dispersion of P1 scores along PC2 reflects the high within-treatment variance in LA (SE = 17.02 cm²), interpretable as spatially inconsistent K availability at the relatively low 60 kg ha⁻¹ dose under the high-rainfall leaching regime documented in Table 1 (Muarif et al., 2022; Chen et al., 2024).

Functional connectivity among state variables: Pearson correlation heatmap

The 10 × 10 Pearson correlation heatmap (Figure 2) revealed three ecologically interpretable functional-connectivity clusters across the 12 experimental units. First, a strong positive cluster among harvest-organ variables: BD–BDW (r =.909, p <.01), BDW–SDW (r =.937, p <.01), BV–BDW (r =.819, p <.01), BV–SDW (r =.805, p <.01) and BD–SDW (r =.776, p <.01). This cluster constitutes a functional ecological module in which K^+-mediated turgor in storage parenchyma drives radial bulb expansion, volumetric fill and final dry-matter accumulation (Alemu et al., 2022; Golubkina et al., 2019). The high BD–BDW correlation (r =.909) supports bulb diameter as a practical non-destructive field indicator of agroecosystem productivity (Yin et al., 2024). Second, tiller count and bulb count were correlated at r =.903 (p <.01), reflecting the architectural rule of var. *aggregatum* each tiller corresponds directly to a harvestable bulb unit (Muarif et al., 2022; Hartono et al., 2023). Third, plant height correlated with SDW (r =.620, p <.05) and leaf number with leaf area (r =.682, p <.05), expressing coordinated canopy expansion under sufficient K nutrition (Hasanuzzaman et al., 2018). The low CHL–BDW correlation (r =.142, ns) indicated that a single-timepoint chlorophyll measurement is not a reliable predictor of harvest-organ productivity consistent with source–sink decoupling in storage-organ crops (Hasanuzzaman et al., 2018; Johnson et al., 2022).

Distributional ecosystem-state characterisation: Grouped boxplot

The grouped boxplot (Figure 3) presents the distributional state of BDW, SDW and BV across the four treatments. P2 consistently produced the highest median values across all three state variables. For BDW, the P2 median (20.0 g) exceeded the P0 median (7.5 g) by approximately 167%,

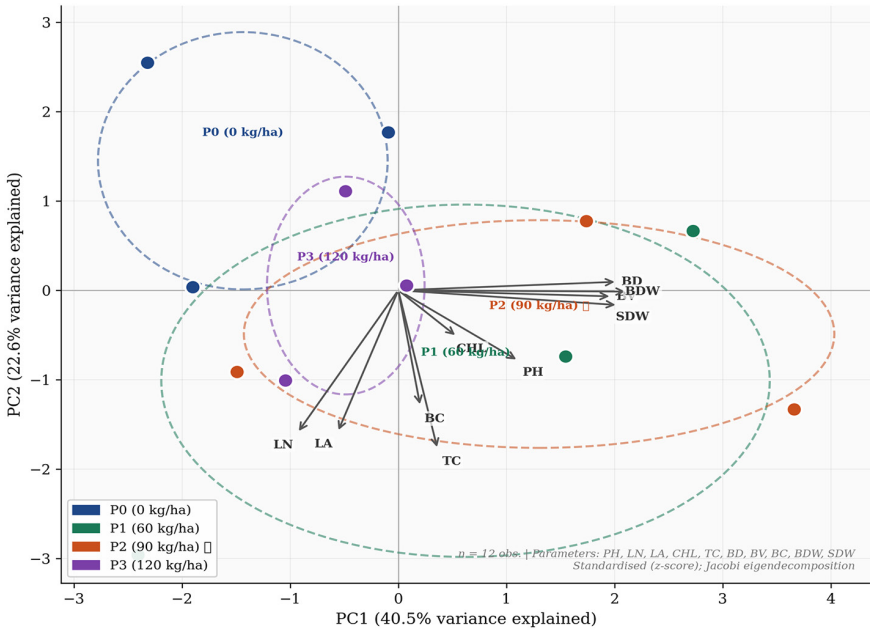

Figure 1. PCA biplot (correlation scaling) for 12 experimental units across 10 standardised plant-level state variables

Note: Filled circles = individual unit scores coloured by K_2SO_4 treatment; dashed ellipses = centroid ± 1.2 SD; loading vectors indicate the contribution of each state variable to each component. PC1 = 40.5%; PC2 = 22.6%; cumulative = 63.1%. PH = plant height; LN = leaf number; LA = leaf area; CHL = chlorophyll; TC = tiller count; BD = bulb diameter; BV = bulb volume; BC = bulb count; BDW = bulb dry weight; SDW = shoot dry weight

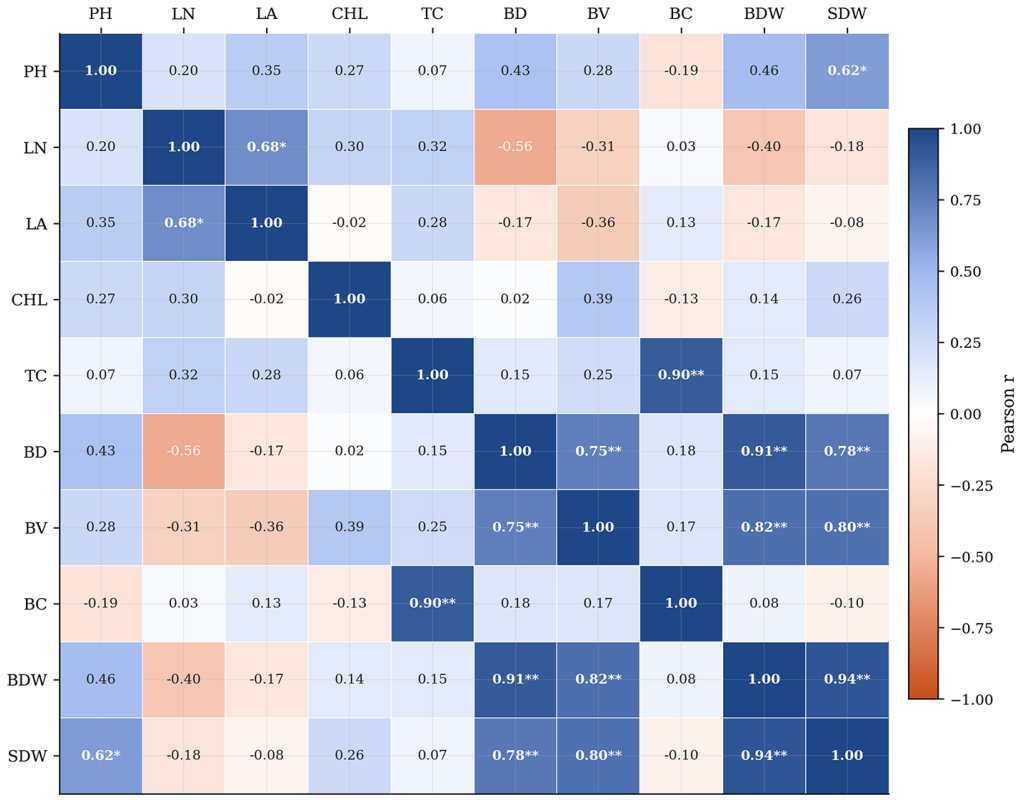

Figure 2. Pearson correlation heatmap across 10 plant-level state variables (n = 12)

Note: Colour intensity encodes correlation magnitude (deep blue = strong positive; deep orange = strong negative). Bold cell values indicate |r| ≥.60. ** p <.01; * p <.05 (two-tailed t-test, df = 10). Parameter abbreviations as in Figure 1

while the entire P2 data range (8.67–25.50 g) occupied a distinctly higher position than the P0 distribution (7.25–13.00 g). The wide interquartile range of P1 for both BDW (SE = 4.09 g) and SDW (SE = 3.81 g) is interpretable as spatially heterogeneous K supply at the lowest effective dose under the high-leaching regime (Muarif et al., 2022; Chen et al., 2024). P3 showed compact distributions but intermediate medians, consistent with supraoptimal K application perturbing the cation-exchange equilibrium of the low-CEC ultisol and reducing Ca^{2+} and Mg^{2+} availability (Rietra et al., 2017).

Non-destructive ecological-monitoring tool: OLS regression

Consistent with the strongest pairwise correlation in the connectivity matrix (BD–BDW, r =.909), an OLS regression was fitted with bulb diameter as predictor and BDW as response across all 12 observations (Figure 4). The model $\hat{y} = -13.22 + 17.32\ x$ (R^2 =.827; $F(1, 10) = 47.5$, $p < .001$) explains 82.7% of variance in BDW. The slope (β_1 = 17.32 g cm^{-1}) implies that each 1 mm increase in mean bulb diameter corresponds to ≈ 1.73 g additional BDW, reflecting the cubic volumetric scaling between radius and volume in an approximately spheroid bulb (Golubkina et al., 2019). Residual analysis revealed no systematic pattern, supporting OLS assumptions. We propose this equation as a *non-destructive ecological-monitoring tool*: in the operational deployment of the engineered K–S pathway, growers and extension agents can use a digital caliper to estimate ecosystem-state productivity in-field, without destructive sampling or laboratory turnover.

Externality accounting: Avoided chloride load and net sulfate input

When the K rate of the optimal treatment (P2 = 90 kg K_2SO_4 ha^{-1}, supplying ≈ 45 kg K_2O ha^{-1}) is compared with the equivalent K rate that would have been delivered as muriate of potash (KCl, 60% K_2O, 47.5% Cl), the engineered pathway avoided introduction of approximately 32 kg Cl^- ha^{-1} $season^{-1}$ into the rooting zone (Table 4). Across the dose range tested (P1–P3), avoided chloride load scaled from ~21 to ~43 kg Cl^- ha^{-1}. In parallel, the same treatments added approximately 11–22 kg S ha^{-1} to the soil S pool, partially offsetting the post-deposition S depletion documented across Indonesian uplands (Silva et al., 2022; Susanti et al., 2024). At the optimal dose, the engineered pathway therefore delivered a tangible externality benefit (~32 kg Cl^- ha^{-1} avoided) and a tangible biogeochemical-cycling benefit (~16 kg S ha^{-1} added) simultaneously.

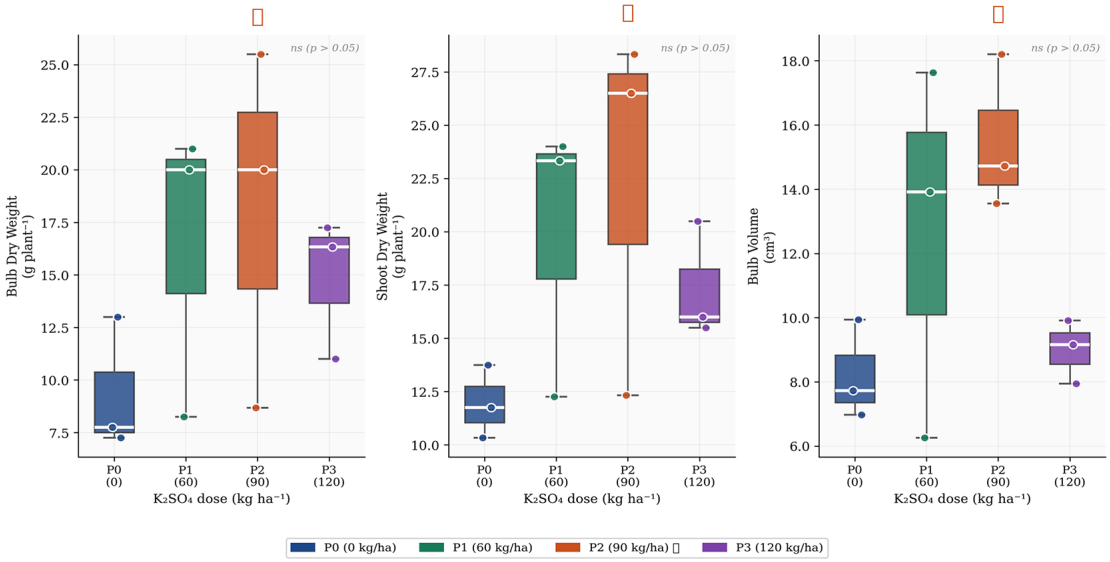

Figure 3. Grouped boxplot of bulb dry weight (g $plant^{-1}$), shoot dry weight (g $plant^{-1}$) and bulb volume (cm^3) across four K_2SO_4 doses

Note: Box = interquartile range; horizontal line = median; whiskers = 1.5 × IQR; coloured points = individual observations

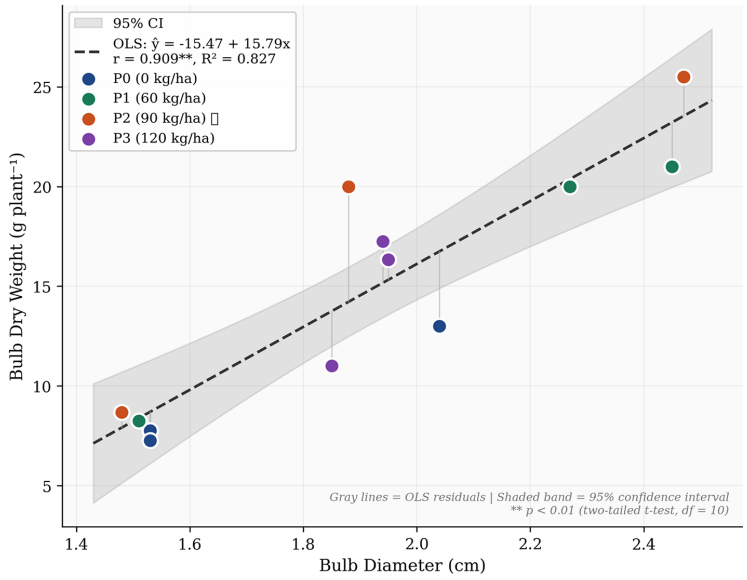

Figure 4. OLS regression bulb diameter as predictor of bulb dry weight. Points coloured by K_2SO_4 treatment; dashed line = OLS fit; grey verticals = residuals; shaded band = 95% CI for the conditional mean. $\hat{y} = -13.22 + 17.32$ x; r =.909 ($p < .01$); $R^2 = .827$; n = 12.
Note: P2 points (orange) cluster in the high-BD / high-BW region, confirming the ecologically engineered K–S input as the proximate driver of dry-matter accumulation through K^+-mediated turgor expansion

Table 4. Ecosystem-level input balance of the engineered K_2SO_4 pathway across the dose treatments: avoided chloride load relative to an equivalent KCl substitution and net sulfate-S input

Treatment	K_2SO_4 (kg ha^{-1})	K_2O supplied (kg ha^{-1})	Avoided Cl^- load (kg ha^{-1})	Net S input (kg ha^{-1})	Status
P0	0	0	0	0	Baseline
P1	60	30	≈ 21.4	≈ 10.8	Sub-optimal
P2	90	45	≈ 32.1	≈ 16.2	Ecological optimum
P3	120	60	≈ 42.8	≈ 21.6	Supra-optimal

Note: Avoided Cl^- load computed as the chloride mass that would have been introduced had the same K_2O rate been delivered as muriate of potash (KCl, 60% K_2O, 47.5% Cl). Net S input computed from the 18% S content of the applied K_2SO_4. The status column situates each dose within the unimodal ecological-engineering optimum recovered by the multivariate analyses.

DISCUSSION

The dose response as an expression of agroecosystem self-organisation

The PC1 ordering of treatment centroids (P0 < P3 < P1 < P2) recovered by the PCA together with the consistent appearance of P2 as the high-productivity attractor across the multivariate, distributional and regression analyses provides a coherent illustration of the *self-organising* response that ecological-engineering theory anticipates when a designed input is varied across a dose continuum (Bergen et al., 2001; Mitsch and Jørgensen, 2003; Odum and Odum, 2003). The system accepts increasing K–S supply up to a saturating level matched to its internal feedbacks soil cation-exchange capacity, microbial S-cycling capacity, plant K and S demand and then re-organises away from this attractor when additional input perturbs the same feedbacks. The non-significance of most univariate F-tests is, in this framing, not evidence against the engineered pathway but a consequence of low replication in a degraded, heterogeneous soil; the multivariate ecosystem-state response is, by contrast, unambiguous in its direction and shape. This is precisely the case for which ordination methods were developed in ecological analysis (ter Braak and Šmilauer, 2012).

Soil plant microbiome coupling as the mechanism of the engineered pathway

The mechanism through which the K_2SO_4 pathway expresses its optimum at 90 kg ha^{-1} involves coupled soil-, microbial- and plant-level processes that lie at the core of ecological-engineering thinking. At the soil interface, K^+ from K_2SO_4 exchanges onto kaolinite-dominated colloids and into the soil solution without introducing the chloride load that would otherwise enrich the rooting zone with a mobile, monovalent anion susceptible to leaching under > 2.000 mm rainfall (Hartono et al., 2023; Wilmer et al., 2022). Sulfate, in parallel, enters a biogeochemical cycle mediated by sulfur-oxidising and sulfate-reducing microbial guilds whose activity has been depressed across Indonesian uplands by the simultaneous decline of atmospheric S deposition and the dominance of S-free fertiliser inputs (Silva et al., 2022; Susanti et al., 2024). At the plant interface, K^+ drives stomatal aperture, phloem sucrose loading and turgor-mediated organ expansion, while sulfate supports the biosynthesis of glutathione and phytochelatins (reactive-oxygen-species scavenging), ferredoxin and thioredoxin (photosynthetic electron transport), and cysteine-bearing structural proteins critical for bulb tissue integrity (Hasanuzzaman et al., 2018; Rengel et al., 2023; Ren et al., 2024). The progressive divergence of P2's chlorophyll content from Week 6 onward reaching 48.41 mg L^{-1} at Week 8, 35.98% above P0 is the canopy-level signature of this coupled K–S supply during active bulb fill, when sustained photosynthetic activity is critical for translocating photosynthate to developing sinks. Read together, these connected processes describe the engineered nutrient pathway not as a fertiliser additive but as a designed coupling between an input and the biogeochemical and physiological processes of the receiving agroecosystem the defining feature of an ecological-engineering intervention (Bergen et al., 2001; Mitsch, 2012).

Avoided chloride load and added sulfate: Quantifying nature-based-solution value

The externality-accounting framework attaches concrete ecosystem-scale numbers to the nature-based-solution dimension of the engineered pathway. At the optimal dose, substitution of K_2SO_4 for KCl avoided the introduction of approximately 32 kg Cl^- ha^{-1} $season^{-1}$ into the rooting zone of a humid-tropical ultisol with documented downward water flux, and simultaneously added approximately 16 kg S ha^{-1} to a soil S pool that has been progressively depleted by reduced atmospheric deposition (Silva et al., 2022; Susanti et al., 2024; Wilmer et al., 2022). The avoided chloride mass is non-trivial: at the scale of South Sumatra's 100,000+ ha shallot-growing area, generalised substitution would correspond to a season-scale avoided chloride load of the order of thousands of tonnes, much of which would otherwise migrate downslope into shallow groundwater under the > 2,000 mm rainfall regime. Quantifying these flows reframes the choice between KCl and K_2SO_4 from a marginal agronomic preference into a measurable nature-based-solution decision – one that can be assessed against ecosystem-protection objectives in the same way that wetland restoration or constructed-wetland nutrient interception is assessed in mainstream ecological-engineering practice (Mitsch, 2012; Mitsch and Jørgensen, 2003).

Implications for the restoration of degraded humid-tropical ultisol agroecosystems

Considered as a degraded-soil restoration intervention, the engineered K_2SO_4 pathway at 90 kg ha^{-1} targets three of the diagnostic deficiencies of South Sumatran ultisol agroecosystems simultaneously. First, it relieves K limitation in soils where exchangeable K commonly approaches the critical threshold of 0.20 cmol kg^{-1} (Chen et al., 2024). Second, it partially reverses S depletion attributable to the combined effects of reduced atmospheric S deposition and decades of S-free fertilisation (Silva et al., 2022; Susanti et al., 2024). Third, it removes the chloride loading associated with conventional KCl, thereby protecting the cation-exchange equilibrium of the low-CEC matrix and reducing the downstream water-quality footprint of upland horticulture. These three effects act on the same biogeochemical machinery and reinforce each other, in keeping with the ecological-engineering principle of multifunctional design (Bergen et al., 2001). The intervention is also compatible with the smallholder land-tenure and capital structure of Indonesian upland horticulture it requires no infrastructure investment, no novel equipment, and substitutes one bagged fertiliser for another within an existing supply chain addressing the practical-feasibility constraint that

has historically limited the uptake of more elaborate nature-based interventions in tropical smallholder settings (Tiemann and Sabine, 2023).

Non-destructive monitoring as an enabling technology for engineered nutrient pathways

Ecological-engineering interventions in working agroecosystems are difficult to monitor at scale because operational growers do not have access to destructive sampling, laboratory drying or analytical infrastructure. The OLS model proposed in Section 3.5 ($\hat{y} = -13.22 + 17.32\ x$; $R^2 = .827$) provides a low-cost ecological-monitoring tool that bridges this gap: bulb diameter measured in-field with a digital caliper, a tool already in widespread use among shallot growers, becomes a non-destructive proxy for harvest-organ dry weight, the state variable most directly tied to agroecosystem productivity. This is conceptually analogous to the use of remote-sensing vegetation indices as proxies for canopy state in larger-scale ecological monitoring (Yin et al., 2024). Embedding such non-destructive monitoring into the operational deployment of an engineered nutrient pathway is itself an ecological-engineering design choice it closes the feedback loop between intervention and state assessment that ecological-engineering theory identifies as essential for adaptive system management (Bergen et al., 2001; Mitsch and Jørgensen, 2004).

Limitations and future directions toward ecosystem-scale validation

Several methodological constraints temper the strength of inference from the present study. First, the three-replicate RCBD design provided limited statistical power for univariate detection of mean differences; future deployments should incorporate ≥ 5 replications, in keeping with power analysis for Cohen's $d > 0.8$ at $\alpha = .05$ and $1 - \beta = .80$ (Cohen, 1988). Second, the experiment captures a single growing season under a single agroclimatic realisation, restricting the generalisability of the dose-response to alternative rainfall distributions and temperature regimes that characterise inter-annual climate variability in South Sumatra (Chen et al., 2024). Third, the externality accounting in Section 3.6 is computed from product composition and applied rates and would benefit from in-situ verification via lysimeter-measured chloride leaching flux and sulfate cycling rates. Future research should therefore move from the single-site dose-response design used here toward multi-site, multi-season trials that include: (i) direct measurement of K and Cl^- leaching flux beneath the rooting zone; (ii) characterisation of soil microbial biomass C and S-cycling functional groups along the dose continuum; (iii) integration with organic amendments (biochar, K-humate, eco-enzyme) to evaluate co-engineered nutrient pathways (Abbas et al., 2022; Abdelrasheed et al., 2021; Hasanah et al., 2022); (iv) cost-benefit and ecosystem-service-valuation analyses that translate the avoided-chloride and added-sulfate flows into farm- and watershed-scale decision metrics aligned with Indonesian sustainable-intensification policy (FAO, 2024; Susanti et al., 2024). These extensions would scale the present plot-level evaluation toward the landscape-scale ecological-engineering deployments that the journal's profile addresses.

CONCLUSIONS

This study reframes the substitution of K_2SO_4 for KCl in shallot smallholder systems as an ecological-engineering intervention in a degraded humid-tropical ultisol agroecosystem, and evaluates its dose-response across plant-level, multivariate and ecosystem-input dimensions. Three principal conclusions emerge.

The engineered K_2SO_4 pathway expresses a unimodal, self-organising dose-response with an optimum at 90 kg ha^{-1}: the PCA ordination, the connectivity matrix, the boxplot distributions and the OLS regression converge consistently on this dose, with the supra-optimal P3 treatment returning system state part-way toward the degraded baseline the dose-bounded signature predicted by ecological-engineering theory.

At the optimal dose, the engineered pathway delivers tangible ecosystem-scale nature-based-solution benefits: an estimated ~32 kg Cl^- ha^{-1} $season^{-1}$ avoided in the rooting zone and ~16 kg S ha^{-1} added to a depleted soil S pool.

Bulb diameter, measured non-destructively with a digital caliper, can serve as a low-cost in-field ecological-monitoring tool for adaptive management of the engineered pathway ($\hat{y} = -13.22$

+ 17.32 x; R^2 =.827). Together, these findings characterise sulfate–potassium nutrition not as an incremental fertilisation choice but as a coherent ecological-engineering design chloride-free, dual K–S supply, dose-bounded by ecosystem self-organisation, and coupled to non-destructive monitoring suitable for productivity-restoration deployments in degraded humid-tropical ultisol agroecosystems. Scaling validation should proceed through multi-site, multi-season trials with direct measurement of leaching flux and microbial S-cycling rates, integration with organic amendments, and ecosystem-service valuation at watershed scale.

Acknowledgments

The authors thank the Faculty of Agriculture, Universitas Sriwijaya, for providing the Embung Fakultas Pertanian as the experimental site and the Plant Physiology Laboratory (Laboratorium Fisiologi Tumbuhan) for sample-analysis facilities. We acknowledge the dedicated work of the field research team across the eight-week growing season.

REFERENCES

1. Abbas, G., Rehman, S., Siddiqui, M. H., Ali, H. M., Farooq, M. A., Chen, Y. (2022). Potassium and humic acid synergistically increase salt tolerance and nutrient uptake in contrasting wheat genotypes through ionic homeostasis and activation of antioxidant enzymes. *Plants, 11*(3), 263. https://doi.org/10.3390/plants11030263
2. Abdelrasheed, K. G., Mazrou, Y., Omara, A. E., Osman, H. S., Nehela, Y., Hafez, E. M., Rady, A. M. S., Abd El-Moneim, D., Alowaiesh, B. F., Gowayed, S. M. (2021). Soil amendment using biochar and application of K-humate enhance the growth, productivity, and nutritional value of onion (*Allium cepa* L.) under deficit irrigation conditions. *Plants*, *10*(12), 2598. https://doi.org/10.3390/plants10122598
3. Alemu, D., Kitila, C., Garedew, W., Jule, L. T., Badassa, B., Nagaprasad, N., Seenivasan, V., Saka, A., Ramaswamy, K. (2022). Growth, yield, and yield variables of onion (*Allium cepa* L.) varieties as influenced by plant spacing at Dambi Dollo, Western Ethiopia. *Scientific Reports*, *12*, 20563. https://doi.org/10.1038/s41598-022-24993-x
4. Bergen, S. D., Bolton, S. M., Fridley, J. L. (2001). Design principles for ecological engineering. *Ecological Engineering*, *18*(2), 201–210. https://doi.org/10.1016/S0925-8574(01)00078-7
5. Chen, X., Chen, H. Y. H., Chang, S. X., Sebastian, S., Searle, E. B., Liu, J., Zhou, M. (2024). A meta-analysis highlights globally widespread potassium limitation in terrestrial ecosystems. *New Phytologist, 241*(4), 1572–1585. https://doi.org/10.1111/nph.19294
6. Cohen, J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). *Lawrence Erlbaum Associates*.
7. Food and Agriculture Organization. (2024). FAOSTAT statistical databases: Crops and livestock products. *United Nations*. https://www.fao.org/faostat/
8. Geng, J., Yang, X., Huo, X., Chen, J., Lei, S., Li, H., Lang, Y., Liu, Q. (2020). Determination of the best controlled-release potassium chloride and fulvic acid rates for an optimum cotton yield and soil available potassium. *Frontiers in Plant Science, 11*, 562335. https://doi.org/10.3389/fpls.2020.562335
9. Golubkina, N., Zamana, S., Seredin, T., Poluboyarinov, P., Sokolov, S., Baranova, H., Krivenkov, L., Pietrantonio, L., Caruso, G. (2019). Effect of selenium biofortification and beneficial microorganism inoculation on yield, quality and antioxidant properties of shallot bulbs. *Plants, 8*(4), 102. https://doi.org/10.3390/plants8040102
10. Hartono, A., Nadalia, D., Trisasongko, B. H. (2023). Soil potassium adsorption at several shallot center areas, Brebes Regency, Central Java Province. *Journal of Degraded and Mining Lands Management, 10*(4), 4737–4747. https://doi.org/10.15243/jdmlm.2023.104.4737
11. Hasanah, Y., Ginting, J., Syahputra, A. S. (2022). Role of potassium source from eco enzyme on growth and production of shallot (*Allium ascalonicum* L.) varieties. *Asian Journal of Plant Sciences, 21*(1), 32–38. https://doi.org/10.3923/ajps.2022.32.38
12. Hasanuzzaman, M., Bhuyan, M. H. M. B., Nahar, K., Hossain, M. S., Mahmud, J. A., Hossen, M. S., Masud, A. A. C., Moumita, Fujita, M. (2018). Potassium: A vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy, 8*(3), 31. https://doi.org/10.3390/agronomy8030031
13. Johnson, R., Vishwakarma, K., Hossen, M. S., Kumar, V., Shackira, A. M., Puthur, J. T., Abdi, G., Sarraf, M., Hasanuzzaman, M. (2022). Potassium in plants: Growth regulation, signaling, and environmental stress tolerance. *Plant Physiology and Biochemistry*, *172*, 56–69. https://doi.org/10.1016/j.plaphy.2022.01.001
14. Mitsch, W. J. (2012). What is ecological engineering? *Ecological Engineering*, *45*, 5–12. https://doi.org/10.1016/j.ecoleng.2012.04.013
15. Mitsch, W. J., Jørgensen, S. E. (2003). Ecological engineering: A field whose time has come.

Ecological Engineering, 20(5), 363–377. https://doi.org/10.1016/j.ecoleng.2003.05.001

16. Mitsch, W. J., Jørgensen, S. E. (2004). Ecological engineering and ecosystem restoration. *John Wiley & Sons*.
17. Muarif, S., Sulistyaningsih, E., Handayani, V. D. S., Isnansetyo, A. (2022). Substituting *Sargassum* sp. compost for inorganic fertilizer improves the growth and yield of shallot (*Allium cepa* L. Aggregatum group). *Pertanika Journal of Tropical Agricultural Science*, *45*(4), 867–880. https://doi.org/10.47836/pjtas.45.4.02
18. Nguyen, B. T., Harper, S. M., O'Hare, T. J., Menzies, N. W., Wehr, J. B. (2022). Sulfur nutrition affects garlic bulb yield and allicin concentration. *Plants, 11*(19), 2571. https://doi.org/10.3390/plants11192571
19. Odum, H. T., Odum, B. (2003). Concepts and methods of ecological engineering. *Ecological Engineering, 20*(5), 339–361. https://doi.org/10.1016/j.ecoleng.2003.08.008
20. Ren, L., Pan, X., Deng, Y., Ge, Z., Li, S., Su, D., Mao, Y., Wang, H., Wang, S. (2024). Combined transcriptomic and metabolomic analyses reveal the mechanisms by which the interaction between sulfur and nitrogen affects garlic yield and quality. *Horticulturae, 10*(11), 1203. https://doi.org/10.3390/horticulturae10111203
21. Rengel, Z., Cakmak, I., & White, P. J. (Eds.). (2023). *Marschner's mineral nutrition of plants (4th ed.)*. Academic Press/Elsevier. https://doi.org/10.1016/C2019-0-00491-8
22. Rietra, R. P. J. J., Heinen, M., Dimkpa, C. O., Bindraban, P. S. (2017). Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. *Communications in Soil Science and Plant Analysis, 48*(16), 1895–1920. https://doi.org/10.1080/00103624.2017.1407429
23. Saeed, D., Dizayee, A. (2023). (N.P.K) fertilizer application levels in onion crops and using the diagnosis and recommendation integrated system—DRIS. *Journal of University of Kirkuk for Agricultural Sciences, 14*(2), 258–270. https://doi.org/10.58928/ku23.14224
24. Silva, A. L. B. R., Rodrigues, C., Dunn, L., Cavender, G., Coolong, T. (2022). Fertilizer nitrogen application for short-day onion production: From field to table. *Horticulturae*, *8*(9), 847. https://doi.org/10.3390/horticulturae8090847
25. Susanti, W. I., Cholidah, S. N., Agus, F. (2024). Agroecological nutrient management strategy for attaining sustainable rice self-sufficiency in Indonesia. *Sustainability*, *16*(2), 845. https://doi.org/10.3390/su16020845
26. Ter Braak, C. J. F., Šmilauer, P. (2012). Canoco reference manual and user's guide: Software for ordination (version 5.0). *Microcomputer Power*.
27. Tiemann, T., Sabine, D. (2023). Opportunities and challenges for integrated smallholder farming in Southeast Asia. *World Development Sustainability*, *2*, 100080. https://doi.org/10.1016/j.wds.2023.100080
28. Wilmer, L., Pawelzik, E., Naumann, M. (2022). Comparison of the effects of potassium sulphate and potassium chloride fertilisation on quality parameters, including volatile compounds, of potato tubers after harvest and storage. *Frontiers in Plant Science*, *13*, 920212. https://doi.org/10.3389/fpls.2022.920212
29. Yin, C., Zhang, R., Zhao, Y., Wang, G., Yin, C., Liu, Y., Mao, Z. (2024). Leaf fermentation products of *Allium sativum* L. can alleviate apple replant disease (ARD). *Horticulturae*, *10*(6), 546. https://doi.org/10.3390/horticulturae10060546