

Application of the non-zero entropy, finite-area solar exergy model for thermodynamic characterization of Nitrogen and phosphorus nutrient stress in greenhouse-grown cucumber (*cucumis sativus*)

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Abstract

Conventional nutrient stress diagnostics identify symptoms without explaining the underlying thermodynamic mechanisms. This study presents the first experimental application of the non-zero-entropy, finite-area solar exergy model (Model 2) to characterize nitrogen and phosphorus (N/P) stress in greenhouse-grown cucumber (*Cucumis-sativus*). A Randomized Complete Block Design comprising 48 plants across four N/P treatment levels T1 = 120/40 mg·kg⁻¹ (optimal), T2 = 80/30 (moderate), T3 = 40/20 (severe), T4 = 0/10 mg·kg⁻¹ (extreme deficiency) was conducted over 44days. Canopy temperatures were acquired using a UTi120s thermal imager under 800 Wm⁻² irradiance. Exergy balance analysis revealed that solar exergy input declined from 357W (T1) to 235W (T4), driven by nutrient-induced leaf area reduction. Emitted exergy increased from 42–138 W, reflecting T₄ radiative amplification of canopy temperature elevation, while chemical exergy collapsed 83% (234 – 39 W) and exergy destruction escalated from 17–112 W. The exergy performance index (ΨX) declined from 0.952 to 0.523 and the normalized stress index increased exponentially (0.000–0.450). Polynomial regression of canopy temperature against exergy efficiency yielded statistically significant relationships across all treatments (R² = 0.506–0.668; p < 0.05), confirming early-to-moderate stress as the optimal diagnostic window. Exergy destruction is validated as the most sensitive thermodynamic metric for precision agriculture nutrient stress monitoring.

1.0 Introduction

Nitrogen (N) and phosphorus (P) are the two most agronomically critical macronutrients governing photosynthetic enzyme synthesis, chlorophyll formation, electron transport efficiency, and biomass accumulation in vegetable crops. Their deficiency in commercial cucumber (*Cucumis sativus* L.) production suppresses Rubisco activity, reduces chlorophyll content, impairs stomatal regulation, and ultimately collapses photosynthetic productivity all of which manifest observably as elevated canopy temperature, reduced leaf area, stunted growth, and diminished yield (Evans 1989). Early detection of these deficiencies is therefore a central challenge in precision agriculture, where the goal is to enable targeted, site-specific fertilizer intervention before irreversible yield losses occur. Existing nutrient stress detection approaches spectral indices, visual assessment, tissue analysis, chlorophyll fluorometry, and thermal infrared (TIR) imaging identify stress symptoms without providing a physically grounded explanation of the thermodynamic mechanisms driving the observed canopy thermal responses (Islam et al. 2024; Pineda et al. 2021). This limitation restricts the predictive capability and mechanistic interpretability of current diagnostic frameworks. TIR imaging, in particular, captures canopy temperature anomalies that correlate empirically with nutrient stress, but the causal thermodynamic pathway from nutrient deficiency to photosynthetic inefficiency to entropy generation to canopy temperature elevation remains unquantified in the precision agriculture literature (Messina and Modica 2020; Zhou et al. 2021).

Exergy analysis, grounded in the Second Law of Thermodynamics, offers a fundamentally different diagnostic paradigm. Unlike energy-based accounting, which conserves quantity, exergy analysis quantifies the quality of energy flows specifically, the fraction of incident solar radiation that is converted

to useful biochemical work (biomass) versus irreversibly dissipated as heat. The exergy destruction principle predicts that nutrient-stressed plants, unable to sustain efficient photosynthetic apparatus assembly, generate increased entropy and exhibit elevated canopy temperatures relative to unstressed controls. This principle has been theoretically established and partially supported in corn (*Zea mays* L.) by Lawrence et al. (2019, 2021), who demonstrated statistically significant inverse correlations between nitrogen supply rate and canopy temperature consistent with the exergy destruction framework. However, no prior study has applied a fully resolved exergy balance computing all exergy flow components including solar input, emitted, reflected, chemical, and destruction terms under a replicated, multi-level N/P treatment gradient in any vegetable crop.

The non-zero-entropy, finite-area solar exergy model (Model 2), derived by Kabelac (1994) and subsequently applied to crop systems by Alzaben and Fraser (2025), provides a physically rigorous and computationally tractable framework for this analysis. Model 2 assumes non zero internal entropy production (consistent with the Carnot reversible engine analogy) and a finite canopy surface area, enabling calculation of solar exergy input as a function of canopy temperature, leaf area, and incident irradiance. It has been identified as the most appropriate model for controlled greenhouse applications where boundary conditions are stable and canopy temperature is the primary thermodynamic state variable (Alzaben and Fraser 2025; Bararzadeh Ledari et al. 2020).

This paper presents the first experimental application of Model 2 to characterize exergy flows across a four-level N/P treatment gradient in greenhouse-grown cucumber, with the following specific objectives: (1) compute all exergy balance components ($X_{\text{solar,in}}$, X_{emitted} , $X_{\text{reflected}}$, X_{chemical} , X_{des}) for each treatment level, (2) derive and evaluate the exergy performance index (Ψ_X) and normalized stress index as thermodynamic diagnostic metrics, (3) validate Model 2 through polynomial regression analysis of canopy temperature against exergy efficiency across the full treatment and temporal gradient; and (4) establish exergy-based nutrient stress classification thresholds for precision agriculture applications in cucumber production.

2.0 Materials and Methods

2.1 Experimental site and greenhouse conditions

The experiment was conducted in a glass-covered greenhouse at the University of Nigeria, Nsukka (6.23°E, 7.35°N, elevation 447 m), located in the humid tropical zone with pronounced wet-season conditions. The greenhouse (13.7 m × 7.6 m × 3.5 m, L×W×H) was equipped with natural roof-vent ventilation, drip irrigation for uniform water delivery, and LED supplemental lighting for cloudy-day photosynthetically active radiation (PAR) maintenance. Environmental conditions were maintained within the following ranges; daytime temperature 25–35°C, relative humidity 60–70%, PAR 800–1 500 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and soil moisture at 60–90% of field capacity.

2.2 Plant material, experimental design, and nutrient treatments

Cucumber (*Cucumis sativus* L.) was selected as the experimental species due to its demonstrated high sensitivity to N/P deficiency, economically significant greenhouse production status, and well characterized thermal stress responses (Islam et al. 2024, Nikolaou et al. 2017). Cucumber (*Cucumis sativus* L.) seeds were obtained from department of crop science University of Nigeria Nsukka (variety: Marketmore 76). The greenhouse experimental site was located at the University of Nigeria, Nsukka (coordinates: 6.23°E, 7.35°N; elevation 447 m). No wild collection occurred. A Randomized Complete Block Design (RCBD) was adopted, comprising 48 plants distributed across four spatial blocks (A - D), each containing four nutrient treatment replicates (n = 3 plants per treatment per block). Block assignment controlled for microenvironmental variation in light and temperature within the greenhouse. Treatments were randomly assigned within each block with weekly positional rotation to minimize microclimate bias. Four nitrogen and phosphorus treatment levels were applied through fertigation (calcium ammonium nitrate and urea in drip irrigation water) throughout the 44day experimental period as described in Table 1.

Table 2.1
Nutrient treatment levels and physiological interpretation.

Treatment	N/P Level (mg·kg ⁻¹)	Stress Category	Physiological Rationale
T1	120/40	Optimal	Full photosynthetic apparatus capacity, reference condition
T2	80/30	Moderate Stress	67% of optimal N, early chlorophyll and Rubisco reduction
T3	40/20	Severe Stress	33% of optimal N, substantial photosynthetic impairment
T4	0/10	Extreme Deficiency	Zero N supply, near-complete photosynthetic collapse
Note: N/P levels expressed as mg·kg ⁻¹ substrate dry weight. All other macro- and micro-nutrients were supplied at agronomically optimal levels across all treatments.			

2.3 Thermal imaging and canopy temperature acquisition

Canopy temperatures were acquired every four days over the 44day monitoring period (12 measurement occasions: Days 1, 4, 8, 12, 16, 20, 24, 28, 32, 36, 40, 44)

using a UTi120s professional thermal imager (120×90 pixel resolution, spectral range 7.5–14 μm, emissivity ε = 0.95, accuracy ± 2°C per manufacturer specification, UTi Technology Co. Ltd, Shenzhen, China). All images were captured at a fixed height of 20 cm above the leaf surface, with a consistent 45–90° incidence angle to minimize reflection errors. Measurements were conducted between 11:00 and

14:00 to maximize canopy-to-air temperature differentiation under peak irradiance. Instrument accuracy was validated against a calibrated type-K thermocouple ($\pm 0.5^{\circ}\text{C}$) on five representative plant surfaces at Days 8, 24, and 40, yielding a mean absolute error of $\leq 1^{\circ}\text{C}$ across 15 paired measurements. Thermal images were processed in MATLAB R2018B (MathWorks Inc.) using the Image Processing Toolbox. For each plant, a region of interest (ROI) was manually delineated excluding pixels within 5 mm of the pot edge and any pixel deviating more than

3°C from the canopy mean, to eliminate non-canopy contamination. Mean ROI canopy temperature (T_s) was extracted for all downstream exergy calculations. Atmospheric correction was not applied as measurements were conducted under controlled greenhouse conditions.

2.4 Computation of exergy balance components

Each cucumber plant canopy is modelled as a finite-area, open thermodynamic control volume. The exergy balance under quasi-steady-state conditions is shown in Eq. 2.1.

$$X_{\text{in}} = X_{\text{out}} + X_{\text{des}} \quad (2.1)$$

where the total exergy input X_{in} is the incident solar exergy $X_{\text{solar,in}}$, and the total exergy output X_{out} comprises three terms as seen in Eq. 2.2.

$$X_{\text{out}} = X_{\text{emitted}} + X_{\text{reflected}} + X_{\text{chemical}} \quad (2.2)$$

Exergy destruction X_{des} is therefore shown in Eq. 2.3.

$$X_{\text{des}} = X_{\text{solar,in}} - (X_{\text{emitted}} + X_{\text{reflected}} + X_{\text{chemical}}) \quad (2.3)$$

2.4.1 Solar exergy input ($X_{\text{solar,in}}$)

Solar exergy input was computed using the Model 2 formulation (Eq. 2.4) as:

$$X_{\text{solar,in}} = A \times G \times [1 - (4/3)(T_s/T_{\text{sun}}) + (1/3)(T_s/T_{\text{sun}})^4] \quad (2.4)$$

Where;

A is the effective photosynthetically active leaf area (m^2),

G is the measured incident solar irradiance (Wm^{-2}),

T_s is the canopy surface temperature in Kelvin, and

T_{sun} = 5 778 K (Eq. 2.4).

Leaf area per plant was estimated non-destructively using the length-width-correction factor method: $LA = L \times W \times k$, where $k = 0.75$ for broadleaf geometries, validated against a scanned leaf subset at harvest.

Incident irradiance was maintained at a controlled $800 \text{ W}\cdot\text{m}^{-2}$ throughout the experiment.

2.4.2 Emitted exergy (X_{emitted})

Exergy of longwave thermal radiation emitted by the canopy was computed using the Stefan–Boltzmann relationship with a Carnot efficiency correction using Eq. 2.5.

$$X_{\text{emitted}} = \varepsilon \times \sigma \times A \times (T_s^4 - T_a^4) \times (1 - T_a/T_s) \quad (2.5)$$

where $\varepsilon = 0.95$ (canopy emissivity), $\sigma = 5.67 \times 10^{-8} \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$, T_s is canopy temperature and T_a is ambient air temperature, both in Kelvin (Alzaben and Fraser 2025).

2.4.3 Reflected exergy ($X_{\text{reflected}}$)

Exergy of reflected shortwave solar radiation was calculated using Eq. 2.6

$$X_{\text{reflected}} = \alpha \times G \times A \times \phi_{\text{solar}} \quad (2.6)$$

Where;

α is the effective canopy albedo (reflectance coefficient) and

$\phi_{\text{solar}} = 0.93$ is the solar exergy factor derived from the Model 2 formulation at ambient temperature conditions (Kabelac 1994).

2.4.4 Chemical exergy (X_{chemical})

The chemical exergy stored in net biomass accumulation was computed using Eq. 2.7.

$$X_{\text{chemical}} = \Delta m \times b_{\text{bio}} \quad (2.7)$$

Where;

Δm (kg) is the net dry biomass increment measured gravimetrically and

$b_{\text{bio}} = 18.7 \text{ MJ}\cdot\text{kg}^{-1}$ is the standard specific chemical exergy of plant dry matter, consistent with the elemental-composition-based estimates established in the literature for C3 crops (Righetto and Mady 2023, Silva et al. 2015). Biomass gain was measured at weekly intervals using a calibrated digital balance (0.01 g resolution) after oven-drying at 60°C for 48 h.

2.4.5 Exergy destruction metrics

Exergy destruction was derived from the balance equation (Eq. 2.3) and further described using Eq. 2.8

$$X_{\text{des}} = T_o \times S_{\text{gen}} \quad (2.8)$$

Where;

X_{des} (W) is the exergy destruction rate and

S_{gen} (W·K⁻¹) is the rate of entropy generation within the control volume

2.5 Exergy performance index and stress quantification

To facilitate quantitative comparison across treatments, a relative exergy performance index ΨX was computed using Eq. 2.9.

$$\Psi X = 1 - (X_{des} / X_{in}) \quad (2.9)$$

This dimensionless index, bounded between 0 and 1, represents the fraction of incoming solar exergy not destroyed by irreversibility within the plant system. A normalised thermodynamic stress index is then derived as shown in Eq. 2.10.

$$\text{Stress Index} = (\Psi X_{opt} - \Psi X_{treatment}) / \Psi X_{opt} \quad (2.10)$$

Where;

ΨX_{opt} is the performance index under optimal nutrient conditions (T1).

This index ranges from 0 (no stress) to 1 (maximum stress within the experimental range) and enables objective, dimensionless comparison of thermodynamic degradation across treatments (Fraser and Kay 2004).

2.6 Statistical Analysis

Polynomial (second-order) regression analysis was employed to model the relationship between canopy temperature (independent variable) and exergy efficiency (dependent variable, defined as $\eta_{ex} = 1 - T_a/T_s$) over the 44day monitoring period ($n = 12$ time points per treatment). Separate regression models were fitted for each nutrient treatment. Model performance was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE). Analysis of variance (ANOVA) was applied to each regression to test statistical significance at the $\alpha = 0.05$ level. All analyses were performed in MATLAB R2018B using the polyfit, polyval, and anovan functions. The level of significance is indicated using standard abbreviations (** $p < 0.01$; * $p < 0.05$).

3.0 Results

3.1 Measured primary parameters and morphological responses

The progressive nutrient limitation resulted in measurable and monotonic changes in all primary plant parameters as shown in Table 3.1.

Table 3.1

Measured primary morphological and thermal parameters across N/P treatments (normalized to plant control volume, Day 32–44 mature canopy phase).

Treatment	Leaf Area A (m ²)	Canopy Temp Ts (K)	Albedo α	Biomass Gain (kg)
T1 (Optimal: 120/40)	0.48	300	0.18	0.0125
T2 (Moderate: 80/30)	0.45	303	0.20	0.0092
T3 (Severe: 40/20)	0.39	307	0.23	0.0054
T4 (Extreme: 0/10)	0.32	311	0.26	0.0021

Ts: mean canopy surface temperature during measurement period; ambient air temperature Ta = 298 K across all treatments.

From Table 3.1, Leaf area declined from 0.48 m² (T1, optimal) to 0.32 m² (T4, zero nitrogen), representing a 33% structural reduction driven by nitrogen's essential role in governing cell division and meristematic activity. Canopy temperature increased correspondingly from 300 K (T1) to 311 K (T4), reflecting the impairment of transpirational cooling as photosynthetic and stomatal regulatory capacity declined (Pineda et al. 2021; Nikolaou et al. 2017). Canopy albedo increased modestly from 0.18 (T1) to 0.26 (T4), consistent with chlorophyll degradation reducing light absorption efficiency. Biomass gain exhibited the most pronounced decline, from 0.0125 kg (T1) to 0.0021 kg (T4) reduction directly attributable to collapsed photosynthetic carbon fixation capacity (Evans 1989).

3.2 Exergy balance analysis

The results of exergy balance analysis are shown in Table 3.2. All the values represent mean exergy fluxes computed for the mature canopy phase. ($G = 800 \text{ Wm}^{-2}$, $T_a = 298 \text{ K}$, $\epsilon = 0.95$, $\phi_{\text{solar}} = 0.93$)

Table 3.2

Computed exergy balance components (W per plant) across N/P treatment levels.

Treatment	X _{solar,in} (W)	X _{emitted} (W)	X _{reflected} (W)	X _{chemical} (W)	X _{out} (W)	X _{des} (W)
T1 (Optimal)	357	42	64	234	340	17
T2 (Moderate)	334	61	67	172	300	34
T3 (Severe)	289	96	66	101	263	66
T4 (Extreme)	235	138	62	39	239	112

3.2.1 Solar exergy input (X_{solar,in})

Solar exergy input decreased monotonically from 357 W (T1) to 235 W (T4), a 34% reduction (Table 3.2, Fig. 3.1). This decline is attributable exclusively to the progressive reduction in effective

photosynthetically active leaf area under nutrient stress, as incident irradiance was maintained constant at $800 \text{ W}\cdot\text{m}^{-2}$ throughout the experiment. The intermediate treatments showed proportional intermediate reductions ($T_2 = 334 \text{ W}$; $T_3 = 289 \text{ W}$), establishing a clear morphological - exergetic coupling: nutrient availability governs canopy architecture, which in turn determines the fundamental energy budget entering the plant system.

4.2.2 Emitted exergy (X_{emitted})

Emitted exergy exhibited the most dramatic response to nutrient stress, increasing 3.3-fold from 42 W (T_1) to 138 W (T_4), with intermediate values of $T_2 = 61 \text{ W}$ and $T_3 = 96 \text{ W}$ (Table 3.2, Fig. 3.2). This non-linear escalation reflects the T_4 dependence of radiative heat transfer: the canopy temperature increase of 11 K from T_1 to T_4 ($300\text{--}311 \text{ K}$) is amplified by the quartic relationship into a disproportionately large radiative exergy signal (Kabelac 1994). Under optimal nutrition, robust transpiration driven by high photosynthetic activity maintains canopy temperature near ambient through evaporative cooling. As nitrogen limitation reduces photosynthetic capacity, transpiration rates decline, stomatal conductance decreases (Nikolaou et al. 2017), and leaf surface temperature rises dramatically increasing the radiative exergy dissipated to the environment.

4.2.3 Reflected exergy ($X_{\text{reflected}}$)

Reflected exergy remained relatively invariant across all treatments, ranging from 62 to 67 W with a coefficient of variation of only 3.4% (Table 3.2, Fig. 3.3). This constancy is mechanistically significant: it demonstrates that the primary exergetic failure under nutrient stress is metabolic and thermal rather than optical. Proportional reflectance increased from 17.9% (T_1 : $64/357 \text{ W}$) to 26.4% (T_4 : $62/235 \text{ W}$), however, indicating that while absolute reflectance is stable, a larger fraction of the reduced exergy budget is returned to the environment via reflection under severe stress.

4.2.4 Chemical exergy (X_{chemical})

Chemical exergy showed the most fundamental decline across treatments, decreasing from 234 W (T_1) to 39 W (T_4) an 83% reduction representing the near-complete collapse of the plant's primary energy conversion function (Table 3.2, Fig. 3.4). Intermediate treatments showed proportional degradation ($T_2 = 172 \text{ W}$; $T_3 = 101 \text{ W}$). Mechanistically, this decline directly reflects nitrogen's indispensable role as the central atom of chlorophyll and as a component of Rubisco, P700, P680, and cytochrome-b/c electron transport complexes (Evans 1989; Bararzadeh Ledari et al. 2020). Reducing nitrogen availability therefore simultaneously impairs light absorption, electron transport rate, and carbon fixation capacity a concerted collapse of the entire photosynthetic exergy conversion apparatus.

4.2.5 Exergy destruction (X_{des})

Exergy destruction increased from 17 W (T_1) to 112 W (T_4) (Table 3.2, Fig. 3.5), a six-fold escalation, exhibiting the largest proportional change of any exergy balance component and showing a roughly exponential progression: $T_1 = 17 \text{ W}$; $T_2 = 34 \text{ W}$ ($2.0\times$); $T_3 = 66 \text{ W}$ ($3.9\times$); $T_4 = 112 \text{ W}$ ($6.6\times$). The symmetry between the 6.6 -fold decrease in chemical exergy and the 6.6 -fold increase in exergy destruction is

physically non-coincidental: it directly expresses the Second Law energy not captured in biomass must be dissipated through entropy-generating irreversibilities (Fraser and Kay 2004). Mechanistic sources of accelerating exergy destruction under nutrient stress include: non-photochemical quenching of excess absorbed photons as thermal dissipation; disruption of metabolic pathway flux creating futile cycles with high entropy production; increased baseline respiration-to-photosynthesis ratio; and viscous dissipation from osmolyte synthesis under incipient water stress accompanying nutrient limitation.

3.3 Exergy performance index and normalized stress analysis

The exergy performance index (ΨX) declined systematically from 0.952 (T1) to 0.523 (T4), representing a 45% relative decline in Second Law efficiency (Table 3.3).

Table 3.3
Exergy performance indicators across N/P treatment levels.

Treatment	X_{des} (W)	$\Psi X = 1 - (X_{des}/X_{in})$	Stress index	Classification
T1 (Optimal: 120/40)	17	0.952	0.000	Adequate/Optimal
T2 (Moderate: 80/30)	34	0.898	0.057	Moderate Stress
T3 (Severe: 40/20)	66	0.772	0.189	Severe Stress
T4 (Extreme: 0/10)	112	0.523	0.450	Critical Deficiency

From Table 3.3, this degradation reflects two concurrent effects; diminished input exergy due to reduced leaf area (34% decrease) and dramatically increased exergy destruction. The T1 value ($\Psi X = 0.952$) indicates operation near theoretical reversibility, consistent with evolutionary optimization of the photosynthetic apparatus for minimal entropy production under adequate nutrient supply. The T4 value ($\Psi X = 0.523$) indicates severely compromised efficiency, with the system dissipating nearly double the exergetic fraction per unit input compared to optimal conditions.

The normalized stress index (Table 3.3, Fig. 3.6b) progressed as 0.000 (T1), 0.057 (T2), 0.189 (T3), and 0.450 (T4), revealing a non-linear, approximately exponential relationship between nutrient limitation intensity and thermodynamic degradation. The accelerating increments (0.057, 0.132, 0.261) demonstrate that early-stage stress (T2) causes modest efficiency loss (5.7% of maximum stress), while severe stress (T3, T4) causes disproportionately large efficiency collapse consistent with threshold-based physiological responses characteristic of biological systems where nutrient concentration below critical levels triggers cascading failures in photosynthetic apparatus assembly.

4.4 Validation (polynomial regression of canopy temperature against exergy efficiency)

Polynomial (second-order) regression analysis of canopy temperature versus exergy efficiency yielded statistically significant relationships across all four nutrient treatments, satisfying the predefined

validation criteria (Table 3.4). R^2 values ranged from 0.668 (T1, optimal) to 0.506 (T4, extreme deficiency), with all models significant at $p < 0.05$.

Table 3.4
ANOVA results for polynomial regression of canopy temperature versus exergy efficiency across N/P treatments.

Treatment	R^2	Adj. R^2	RMSE	F-stat	p-value	Significance
T1 (Optimal)	0.668	0.602	7.92	8.46	0.008	**
T2 (Moderate)	0.641	0.569	8.21	7.91	0.011	*
T3 (Severe)	0.582	0.498	8.87	6.25	0.020	*
T4 (Extreme)	0.506	0.407	9.31	5.14	0.033	*

** $p < 0.01$; * $p < 0.05$; $n = 12$ time points per treatment; DF regression = 2; DF residual = 9. RMSE units: $\times 10^{-3}$ exergy efficiency.

Under optimal nutrition (T1: $R^2 = 0.668$, $F = 8.46$, $p = 0.008$), the regression achieved the strongest coupling, indicating that approximately two-thirds of exergy efficiency variation is thermally explained even when plants are physiologically resilient. Under moderate stress (T2: $R^2 = 0.641$, $F = 7.91$, $p = 0.011$), the slight decrease in coupling strength (4.1 percentage points from T1) reflects emerging but not yet dominant physiological constraint. This treatment represents the operationally optimal diagnostic window: thermal efficiency coupling is strong ($R^2 > 0.64$) and the stress is still reversible with targeted fertilizer intervention. Under severe stress (T3: $R^2 = 0.582$, $F = 6.25$, $p = 0.020$) and extreme deficiency (T4: $R^2 = 0.506$, $F = 5.14$, $p = 0.033$), coupling strength declines progressively as metabolic instability increases and canopy temperature converges near-maximum values with reduced variance, limiting the discriminatory power of the thermal signal. The systematic decline in R^2 (16.2 percentage-point total decrease across the treatment gradient) establishes a critical practical principle; TIR-based exergy diagnostics are most reliable and actionable for early-to-moderate stress detection.

4.5 Proposed exergy-based nutrient stress classification

Based on the exergy efficiency ranges observed during the mature canopy phase (Days 32–44) and corroborated by the Ψ_X values, the following thermodynamically derived nutrient status classification thresholds are proposed for greenhouse cucumber (Table 3.5)

Table 3.5
Exergy efficiency-based nutrient stress classification thresholds for greenhouse cucumber.

Exergy performance index (ΨX) range	Nutrient status classification / Recommended management action
$\Psi X > 0.90$	Adequate to Optimal: No intervention required
$\Psi X = 0.77\text{--}0.90$	Moderate Stress: Monitor closely; consider targeted N/P supplementation
$\Psi X = 0.55\text{--}0.77$	Severe Stress: Fertilizer intervention required; yield penalty likely
$\Psi X < 0.55$	Critical Deficiency: Immediate corrective treatment necessary; high yield loss risk

4.0 Conclusion

This study provides a rigorous thermodynamic interpretation of nitrogen and phosphorus (N/P) nutrient stress in cucumber by integrating exergy analysis with thermal infrared diagnostics. The results demonstrate that nutrient stress is fundamentally a manifestation of reduced thermodynamic efficiency and increased irreversibility within the plant system, consistent with the First and Second Laws of Thermodynamics (Fraser and Kay, 2004; Bararzadeh Ledari et al., 2020). A major outcome is the inverse symmetry between chemical exergy and exergy destruction, both varying by a factor of 6.6 across treatments, confirming that reductions in biomass energy storage are directly dissipated as entropy. The increase in emitted exergy shows the diagnostic strength of thermal infrared imaging, where small canopy temperature elevations are amplified through T_4 radiative scaling, providing a sensitive indicator of physiological inefficiency. The stability of reflected exergy ($CV = 3.4\%$) further confirms that stress-induced failure occurs within the photosynthetic conversion system rather than canopy structure. Nitrogen/phosphorus were identified as the dominant regulator of photosynthetic exergy conversion, with an 83% reduction in chemical exergy linked to its biochemical role in chlorophyll, Rubisco, and electron transport systems (Evans, 1989; Bararzadeh Ledari et al., 2020). Model validation showed statistically significant thermal-efficiency coupling ($R^2 = 0.506\text{--}0.668$; $p < 0.05$), with stronger predictive capability under early-to-moderate stress, establishing this range as the optimal intervention window. Compared with prior studies (Lawrence et al., 2019, 2021; Alzaben and Fraser, 2025), this work advances the field through full exergy balance validation, dual nutrient stress analysis, and experimentally derived diagnostic thresholds. Therefore, this study confirms exergy destruction as the most sensitive stress indicator, establishes dimensionless performance indices for decision support, and demonstrates that thermal imaging, when grounded in exergy theory, provides a mechanistic and scalable tool for precision agriculture nutrient management.

Declarations

Author contributions

C.G.U.: Conceptualization, Methodology, Data Collection, Formal Analysis, Writing Original Draft. O.A.: Supervision, Writing Review and Editing. O.O.: Supervision, Writing Review and Editing. All authors have read and agreed to the published version of the manuscript.

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Conflict Of interest

The authors declare no conflict of interest.

Permissions for plant collection:

The cucumber seeds used in this study were commercially purchased/cultivated at the University of Nigeria Nsukka greenhouse facility (institution-owned land). No collection from government-owned land, private farmland, or protected areas was conducted. Therefore, no specific permits or licences were required. All activities complied with institutional research policies.

Data availability statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Consent to publish declaration

Not applicable.

Consent to participate declaration

Not applicable.

Ethics declaration

Not applicable. this study did not involve human participants, human data, human tissue, or animal subjects requiring ethical approval. This study involved cultivated cucumber plants (*cucumis sativus* L.), which are neither endangered nor protected species. no wild collection was performed. all plant handling complied with institutional guidelines of the university of Nigeria, Nsukka, and with local and national agricultural research regulations of Nigeria. no specific ethical approval was required for this study.

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Figures

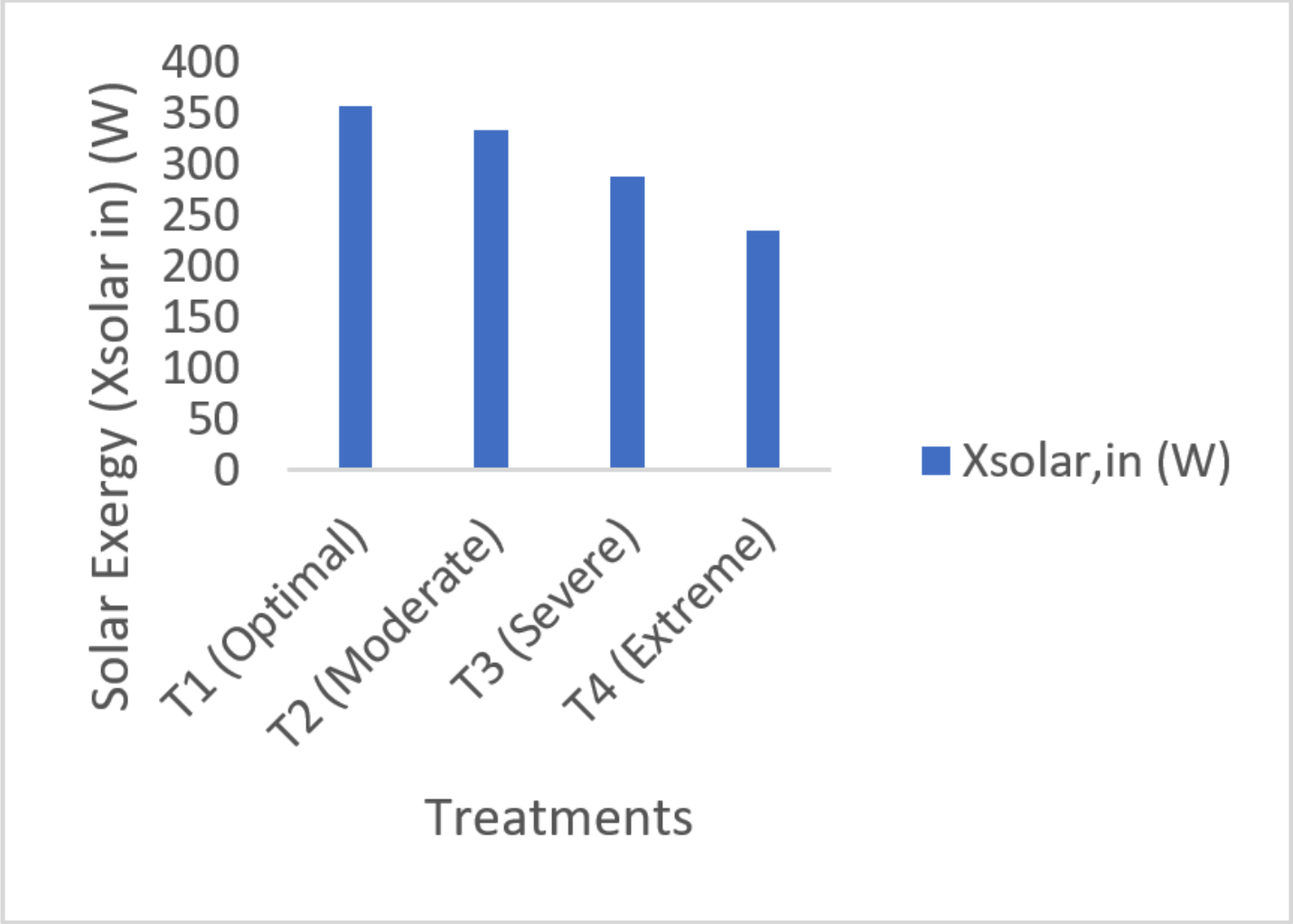


Figure 1

3.1: Computed Solar exergy in components (W per plant) across N/P treatment levels (T1-T4).

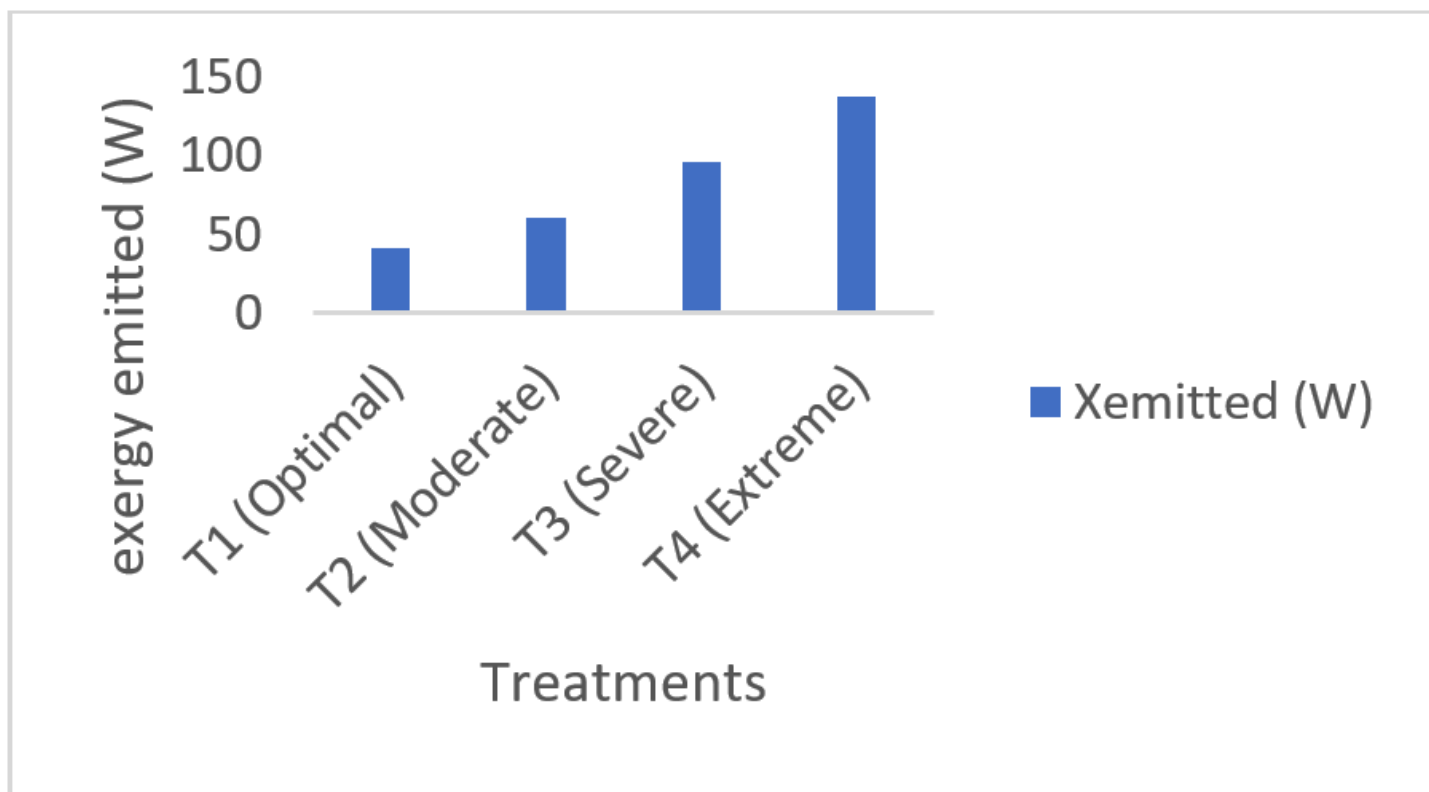


Figure 2

3.2: Computed exergy emitted components (W per plant) across N/P treatment levels (T1-T4).

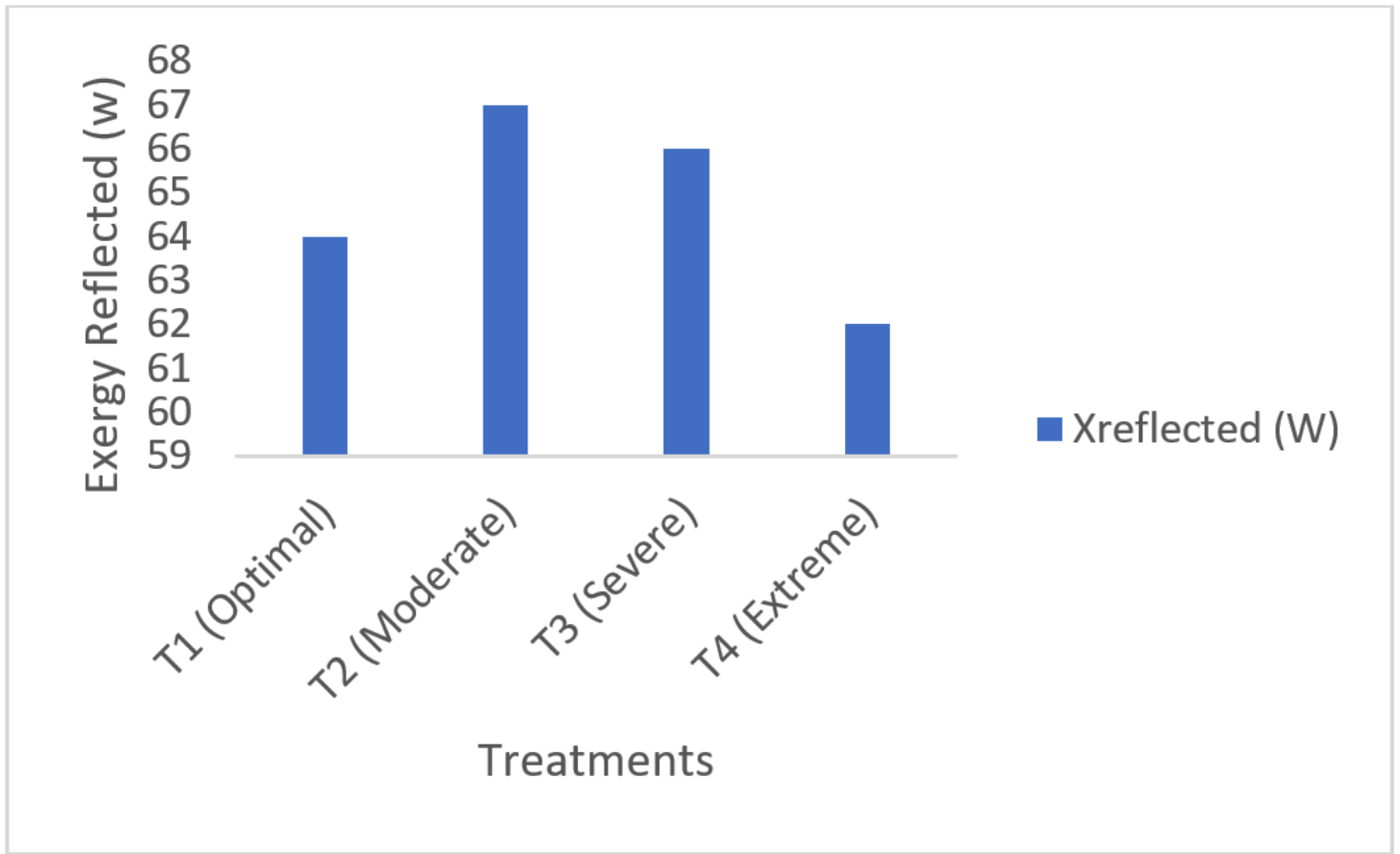


Figure 3

3.3: Computed exergy Reflected components (W per plant) across N/P treatment levels (T1-T4).

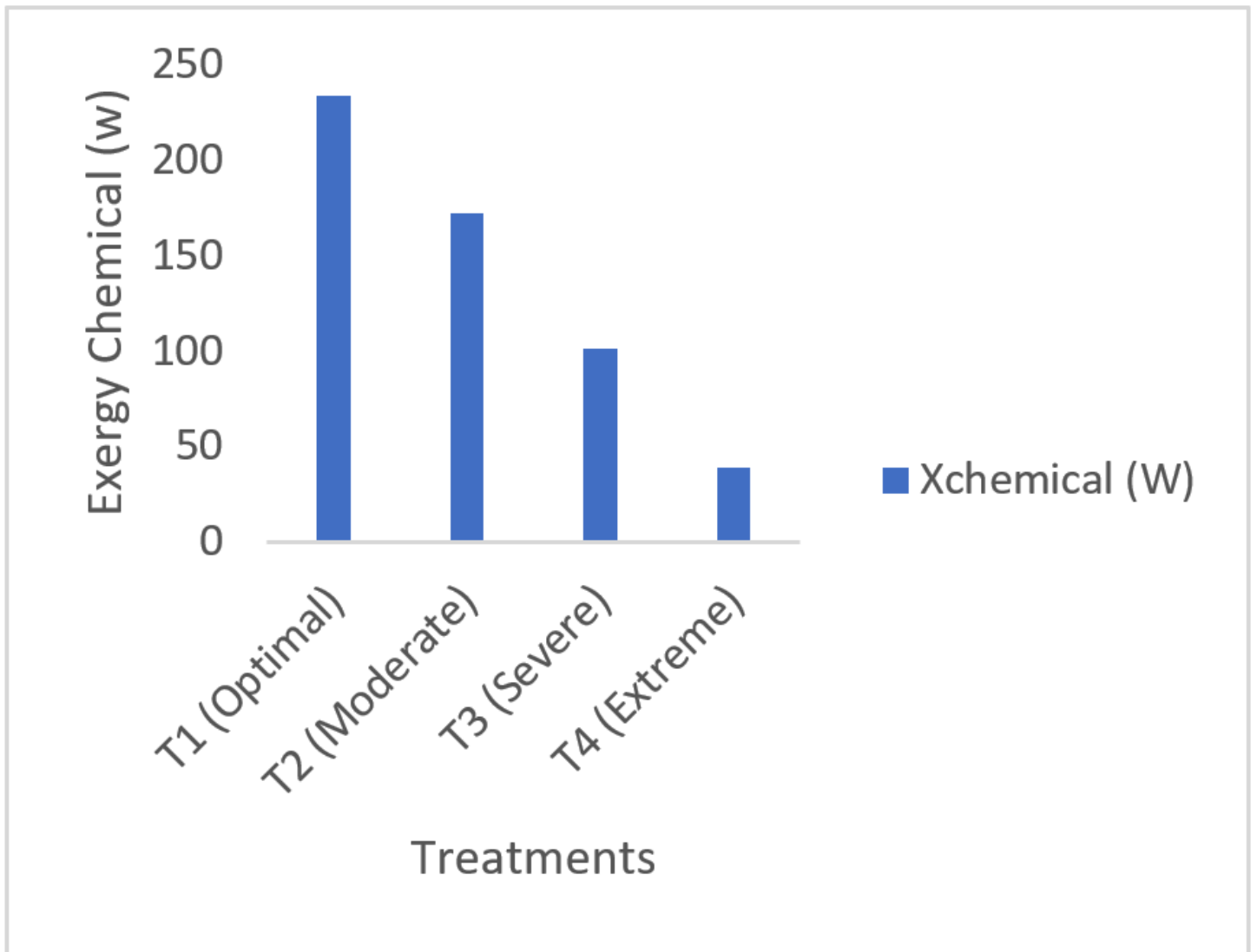


Figure 4

3.4: Computed exergy chemical components (W per plant) across N/P treatment levels (T1-T4).

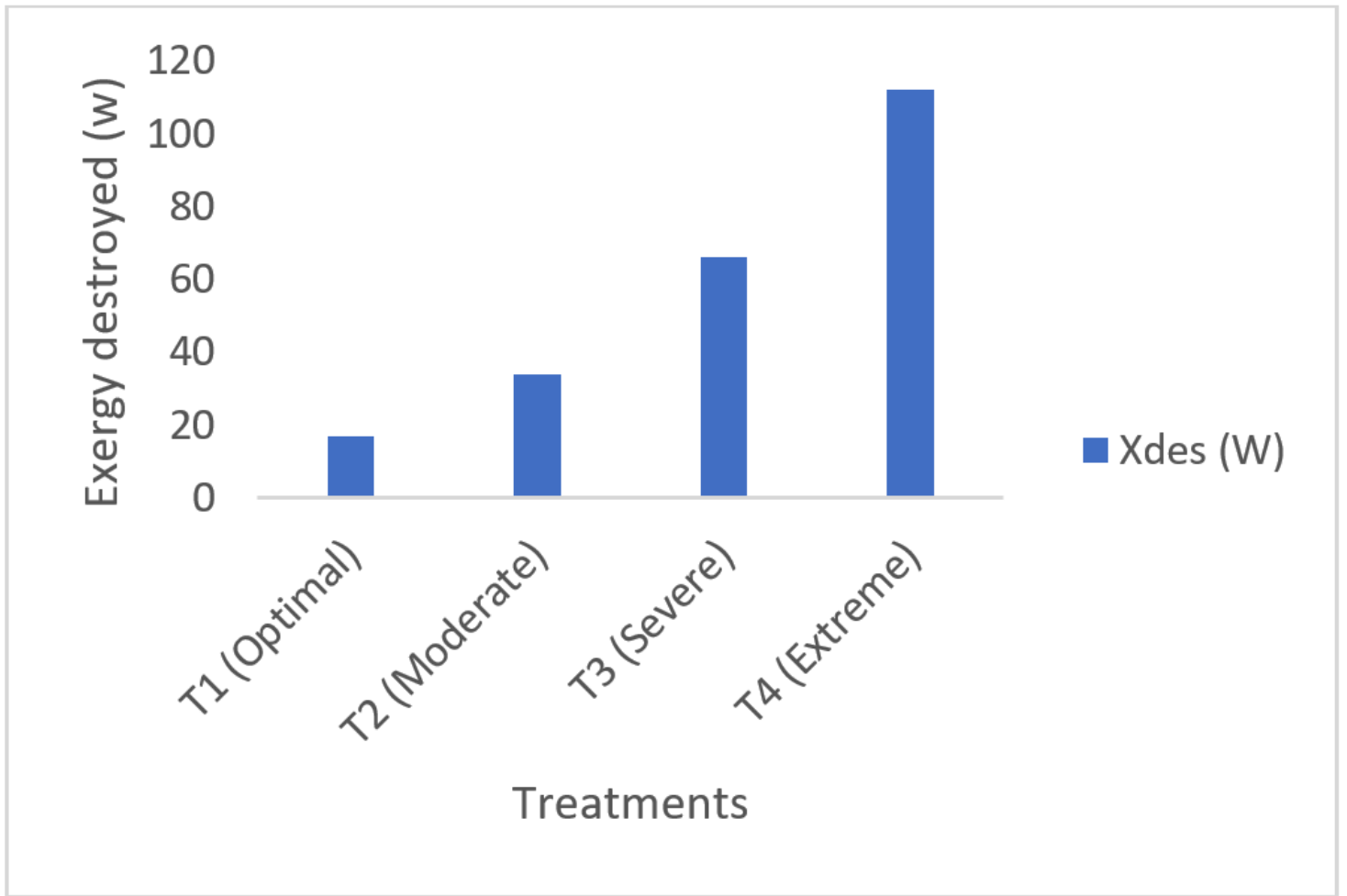


Figure 5

3.5: Computed exergy destroyed components (W per plant) across N/P treatment levels (T1-T4).

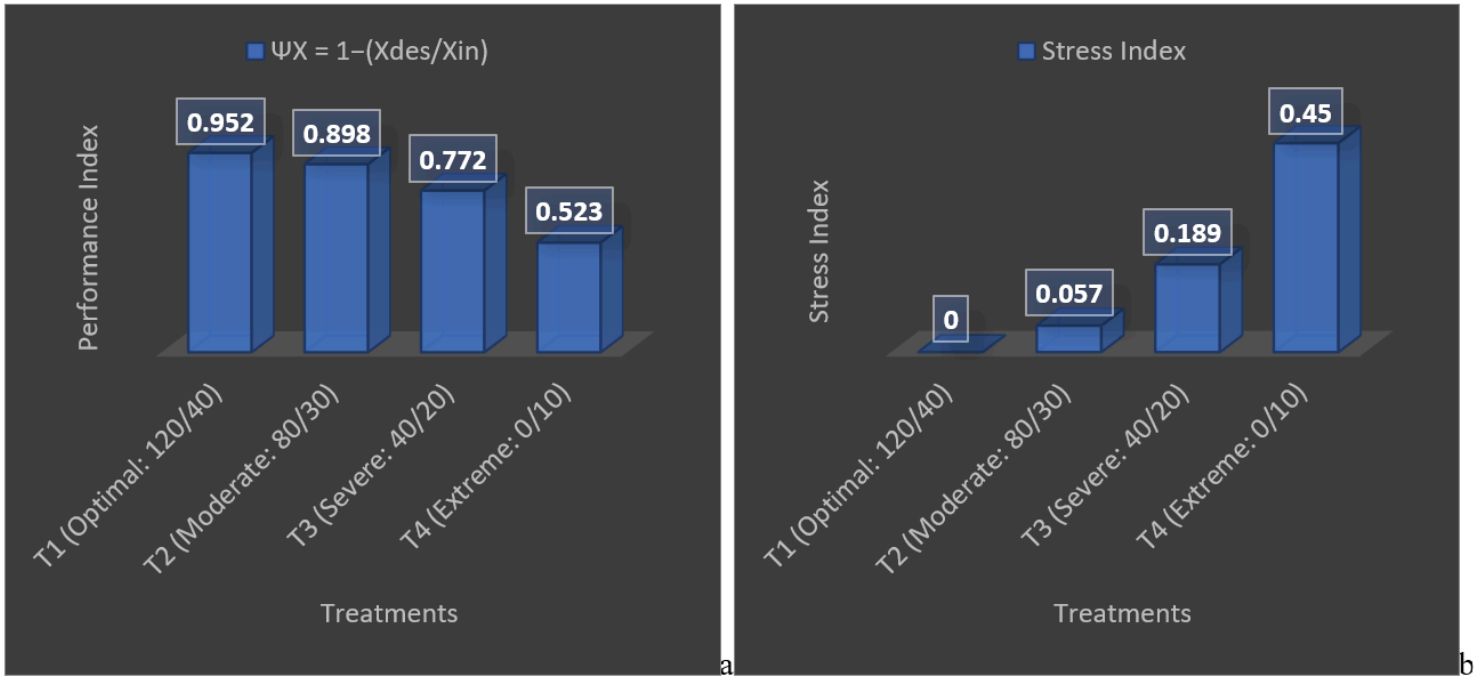


Figure 6

3.6 (a) Exergy performance index (b) Stress index analysis