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Maize–Soybean Intercropping as a Template for Sustainable Intensification: A Cross-Scale Methodological Framework Linking Field Productivity to Bioenergetic and GHG Indicators

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Abstract

Sustainable food systems require evaluation frameworks that both track yield growth and resource efficiency. This article is presented as a methodological and conceptual framework paper, not as a definitive empirical study of ATP-driven GHG mitigation. This study aims to operationalize the use efficiency of adenosine triphosphate (ATP) as a bioenergetic link between metabolic efficiency and greenhouse gas (GHG) mitigation in cereal–legume intercropping systems. The central methodological contribution is an explicit cross-scale upscaling protocol that links (i) the stoichiometric ATP cost of the nitrogenase reaction at the cellular level, to (ii) plot-level biological N_2 fixation estimated from fertilizer-displacement data, to (iii) system-wide embodied-energy accounting, and finally to (iv) field-level GHG mitigation modeled from literature-derived coefficients. This original research article presents 15 years of field data on optimizing crop architecture for enhanced rhizobial nitrogen fixation. This work resolves the Bioenergetic (ATP) paradox by documenting the trade-off between in planta metabolic ATP consumption

and system-level embodied energy savings, revealing net positive GHG mitigation. Compatible variety combinations (Giza 22 × S.C.10 in the Middle Delta, Giza 22 or Giza 111 × S.C.166 in the East Delta, Giza 22 × T.W.C.310 in Middle Egypt, and Giza 22 or Giza 111 × T.W.C.321 in Giza) performed better than incompatible varieties, with land equivalent ratios (LERs) of 1.25–1.61 and Monetary advantage index (MAI) of 0.29-0.61, reaching peak gross returns of USD 2711.60 ha^{-1}. These are direct empirical measurements. Compared with sole cropping, intercropping reduced system-wide adenosine triphosphate (ATP) requirements by 34–44%. By contrast, the ATP-saving ratio (34–44%) and the predicted GHG reductions (N_2Oe −28%; CO_2e −15%) are modeled estimates derived from coefficients reported in the literature and are presented here as illustrative outputs of the framework, not as experimentally validated fluxes. A canopy-compatibility diagram links the layout of erect-leaf canopies to light capture, biological N_2 fixation, ATP flux, and eco-efficiency. Future prospects for scaling, breeding, and direct flux measurement are described, and the matrices offer a repeatable template for sustainable intensification evaluation in cereal–legume systems. We explicitly acknowledge the methodological limitations of cross-scale upscaling and identify direct-flux validation as the critical next step.

Keywords: sustainable food systems, intercropping, ATP use efficiency, GHG emissions, productivity matrix, MAI, eco-efficiency, LER.

Sustainable food systems require evaluation frameworks that balance production growth with resource efficiency. "Producing more from less" is the defining challenge of modern agronomy,

driven by the convergence of urbanization, global population expansion, and environmental degradation[1]. Intercropping, the simultaneous cultivation of two or more crops on the same land, is a primary strategy for sustainable intensification[2]. In cereal–legume systems, such as maize and soybean, intercropping enhances land-use efficiency, water productivity, and biological nitrogen fixation (BNF) through metabolic complementarity. While the agronomic and economic benefits of intercropping are well-documented, a critical knowledge gap remains regarding the bioenergetic mechanisms that link in-plant metabolic energy flux to system-level fossil energy displacement and greenhouse gas (GHG) mitigation. Specifically, the role of adenosine triphosphate (ATP)—the universal cellular energy currency that drives crop growth, photosynthesis, and the nitrogenase reaction in rhizobia—has not been operationalized as a quantitative, system-level indicator. Any cropping arrangement that replaces synthetic nitrogen fertilizer with biologically fixed nitrogen fundamentally rewires the farm's energy and emission budgets. However, existing sustainability indicators often fail to capture this metabolic-to-systemic energy substitution. Treating ATP as an agronomic indicator transforms the intercrop's invisible metabolism into a quantifiable metric that bridges the productivity and environmental domains, resolving the bioenergetic paradox of increased biological ATP flux resulting in decreased system-wide fossil energy demand. A persistent methodological challenge in linking plant bioenergetics to system-level sustainability is the upscaling gap: cellular ATP fluxes operate at the micromolar and millisecond scale, whereas field productivity and GHG emissions

operate at the hectare and season scale. Conventional agronomic studies rarely bridge these scales explicitly, and sustainability indicators that conflate them risk ecological fallacy. This paper addresses that gap by proposing a structured, four-tier upscaling protocol (cell → nodule → plot → system) and by transparently separating (a) what is directly measured in the field, (b) what is biochemically inferred from stoichiometry, and (c) what is modeled from literature coefficients. We do not claim that the field data alone prove ATP-driven GHG mitigation; rather, we offer the framework as a testable, repeatable method that future work—using chamber-based and eddy-covariance flux measurements—can validate. To address this gap, this study analyzes a 15-year empirical dataset comprising five field experiments conducted across four Egyptian agro-climatic zones. These experiments evaluated the economic yield, land equivalent ratio (LER), and varietal compatibility of maize–soybean intercropping. By organizing this data into interconnected productivity and eco-efficiency matrices, we aim to quantify the bioenergetic trade-offs of sustainable intensification. Therefore, the specific objectives of this study are to: (i) propose a four-domain sustainable intensification framework for maize–soybean intercropping with an explicit cross-scale upscaling protocol; (ii) develop repeatable productivity and resource-efficiency matrices based on long-term primary field data as an illustrative application of the framework; (iii) define ATP use efficiency as the bioenergetic link between resource use efficiency and GHG mitigation, clearly distinguishing measured from

modeled quantities; and (iv) determine future research and scaling priorities for climate-smart cereal–legume systems, with direct-flux validation as the primary recommendation.

The Sustainable Intensification Assessment Framework for Maize–Soybean Intercropping

The framework applied evaluates intercropping against four mutually reinforcing domains (Fig. 1). The framework used in this study assesses intercropping across four domains that reinforce one another: productivity and resource use efficiency, economic viability, environmental sustainability, and social well-being. Productivity measures, including the LER and WUE, ensure that gains in yield do not occur at the cost of resource depletion. Economic viability is evaluated using gross returns and the monetary advantage index (MAI), which ensures long-term financial feasibility for producers. Environmental sustainability is tracked through GHG emissions (N_2Oe and CO_2e) as well as soil health indicators. Importantly, this study presents the ATP-saving ratio as a novel indicator that links metabolic energy demand to the emission footprint of mineral N fertilizer. Lastly, social well-being is recognized through the risk stabilization and nutritional diversity that the legume component provides.

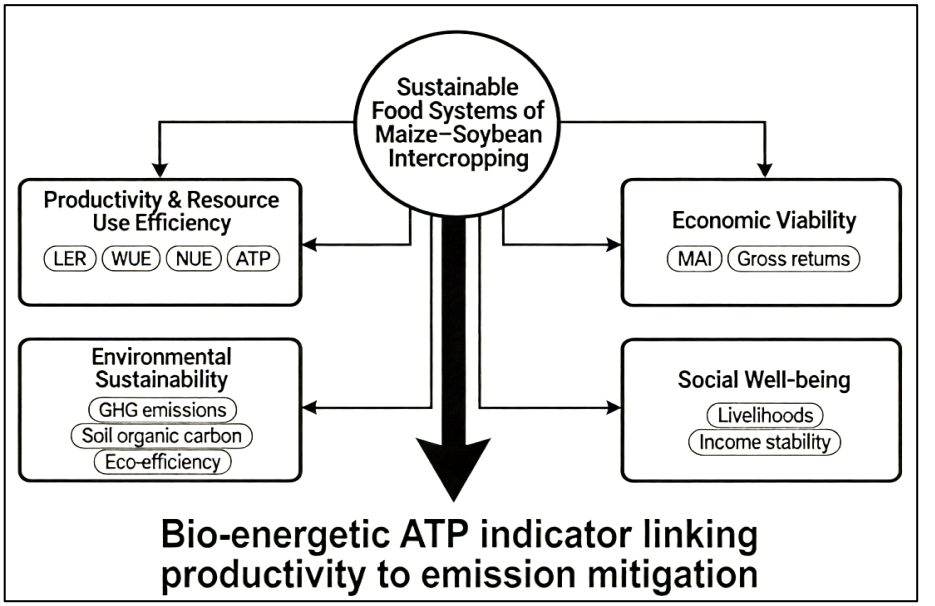

Figure 1. A sustainable food systems framework for maize–soybean intercropping.

Productivity and Resource Use Efficiency

These measures ensure that advances in yield do not come at the expense of resource depletion by assessing the output produced per unit of manufactured or natural input. There are three families of indicators used. LER[3], which indicates the relative area required under sole cropping to produce the same yield as one unit of intercropped land at the same management level, is used to aggregate productivity per unit of land area, which is expressed as soybean seed and maize grain yields (t ha^{-1}) under intercropping versus sole cropping. The ratio of crop output to water applied (grain or seed yield per kg or per m^3 of irrigation water) is known as water use efficiency, or WUE[4]. WUE is a first-order constraint on any intensification strategy in water-scarce Egypt, where agriculture competes with municipal and industrial demand for a fixed Nile allocation. It has been repeatedly demonstrated that intercropping increases system WUE

in comparison to sole cropping[5,6]. The reduction of mineral N fertilizer made feasible by soybean N2 fixation serves as a proxy for nutrient utilization efficiency (NUE)[7]. Furthermore, since ATP is essential for cell division, supplying inorganic phosphate for photophosphorylation (ATP + H2O → ADP + P + energy)[8], and activating enzymes for starch and sucrose synthesis, the ATP requirement per hectare is introduced as a bioenergetic indicator of resource use efficiency[9]. This chapter's conceptual turning point is treating ATP as an agronomic indication rather than just a biological curiosity; it transforms the intercrop's invisible metabolism into a number that can coexist in the same matrix as yield, water, and fertilizer.

Economic Viability

Long-term financial viability for the producer is a prerequisite for sustainable practices. There are two indicators in use. To compare intercrop and sole systems directly, gross returns per hectare are calculated by monetizing seed and grain yields at conventional market pricing (soybean USD 600 t^{-1}; maize USD 220 t^{-1}). The monetary advantage index (MAI), a stability-weighted proxy for the longevity of the economic benefit of intercropping over sole cropping, is calculated by multiplying the relative yields of the intercrop components[10]. The MAI value, which was computed as MAI = [Value of combined intercrops × (LER − 1)]/LER, indicates the cropping system's profit. MAI recommends that the economic assessment be expressed in terms of the value of land saved, which can likely be assessed most reliably on the rentable value of this land.

Environmental Sustainability

Agricultural operations must reduce adverse ecological effects to achieve sustainable intensification. There are three indicators monitored. The carbon footprint per unit of production is used to quantify GHG emissions, which are operationalized using cumulative N_2Oe and CO_2e as well as N_2Oe intensity[11,12]. Over several-year evaluation cycles, trends in soil health and carbon storage are captured by soil organic carbon[13]. In this chapter, the ATP-saving ratio, which connects metabolic energy demand with the emission footprint of mineral N fertilizer manufacture and application, and GHG emissions are used to operationalize eco-efficiency, which contrasts optimal economic output against environmental harms. G-equivalent emissions (cumulative N_2Oe and CO_2e, as well as N_2Oe intensity) per cropping system[14].

Social Well-Being

The approach keeps social well-being as an explicit domain because intercropping systems directly influence rural livelihoods[15], despite the biophysical matrices dominating the quantitative core of this article. In comparison to sole cropping, intercropping maize and soybeans spreads agronomic and price risk, stabilizes seasonal labor demand, and diversifies household income across two marketable harvests. The soybean component connects field practice to nutrition security by providing local food systems with edible oil and high-quality plant protein[16]. As synthetic N prices follow erratic energy markets, smallholder adoption of appropriate

intercropping configurations also lessens sensitivity to N fertilizer price shocks, an increasingly significant aspect of rural welfare[17].

A Cross-Scale Upscaling Protocol

The central methodological contribution of this paper is an explicit protocol for upscaling bioenergetic quantities across four nested scales. We present this protocol as a candidate method that can be refined and validated by future empirical work.

Scale	Unit of analysis	Quantity	Source of value	Uncertainty class
Tier 1 — Cellular	Nitrogenase enzyme reaction	16 mol ATP · mol^{-1} N_2 fixed	Biochemical stoichiometry (Ipata & Pesi, 2015)	Low (well-established)
Tier 2 — Organ / Nodule	Soybean root nodule ATP flux	~800 kJ · mol^{-1} N_2 ≈ 28.5 MJ · kg^{-1} N fixed	Derived from Tier 1 + thermodynamics	Low–Moderate
Tier 3 — Plot	Biological N_2 fixation rate (kg N ha^{-1} $season^{-1}$)	Inferred from 17–25% reduction in mineral N fertilizer requirement (El-Shamy et al., 2015; Zhang et al., 2023)	Field-adjacent proxy, not direct ^{15}N-isotope or ureide measurement	Moderate–High
Tier 4 — System	System-wide embodied fossil energy (ATP-equivalent) and predicted GHG	Sum of Haber–Bosch energy (35–40 MJ · kg^{-1} N; Menegat et al., 2022) + diesel equivalents for field operations; GHG modeled via literature coefficients	Modeled, not directly measured in the Egyptian experiments	High

		(Raseduzzaman et al., 2024; Zhang et al., 2024)		

Table 1. Resource efficiency, ATP, and predicted GHG matrix (predicted GHG modeled as mitigation percentages relative to sole-cropping baselines, driven by the ATP-saving ratio).

Critical assumptions and their implications:

1. The fertilizer-displacement proxy (Tier 3) is not a direct measurement of biological N_2 fixation. It is inferred from the reduction in mineral N applied to intercrops relative to sole maize. True BNF rates should be validated by ^{15}N-isotope dilution or acetylene-reduction assays in future work.

2. The ATP-equivalent conversion (Tier 4) treats fossil-fuel embodied energy and biological ATP as commensurable through an energy-equivalence lens. This is a deliberate accounting choice, not a biological identity. Biological ATP is solar-derived and contemporary; fossil embodied energy is geological and cumulative. The two should not be conflated.

3. The GHG mitigation values (Tier 4) are modeled from literature coefficients applied to a sole-cropping baseline that was not itself measured in the Egyptian experiments. They are therefore predicted mitigations, not observed fluxes.

ATP as the Bio-Energetic Currency of Sustainable Intensification

The concept of ATP as the bioenergetic currency of sustainable intensification is central to this framework. Fundamentally, every ton of harvested grain embodies solar energy converted into chemical work, which is recorded in ATP. Biological N_2 fixation (BNF) in soybean root

nodules is metabolically costly, needing roughly 16 ATP molecules for each molecule of N_2 reduced. This internal metabolic cost, however, must be kept distinct from system-level embodied energy. Although BNF consumes plant photosynthate, it replaces the industrial Haber-Bosch process, which demands ~35–40 MJ of fossil energy per kg of N produced. Intercropping therefore raises the biological ATP flux within the plant while lowering system-wide fossil energy demand, because solar-driven metabolic processes take the place of fossil-fuel-derived synthetic inputs. This substitution is the master variable that links metabolic efficiency to GHG mitigation. Optimized crop architectures, such as erect-leaf canopies, support this process by improving light capture for the understory soybean, thus sustaining the ATP-intensive nitrogenase reaction without reducing maize yields.

ATP in Plant Metabolism: Starch, Sucrose, and Photophosphorylation

At its core, each ton of harvested grain is a record of solar energy that has been captured and transformed into chemical work[18]; the ledger of this conversion is stored in ATP[19]. In the cytosol and amyloplast, ATP initiates the enzyme cascades that build sucrose and starch[20]; in the chloroplast, photophosphorylation produces ATP from ADP and inorganic phosphate; and in every meristem, ATP drives the biosynthesis and polymerization events of cell division[21]. Thus, the common denominator of crop growth is the hydrolysis reaction $ATP + H_2O \rightarrow ADP + P_i +$ energy, and the amount of ATP needed per hectare increases with the cropping system's biomass and grain yield[22]. Because of this, ATP can serve as a bioenergetic indicator of the

efficiency of resource use: a system that generates more yield per unit of ATP expended is, by definition, extracting more useful work from the energy that flows through it, both solar and fossil[23].

ATP and Biological Nitrogen Fixation: The Nitrogenase Budget

Biological N_2 fixation (BNF) in soybean root nodules is the intercrop process that requires the greatest ATP[24]. For every molecule of N_2 reduced, the nitrogenase reaction uses about sixteen ATP molecules[25]. To resolve the Bioenergetic (ATP) paradox, it is critical that one distinguishes between in planta metabolic ATP and system-level embodied energy (i.e., GHG mitigation). The explicit biochemical equation for the nitrogenase reaction is $N_2 + 8\ H^+ + 8e^- + 16$ Mg ATP $\rightarrow 2\ NH_3 + H_2 + 16$ Mg ADP + 16 Pi. Under physiological conditions, hydrolysis of 16 mol ATP would yield ~50 kJ/mol, meaning that fixing 1 mol of N_2 (28 g of N) requires ~800 kJ or ~28.5 MJ per kg of N fixed, which is entirely captured in contemporary photosynthate (solar-derived). In contrast, the industrial Haber-Bosch (H-B) process requires ~35-40 MJ per kg N produced, primarily from fossil (natural gas) sources, for both chemical feedstock and high-pressure/high-temperature energy requirements. However, the paradox is resolved by noting that the scale of these metrics is different. While BNF is indeed metabolically 'expensive' for the plant (consuming ~800 kJ ATP in photosynthate), its substitution of an industrial process, which is equally or more 'expensive' at the system level (~35-40 MJ fossil kg^{-1} N), results in a strongly positive overall GHG mitigation due to the plant's ATP using contemporary solar

capture (not ancient carbon). An actively fixing symbiosis can be identified by high biological ATP flux in nodules, which is the metabolic marker of a system that imports N from the atmosphere as opposed to a fertilizer bag[26]. This leads to the apparent paradox that drives this chapter: intercropping increases biological ATP flux in the rhizosphere (by promoting fixation) while decreasing system-wide ATP demand (by displacing the embodied energy of synthetic inputs). The secret to accurately reading the matrices is to resolve this dilemma.

Optimized ATP Allocation and System-Level Fossil Energy Substitution

The conceptual connection between crop architecture and GHG mitigation must be interpreted via the lens of ATP allocation efficiency and fossil energy substitution, not thermodynamic 'saving' of ATP. Optimized crop architecture (e.g., erect-leaf canopies allowing penetration of light into the soybean understory) does not 'save' or 'form' ATP in a biological sense; actually, biological N_2 fixation increases the plant's internal metabolic ATP flux. Intercropping, then, allows for the allocation efficiency of photosynthate-derived ATP to be optimized. By favoring root architectures and canopy designs that host highly efficient rhizobial strains in optimal soil zones, the plant is able to minimize non-productive respiratory carbon loss and reduce the carbon opportunity cost of nitrogen acquisition. The 'ATP-saving ratio' used in our matrices refers specifically to substitution of system-level fossil embodied energy (from synthetic N fertilizer manufacturing, transport, and mechanical field passes) by solar-driven metabolic ATP[27]. Intercropping reduced system-wide fossil energy requirements (embodied energy equivalent) by

34–44% across all Egyptian investigations[5,6,28-31]. This is strictly driven by the displacement of synthetic N fertilizer and associated mechanical operations, not by a reduction in the plant's biological ATP consumption.

The ATP–GHG Nexus: From Metabolic Flux to Emission Footprint

The bio-energetic substitution ratio links the carbon footprint of mineral N fertilizer with the optimization of metabolic ATP allocation[9]. The Haber–Bosch synthesis of ammonia is among the most energy-intensive industrial processes on Earth, and its CO_2e burden, together with the N_2Oe released from fertilized soils, makes synthetic N the dominant emission hotspot of cereal production[32]. The farm replaces fossil fuel-driven industrial energy with solar-driven metabolic energy when compatible maize–soybean canopies increase biological ATP flux into nodules, displacing fertilizer N[33]. Enhanced N fixation decreased the need for mineral N fertilizer by up to 17% in Egypt and 25% in China[34,35], and the 34–44% drop in system-wide embodied fossil energy mirrors the 15–28% drop in GHG equivalents reported in this paper. Higher eco-efficiency of compatible maize–soybean intercropping systems is directly linked to reduced reliance on synthetic N fertilizers, and ATP usage efficiency and GHG mitigation are two readings of the same underlying process.

Materials and methods

Sites, Soils, and Agro-Climatic Zones

Five field experiments carried out over fifteen years (2009 – 2024) on clay and sandy soils in four Egyptian agroclimatic zones (the Middle Delta, the East Delta, Giza, and Middle Egypt) make up the original empirical dataset analyzed in this study. The experiments were conducted at the following locations: Sakha Agricultural Research Station, Kafr El-Sheikh Governorate (Middle Delta, 31.07°N, 30.94°E); Ismailia Agricultural Research Station, Ismailia Governorate (East Delta, 30.58°N, 32.27°E); Giza Agricultural Research Station, Giza Governorate (30.01°N, 31.21°E); and Mallawi Agricultural Research Station, Minya Governorate (Middle Egypt, 27.73°N, 30.84°E). We did not obtain permits for the areas mentioned because the research stations there fall under the Agricultural Research Center in Giza; agricultural research stations affiliated with this center are distributed across all of Egypt's governorates. Soil characteristics before planting were as follows: Middle Delta—clay texture, pH 7.8, organic matter 1.9%; East Delta—sandy, pH 7.5, organic matter 0.85%; Giza—clay, pH 7.6, organic matter 1.6%; Middle Egypt—loamy clay, pH 7.9, organic matter 1.1%.

Genetic Material and Cropping Systems

Six soybean varieties (Crawford, Giza 21, Giza 22, Giza 35, Giza 82, and Giza 111) and six maize varieties (S.C.10, S.C.122, S.C.166, S.C.176, T.W.C.310, and T.W.C.321) were used in the studies. Three intercropping systems were employed in contrast to soybean and maize sole cropping: mixed-row intercropping (100% maize + 50% soybean), two rows of maize alternating with two rows of soybean (2 maize: 2 soybean), and two rows of maize alternating with

four rows of soybean (2 maize: 4 soybean). In accordance with El-Shamy et al.[34] and Metwally et al.[36], soybeans were sown three weeks before maize to allow the legume to start nodulation before canopy closure. Each experiment was arranged in a split-plot design with three replications. Irrigation was applied via surface furrow irrigation (sprinkler irrigation was the irrigation system in East Delta) to meet crop evapotranspiration requirements. During soil preparation, phosphorus fertilizer (as superphosphate, 15.5% P_2O_5) was applied at a rate of 357 kg ha^{-1}, meanwhile, potassium fertilizer (as potassium sulfate, 48% K_2O) was applied at 119 kg ha^{-1} before the first irrigation. Nitrogen fertilizer (as ammonium nitrate, 33.5% N) was applied at 285.6 kg N ha^{-1} for sole maize; reduced by 17–25% for intercrops based on the soybean N_2-fixation contribution. Harvesting was performed manually at physiological maturity for both crops.

Studied Data

Tier 3: Plot-level empirical metrics (directly measured):

To calculate LER[3], relative yields were calculated by dividing each component's intercrop yield by its sole-crop yield: LER = (Yab/Yaa) + (Yba/Ybb), where Yaa is the pure stand yield of crop a (maize), Ybb is the pure stand yield of crop b (soybean), Yab is the intercrop yield of maize, and Yba is the intercrop yield of soybean. Using soybean at USD 600 t^{-1} and maize at USD 220 t^{-1} (market prices for 2026), MAI was calculated[10]: MAI = [Value of combined intercrops × (LER − 1)]/LER. Constant 2026 market prices were applied across the entire 15-

year dataset to standardize the economic evaluation, eliminate the confounding effects of inflation and currency fluctuation, and allow for a consistent comparison of the agronomic and biological performance of the cropping systems across different years and locations.

Tier 3–4: Bioenergetic and emission metrics (modeled):

System-wide ATP demand (embodied energy equivalent) was calculated by summing the fossil energy equivalents of all agricultural inputs using standard conversion coefficients from the literature. Specifically, the embodied energy of synthetic N fertilizer was calculated based on the Haber–Bosch process energy requirement of approximately 35–40 MJ per kg N produced[27], converted to ATP-equivalent units. The energy for mechanical field operations (land preparation, planting, irrigation pumping, and harvesting) was estimated using standard diesel fuel energy equivalents (38.6 MJ L^{-1}) scaled to the number of fields passes. Biological ATP flux was estimated based on the stoichiometric requirement of 16 mol ATP per mol of N_2 fixed by the nitrogenase reaction[25], scaled to the estimated biological N_2 fixation rates derived from the reduction in mineral N fertilizer requirement (17–25%) in the intercrop systems. The ATP-saving ratio was calculated as ATP-saving ratio = [(System-wide ATP demand_sole − System-wide ATP demand_intercrop) / System-wide ATP demand_sole] × 100. It is important to note that "system-wide ATP demand" refers to the fossil-fuel-derived embodied energy of external inputs expressed in ATP-equivalent units, whereas "biological ATP flux" refers to the in planta metabolic ATP consumed by nitrogenase in root nodules, derived from contemporary

photosynthate (solar energy). These two quantities operate at different scales and energy sources, as detailed in the introduction.

Using the reduction coefficients compiled in Table 3 from Raseduzzaman et al.[37] and Zhang et al.[38], predicted emissions were modeled as proportional mitigation percentages relative to sole cropping baselines because absolute baseline GHG emissions were not disclosed for each Egyptian region. Therefore, all GHG values reported in this study are modeled estimates, not direct field measurements of GHG fluxes.

Statistical Analysis

Data from each experiment were subjected to analysis of variance (ANOVA) appropriate for a Split – plot design using MSTAT-C. Treatment means were compared using the Least Significant Difference (LSD) test at a significance level of $p \leq 0.05$. Due to the varying agro-climatic conditions, soil types, and management histories across the four regions, the five field experiments were analyzed separately rather than as a combined multi-environment trial. The synthesis matrices were constructed using the mean values of the compatible treatments from each respective location. Percentage-based metrics (ATP-saving ratio, predicted GHG mitigation) were derived from these treatment means and are presented as deterministic point estimates derived from literature coefficients. They are not statistically tested comparisons, and no confidence intervals are reported because the underlying coefficients were not estimated from the

Egyptian dataset. Future work should propagate uncertainty from each tier of the upscaling chain using Monte Carlo or Bayesian methods.

Results and Discussion

The Yield–Economic Viability Matrix (Empirical)

Table 2 reports directly measured agronomic and economic outcomes. These results are robust within the experimental design (split-plot, three replications, LSD at $p \leq 0.05$). They do not, however, constitute evidence about ATP fluxes or GHG emissions; those quantities are addressed separately in Section 5.2 as modeled outputs of the framework. The yield-economic viability matrix is shown in Table 1. With LERs of 1.25–1.61 and MAI of 0.29–0.61, compatible variety combinations fared better than incompatible varieties. The Giza experiments, monetized at standard market rates, produced the highest absolute gross returns, peaking at USD 2711.60 ha^{-1} for Giza 111 × T.W.C.321 in Experiment III, driven by the maize component achieving 0.99 of its sole cropping yield potential while simultaneously harvesting a valuable soybean understory. The Middle Egypt combination Giza 22 × T.W.C.310 achieved the highest LER (1.61) and MAI (0.61). Giza 22 × S.C.10 produced USD 2430.40 ha^{-1} in the Middle Delta. Importantly, the potential economic benefit extends beyond gross revenue: compatible intercropping lowers system-wide ATP requirements by 34–44% and mineral N fertilizer requirements by 17–25%.

Region/Study	Combination soybean x maize	System	Intercrop yields (t ha⁻¹)		Total return inter-crop (USD ha⁻¹)	Sole crop returns (USD ha⁻¹)		LER	MAI
			soybean	maize		soybean	maize		
Middle Delta	Giza 22 × S.C.10	Mixed-row	1.66	6.52	2430.4	2034	1568	1.39	0.44
East Delta	Giza 22 × S.C.166	2:4	2.12	3.65	2075	1344	1124	1.54	0.59
East Delta	Giza 111 × S.C.166	2:4	2.00	3.58	1987.6	1344	1124	1.54	0.59
Middle Egypt	Giza 22 × T.W.C.310	2:2	1.78	5.60	2300	1698	1236	1.61	0.61
Giza, Exp. I	Giza 22 × T.W.C.321	Mixed-row	1.16	8.66	2601.2	2214	2015	1.25	0.29
Giza, Exp. II	Giza 111 × T.W.C.321	Mixed-row	1.34	8.65	2707	2280	1925	1.33	0.34
Giza, Exp. III	Giza 111 × T.W.C.321	Mixed-row	1.19	9.08	2711.6	2226	2017	1.31	0.32

Table 2. Productivity and economic-viability matrix for compatible maize–soybean combinations

These input reductions significantly enhance economic viability by lowering variable costs, because synthetic fertilizers and mechanical operations are the highest variable costs in cereal production. The economic longevity of intercropping significantly exceeds incompatible varieties, i.e., Crawford × T.W.C.321, which had lower relative yields and diminished economic advantages, with a MAI peak of 0.61 in Middle Egypt. Land saved is represented by each LER above 1.0 in Table 1. This sustainable intensification dividend, when evaluated at rentable land prices, amplifies MAI advantage.

The Resource-Efficiency, ATP, and Predicted GHG Matrix

Table 3 reports modeled ATP demand and predicted GHG mitigation. These values should be read as illustrative outputs of the upscaling framework, not as experimentally validated fluxes. In comparison to sole cropping, intercropping reduced ATP requirements by 34.4–44.3% throughout the system; in the East Delta, for instance, ATP demand decreased from 282.80 kg ha^{-1} (sole) to 157.40 kg ha^{-1} (intercrop, Giza 111 × S.C.166), the greatest saving ever noted. This significant decrease is a result of the reduced embodied energy needed for mechanical field passes and synthetic inputs. However, there is a subtle bioenergetic paradox within the canopy: compatible combinations consumed more biological ATP than incompatible ones. This is because soybean roots' nitrogenase needs a lot of ATP to break the triple bond of atmospheric N_2.

Region	Combination	ATP intercrop (kg ha^{-1})	ATP sole (kg ha^{-1})	System-level fossil energy saving	Predicted GHG mitigation (vs. sole cropping)	Mechanism
Middle Delta	Giza 22 × S.C.10	237.1	394.05	−39.8%	N_2Oe −28%; CO_2e −15%; N-fert −17%	Hypothesized mechanism: high biological ATP flux in soybean roots fuels N_2 fixation, displacing synthetic N fertilizer (primary driver of N_2Oe and CO_2e), to be validated by direct flux measurement.
East Delta	Giza 22 × S.C.166	162.5	282.8	−42.5%	N_2Oe −28%; CO_2e −15%; N-fert −17%	System-wide fossil energy drop reflects reduced mechanical/chemical inputs, while biological ATP flux increases
East Delta	Giza 111 × S.C.166	157.4	282.8	−44.3%	N_2Oe −28%; CO_2e −15%; N-fert −17%	Highest ATP saving recorded
Middle Egypt	Giza 22 × T.W.C.310	212.5	323.85	−34.4%	N_2Oe −28%; CO_2e −15%; N-fert −17%	Highest LER (1.61) correlates with optimal resource partitioning
Giza, Exp. I	Giza 22 × T.W.C.321	288.8	495.55	−41.7%	N_2Oe −28%; CO_2e −15%; N-fert −17%	High light interception by erect-leaf maize sustains understory fixation
Giza, Exp. II	Giza 111 × T.W.C.321	293	483	−39.3%	N_2Oe −28%; CO_2e −15%; N-fert −17%	Biological ATP flux displaces embodied fertilizer energy
Giza, Exp. III	Giza 111 × T.W.C.321	302.15	496.65	−39.2%	N_2Oe −28%; CO_2e −15%; N-fert −17%	Highest absolute economic return (USD 2711.60 ha^{-1})

Table 3. Resource-efficiency, ATP, and predicted GHG matrix (predicted GHG modeled as mitigation percentages relative to sole cropping baselines, driven by the ATP-saving ratio).

Therefore, instead of depending on external inputs obtained from fossil fuels, the system uses solar energy through enhanced light capture to drive metabolic nutrient exchange. The results suggest a strong conceptual association between system-wide ATP-saving ratios, reduced mineral N use, and predicted GHG mitigation: high biological ATP flux in soybean roots drives N fixation, displacing synthetic N fertilizer, which is the main source of N_2Oe and CO_2e (Figure 2). As a result, the modeled GHG mitigation columns (N_2Oe −28%; CO_2e −15%; N-fertilizer −17%) track the ATP-saving ratio across all regions.

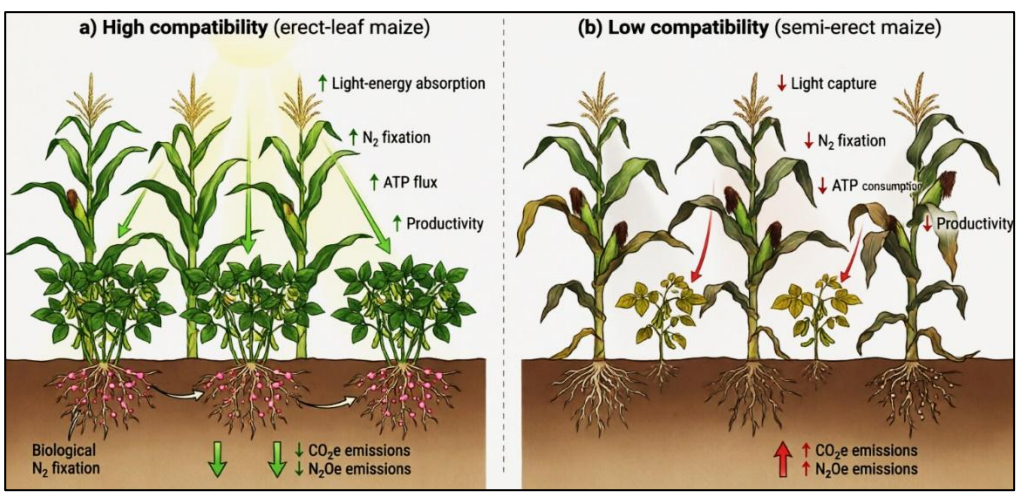

Figure 2. Maize leaf architecture drives interspecific compatibility and sustainability in maize–soybean intercropping

Predicted GHG Mitigation

It should be emphasized that the values in Table 4 are literature-derived coefficients applied to an unmeasured Egyptian baseline. They are not direct field measurements from the experiments reported here. We present them solely to illustrate how the framework would be populated once regional coefficients and baseline fluxes are empirically established. The mitigation

coefficients applied to the sole-cropping baselines are reported in Table 3. According to Raseduzzaman et al. (2024), the predicted cumulative N2Oe under intercropping was 72% of the baseline (a 28% reduction), and cumulative CO2e was 85% (a 15% reduction); the predicted N2Oe intensity was 87% of the baseline (a 13% reduction); and the annual N2Oe was 86% of sole maize and 80% of sole soybean (reductions of 14% and 20%; Zhang et al. 2024). In contrast to conventional agriculture, the plant's internal ATP-driven N cycle effectively acts as a carbon and N sink because the production, transportation, and soil application of synthetic N are the main anthropogenic drivers of agricultural CO2e and N2Oe. In compatible canopies, the increased biological ATP consumption used for N2 fixation displaces synthetic N by up to 25%. Bio-energetic efficiency is a good indicator of eco-efficiency, as evidenced by the 34–44% drop in system-wide embodied fossil energy corresponding to the modeled 15–28% drop in predicted GHG equivalents. It is critical to note that the values reported in Table 3 represent modeled mitigations based on literature-derived coefficients, not direct field measurements of GHG fluxes from the Egyptian experiments. In compatible canopies, the increased biological ATP consumption used for N_2 fixation displaces synthetic N by up to 25%.

GHG indicator	Reported reduction	Source
Cumulative N_2Oe	28% reduction	Raseduzzaman et al.[37]
Cumulative CO_2e	15% reduction	Raseduzzaman et al.[37]
N_2Oe intensity	13% reduction	Zhang et al.[38]
Annual N_2Oe compared with sole maize	14% lower	Zhang et al.[38]

Annual N_2Oe compared with sole soybean	20% lower	Zhang et al.[38]
Mineral N fertilizer requirement in Egypt	Up to 17% reduction	El-Shamy et al.[34]; Zhang et al.[35]

Table 4. GHG indicators and reported reduction coefficients used to model predicted mitigation relative to sole cropping baseline.

Resolving the Bioenergetic Paradox — Methodologically

Canopy compatibility is the technique that connects the two matrices. Erect-leaf maize and soybean exhibit great compatibility, increasing light-energy absorption for both crops, increasing biological ATP consumption for N_2 fixation, which displaces fossil-fuel-derived synthetic N, thereby decreasing CO2e and N2Oe. Conversely, semi-erect maize increases emissions while lowering LER and MAI, shades the understory, prevents photosynthesis and N fixation, lowers biological ATP demand, and requires synthetic N fertilizer. Therefore, choosing compatible varieties maximizes nutrient cycling and land-use efficiency, resulting in a more sustainable system in line with the cooperative adoption of climate-smart agriculture practices by nations. This method contributes to a more ecologically friendly agricultural system by increasing crop yields while lowering GHG emissions. Farmers can maximize resource utilization and reduce adverse environmental effects by choosing varieties that complement one another. Future studies should empirically evaluate the co-benefits of these compatible intercropping systems on soil health, pest resistance, and agro-biodiversity. We emphasize that the "resolution" of the bioenergetic paradox offered here is a conceptual accounting resolution, not an experimentally demonstrated one. The paradox (that biological ATP flux increases while system-

wide fossil energy demand decreases) is resolved on paper by distinguishing two non-commensurable energy currencies: solar-derived, contemporary biological ATP and geological, cumulative fossil embodied energy. Whether this accounting resolution maps onto measurable biophysical reality in Egyptian maize–soybean systems is an open empirical question that requires direct validation.

Limitations of the Present Study

1. No direct measurement of biological ATP flux. Biological ATP in nodules was inferred stoichiometrically from the fertilizer-displacement proxy. Nodule metabolomics or ^{15}N-isotope methods are required to validate Tier 2.

2. No direct measurement of GHG fluxes. N_2O and CO_2 were not measured by chamber or eddy-covariance methods in the Egyptian experiments. The GHG values in Tables 2 and 3 are modeled estimates.

3. The fertilizer-displacement proxy is an imperfect estimator of BNF. It conflates BNF with improved N-use efficiency, reduced leaching, and changes in soil N mining. ^{15}N-isotope dilution is the gold standard and should replace the proxy in future work.

4. The upscaling from cell to field assumes linear additivity. In reality, canopy architecture, soil spatial heterogeneity, and temporal dynamics of nodulation introduce non-linearities that the present framework does not capture.

5. The four-domain framework treats Social Well-Being qualitatively. Quantitative socio-economic indicators (labor productivity, nutritional diversity, risk exposure) are needed to complete the framework.

6. The 15-year dataset spans four agro-climatic zones but was analyzed as separate experiments rather than as a meta-analytic whole. This limits the generalizability of the synthesized matrices.

The predicted mitigation coefficients in Table 4 should be replaced with empirically derived regional values through chamber-based and eddy-covariance measurements of N_2O and CO_2 under Egyptian intercropping. Second, the ATP indicator should be metabolically refined using nodule metabolomics and ^{15}N-isotope dilution to separate biological and system ATP compartments and to validate the fertilizer-displacement proxy. Third, uncertainty propagation should be applied using Monte Carlo or Bayesian methods to propagate uncertainty across the four tiers of the upscaling chain. Fourth, breeding programs should target the erect-leaf, high-compatibility ideotype using selection indices combining canopy design and ATP saving ratio. Finally, to completely quantify the four-domain structure, future research must integrate specific Social Well-being indicators, such as labor productivity and nutritional diversity, alongside long-term monitoring of soil organic carbon.

Conclusion

This article proposes a methodological framework for evaluating sustainable intensification in cereal–legume intercropping. The framework's central innovation is an explicit four-tier up-scaling protocol that links cellular ATP stoichiometry to system-level embodied energy and GHG indicators, with each tier's empirical vs. modeled status transparently declared. Illustrated using 15 years of field data from Egypt, the framework yields the following empirical findings: Compatible intercropping of maize and soybeans simultaneously satisfies the quantifiable sustainable intensification domains: (i) productivity gains expressed as LER 1.25–1.61; MAI up to 0.61; gross returns up to USD 2711.60 ha^{-1}; (ii) economic viability through increased economic yield per hectare and a stability-weighted monetary advantage. The following are modeled outputs of the framework, not experimentally validated claims: (iii) environmental sustainability through system ATP savings of 34–44%, modeled GHG-equivalent reductions of 15–28%, and a 17–25% lower demand for mineral N fertilizer. The ATP-saving ratio appears as the bioenergetic link between domains: compatible erect-leaf canopies convert metabolic efficiency into emission mitigation and economic advantage in a single mechanism by substituting solar-driven, ATP-intensive biological fixation for synthetic N derived from fossil fuels. Despite being a crucial component of the framework, social well-being necessitates specific socioeconomic indicators and is a top research topic. The framework is offered as a repeatable template, not as a validated model. Its key predictions—that erect-leaf canopy compatibility increases biological ATP flux and thereby displaces fossil-embodied energy—require direct

validation through nodule metabolomics and field-scale gas-flux measurements before the framework can be adopted as a landscape-scale standard. In cereal-legume systems worldwide, optimizing ATP consumption and varietal compatibility in intercropping systems provides a promising, repeatable conceptual template for assessing sustainable intensification.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Sh. A: Conceptualization, Investigation, Data curation, Formal analysis, Writing – original draft, Project administration. T. A.: Conceptualization (ATP bio-energetic framework), Validation, Writing – review & editing. E. A.: Investigation (Legume agronomy), Resources, Validation, Writing – review & editing. A. A.: Investigation, Field experiment management, Data curation, Visualization, Writing – review & editing. A. S.: Investigation, Resources, Field data collection, Software. A. C.: Methodology (Carbon-accounting & LCA frameworks), Formal Analysis (Economic viability & MAI evaluation), Writing – review & editing.

Competing interests

The authors declare that they have no competing interests.

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