AgriPV as Resilience Infrastructure for Bioinputs in *Tropical Commodities*: A Research Agenda for the Cerrado and Semi-arid

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ABSTRACT

Global climate projections indicate severe yield losses for rainfed commodities in tropical biomes due to heat stress and irregular rainfall. While Brazil's recent Bioinputs Law (No. 15070/2024) accelerates the adoption of biological agents like Bacillus aryabhattai for drought mitigation, their field efficacy is frequently limited by abiotic extremes. This paper proposes Agrivoltaics (AgriPV) not merely as energy infrastructure, but as a physical resilience strategy to stabilize the microclimate required for bioinput performance. Adopting the Food-Energy-Water (FEW) nexus framework, we establish a causal model linking photovoltaic shading to microbial viability in soybean (Glycine max) and maize (Zea mays) crops. We propose a standardized ***multi-site (N=3), split-split-plot experimental protocol*** *over three cropping seasons to test the synergy between partial shading, water regimes, and biological management. We provide explicit mathematical definitions for Land Equivalent Ratio (LER) and Water Use Efficiency (WUE), aiming to validate AgriPV as the necessary "hardware" to protect the biological "software" in the Brazilian Cerrado transition zones.*

Keywords: *Agrivoltaics; AgriPV; Bioinputs; Climate Resilience; Split-plot Design; Bacillus aryabhattai.*

I. INTRODUCTION

The convergence between the climate crisis and food insecurity imposes the need for new production architectures. Recent data indicate that, without disruptive adaptation measures, the productivity of essential crops such as soybeans and maize in Brazil could suffer drastic reductions — estimated at up to 80% and 51%, respectively, by 2050 — due to rising temperatures and changes in rainfall patterns.

At the same time, Brazil institutionalized a technological transition through Law No. 15070/2024, which regulates the production and use of bioinputs. The market, which already moves R$ 6.7 billion per harvest, bets on microorganisms such as *Bacillus aryabhattai* to mitigate water stress and entomopathogenic fungi (*Metarhizium*) for pest control. However, there is a critical operational paradox: microorganisms introduced into the soil function as "invaders" in established communities, and their colonization is severely limited by hostile abiotic conditions such as excessive UV radiation, lethal soil temperatures (>40°C), and rapid desiccation.

The literature on agrivoltaic systems (AgriPV) demonstrates that co-localization of solar panels and agriculture can reduce evapotranspiration and soil temperature. However, most studies focus on direct physical benefits, leaving a gap in how this environmental modification interacts with the "biological revolution."

Study Contributions This article fills this gap by proposing that AgriPV act as an infrastructure to support biological stability. Unlike previous observational studies, this work delivers three methodological artifacts for research in the Cerrado and Semi-arid region:

1. **Causal Conceptual Model:** The formalization of the mechanisms (abiotic mediators) by which physical infrastructure affects the persistence of microbial inoculums.
2. **Auditable Experimental Protocol:** A randomized block statistical design with *split-split-plots* and power analysis to ensure replicability.

3. **Mathematization of Indicators (KPIs):** The formal definition of formulas for LER, WUE, and PR, allowing comparability in global meta-analyses.

II. THEORETICAL FOUNDATION AND CAUSAL MODEL

The central premise of this work is that AgriPV not only generates energy but mitigates "*midday depression*" in the photosynthesis of C4 (maize) and C3 (soybean) plants, creating a protected ecological niche for bioinputs.

The Proposed Causal Diagram: To overcome the descriptive nature, we structured the interaction through the following flow of mechanisms:

1. **Input:** The interception of shortwave radiation by the photovoltaic modules (transparency 40-50%) changes the energy balance at the surface.
2. **Abiotic (Measurable) Mediators:**
   - Reduction of Maximum Soil Temperature (T_{soil_max}).
   - Reduction of Vapor Pressure Deficit (VPD).
   - Maintenance of Soil Water Potential (ψ_{soil}).
3. **Biological Mechanism ("Black Box" to be opened):**
   - *Bacteria:* The maintenance of humidity favors the motility and formation of biofilms of *Bacillus aryabhattai* in the rhizosphere.
   - *Fungi:* Blocking UV-B radiation increases the half-life of *Metarhizium* and *Beauveria* conidia on the leaf surface.
4. **Outcome:** Stabilization of agricultural productivity (lower interannual σ^2 variance in El Niño years) and increase in the overall efficiency of the system (LER > 1).

III. RESEARCH HYPOTHESES

To ensure scientific rigor and avoid confirmation bias, we formulated a set of falsifiable hypotheses, including the null hypothesis and an explicit rival hypothesis.

- ***H0* (Null Hypothesis):** The installation of AgriPV systems on soybean and maize crops does not significantly change ($p > 0.05$) the survival rate of bioinputs nor the crop productivity compared to cultivation in full sun, or the microclimatic gains do not compensate for the loss due to shading.
- ***H1* (Biological Synergy):** The microclimate modified by AgriPV (lower and higher humidity) increases the abundance of bioinput marker genes (quantified via qPCR) and their agronomic efficacy, resulting in higher root colonization compared to the control.T_{soil}
- ***H2* (Physiological Efficiency):** Intermittent shading mitigates extreme heat stress by reducing photoinhibition and maintaining stomatal conductance during peak irradiation hours, increasing **Water Use Efficiency (WUE).**
- ***H3* (Operational Nexus):** On-site *power generation* reduces irrigation OPEX, enabling precision agriculture that monitors the microclimate to optimize the application of bioinputs.
- ***H4* (Rival Hypothesis - Phytosanitary Risk):** The increase in relative humidity and leaf wetness time under photovoltaic panels favors the proliferation of **unwanted fungal pathogens** (e.g., Asian rust in soybean), nullifying the benefits of bioinputs and requiring greater phytosanitary control.

IV. EXPERIMENTAL METHODOLOGY AND PROTOCOL (REPLICABILITY STANDARD)

To overcome the variability of results pointed out in the literature and ensure external validity for the tropical biome, the following mandatory protocol is established for the execution of the research, focused on the nexus between microclimate and biological efficacy.

A. Sampling and Statistical Design

The experiment should be conducted in a **multi-location** approach, covering a gradient of aridity in the Cerrado-Semiarid transition, critical regions for food security.

- **Experimental Sites (N=3):** It is recommended to install in three distinct macroregions (e.g., Western Bahia, Northern Minas Gerais and Southern Goiás) to capture the *Genotype x Environment x Management* interaction.
- **Duration:** Minimum of **3 full crop seasons** (3 years) to mitigate interannual climate variability, isolate soil *carryovers*, and capture El Niño/La Niña years.
- **Design:** Randomized Complete Blocks (RCBD) with split-plot arrangement (**Split-Split-Plot**), with 4 replications (blocks) per site. The minimum size of the experimental unit should be $10m \times 20m$ to avoid edge effects of the shadow cast by the modules.

B. Factors and Treatments

The experimental arrangement will test three simultaneous factors to isolate causal mechanisms:

1. Principal Installment (Factor A - Coverage):
   - *A1*: AgriPV system (Modules raised >4m, row spacing adjusted for machinery, luminous transparency of 40-50%, with *backtracking* to optimize stray light).
   - *A2*: Open-Air Control (adjacent area without shading influence).
2. Subplot (Factor B - Water Regime):
   - *B1*: Full Irrigation (Replacement of 100% of Crop Evapotranspiration - ETc).
   - *B2*: Controlled Water Deficit (50% of ETc), simulating severe drought scenarios projected for the Cerrado.
3. Sub-subplot (Factor C - Biological Management):
   - *C1*: Standard Chemical Control (Conventional Synthetic Fungicides/Insecticides).
   - *C2*: Management with Mitigation Bioinputs (Protocol defined in section III-C).

C. Bioinput Specification and Regulatory Compliance

To comply with Law No. 15,070/2024 and ensure replicability, the protocol requires the use of strains registered in MAPA with proven agronomic efficacy:

- **Drought Mitigation (Soybean/Maize):** Inoculation via furrow or seed treatment with ***Bacillus aryabhattai*** (CMAA 1363 strain, Embrapa/NOOA technology or commercial equivalent). This bacterium is chosen for its ability to induce tolerance to water stress through the production of exopolysaccharides in the rhizosphere, protecting the roots against desiccation.
- **Biological Control and Resilience:** Foliar application of entomopathogenic fungi ***Metarhizium anisopliae*** (isolate IBCB 425) or ***Beauveria bassiana*** for pest control (e.g., maize leafhopper and stink bugs). These organisms serve as ideal bioindicators of the UV protection offered by the panels, since their persistence (conidia) is degraded rapidly by direct solar radiation and temperatures >30°C.

Viability Monitoring Protocol: The persistence of microorganisms should be quantified via **qPCR** (quantitative PCR) targeting the 16S rRNA (bacteria) and ITS (fungi) genes, or CFU (Colony Forming Units) count, with sampling at $t = 0$, $t = 7$ and $t = 21$ days after application. The goal is to test whether AgriPV acts as a "shield" for the introduced microbiome.

D. Success Metrics (KPIs) and Formulas

Validation of the Food-Energy-Water (FEW) nexus requires the simultaneous collection of standardized data. The formulas for the critical indicators are defined:

1. **Land Equivalent Ratio (RSI):** Primary metric for evaluating land use efficiency in the dual system.

$$LER = \frac{Y_{AgriPV}}{Y_{Mono}} + \frac{E_{AgriPV}}{E_{SolarOnly}}$$

Where Y is agricultural productivity (kg/ha) and E is electricity generation (MWh/ha) in the same area. An LER > 1 indicates that the integrated system is more efficient than the separate uses.

2. **Water Use Efficiency (WUE):** Key to testing Hypothesis 2 (drought resilience).

$$WUE_{crop} = \frac{Y(\frac{kg}{ha})}{ET_a(mm)}$$

Real ETa Evapotranspiration should be measured via soil water balance using neutron probes or capacitive sensors installed at depths of 10, 30 and 60 cm.

3. **Performance Ratio (PR) of the Photovoltaic System:** To test the hypothesis of cooling the modules by crop transpiration.

$$PR = \frac{E_{out}}{P_{peak} \times H_i}$$

Where E_{out} is the energy generated (kWh), Ppeak is the installed power (kWp) and H_i is the solar irradiation in the plane of the arrangement (kWh/m²). Agricultural microclimate is expected to improve PR compared to bare soil.

E. *Statistical Analysis and Power*

The data will be analyzed using **Mixed Linear Models (LMM)** to consider the hierarchical structure of the data and the temporal correlation between harvests.

- **Model:**

$$Y_{ijkl} = \mu + A_i + B_j + C_k + (Interactions) + Bloco_l + \varepsilon_{ijkl}$$

- **Statistical Power:** The sample size was calculated to ensure a statistical power (1 - β) ≥ 0.80, capable of detecting an effect size (Cohen's d) of 0.5 with a significance level α = 0.05. The analysis will focus on the *A* × *C* interactions (Coverage x Bioinput) to validate the synergy thesis.

V. DISCUSSION: AGRIPV AS "HARDWARE" FOR BIOLOGICAL SOFTWARE

The proposal to integrate AgriPV with the agricultural bioeconomy is based on a systems engineering premise: the climate acts as a structural constraint and biotechnology as a management tool. The following discussion situates this interaction in the context of climate projections for Brazil.

A. *Closing the Bioviability Gap*

Projections indicate that, without adaptation, soybean and maize yields in Brazil could fall dramatically — up to 80% and 51%, respectively — by mid-century due to heat and water stress. The institutional response, via Law No. 15070/2024, bets massively on bioinputs such as *Bacillus aryabhattai* and entomopathogenic fungi. However, the literature indicates a paradox: these organisms require specific microclimatic conditions to colonize the rhizosphere and express their potential. Introduced bacteria act as invaders in established communities and their survival decays rapidly under UV radiation and desiccation. The physical evidence that solar panels reduce evapotranspiration and soil temperature is robust in the international literature. The innovation of this agenda lies in connecting this physical phenomenon to biological survival. It is argued that AgriPV acts as the **protective hardware** (reducing UV and thermal shock) required for the **biological software** (the inoculants) to process the induction of drought resistance. Without this physical protection, the effectiveness of the "biological revolution" risks being limited by the climatic extremes of the Cerrado.

B. *The FEW Nexus and Data Governance*

To prevent arable land from being converted into disguised solar plants ("pseudo-agriPV"), it is imperative that Brazil adopts technical standards inspired by DIN SPEC 91434. Public policy should condition tax incentives to the maintenance of primary agricultural productivity. AgriPV should not be seen as a replacement, but as a dual-use infrastructure where electricity generation subsidizes irrigation modernization and precision agriculture, closing the cycle of the Food-Energy-Water (FEW) nexus.

VI. LIMITATIONS OF THE STUDY AND BARRIERS TO ADOPTION

While the proposed synergy is theoretically plausible, this paper acknowledges critical limitations and rival hypotheses that preclude immediate industrial-scale recommendations.

1. **Rival Hypothesis: The Phytosanitary Risk (H4):** The increase in relative humidity under the panels, beneficial for plant hydration, can create a favorable microclimate for necrotrophic fungal pathogens (e.g., Asian rust in soybean). If AgriPV favors diseases more than it favors beneficial bioinputs, the agronomic net balance will be negative. Strict phytosanitary monitoring is therefore mandatory.
2. **The *Trade-off* of Light in C4 Plants:** Crops such as maize have high demand for radiation. There is a real risk that shading, even partial, will reduce productivity in years of mild weather, where heat stress is not the limiting factor. The AgriPV economic model should be evaluated by **crop stability** (lower variance) and not only by the production ceiling.
3. **Technological Maturity (TRL):** Currently, the AgriPV-Bioinputs integration in Brazil is in TRL 3-4 (proof of concept). The proposed research agenda aims to raise this level to TRL 6-7 (demonstration in relevant environment) before massive subsidy policies are designed.

VII. CONCLUSION

The climate crisis imposes the need for additional layers of resilience for tropical agriculture. This *position paper* supported the thesis that Agrivoltaic systems can transcend the energy function to act as a support infrastructure for biotechnology.

It is concluded that:

1. The combination **of "AgriPV + Bioinputs"** represents an unexplored frontier for drought mitigation in *commodities*, potentially superior to the isolated use of each technology.
2. The validation of this thesis requires experimental rigor. The proposed protocol (split-*split-plot* multisite factorial) is the mandatory step to transform plausible hypotheses into safe agronomic recommendations.

It is recommended that development and regulatory agencies (MAPA, Embrapa, ANEEL) finance pilots that integrate biological and energy metrics, ensuring that the Brazilian energy transition strengthens, and does not threaten, its food security.

VIII. GLOSSARY

Bacillus aryabhattai: Bacterium originally isolated from the roots of mandacaru (*Cereus jamacaru*) in the Brazilian Caatinga. It is used as a bioinput to mitigate water stress in crops such as maize and soybeans. Its main function is to induce drought tolerance in the plant through the production of substances that protect the roots from dehydration. In the context of the research, it serves as a model organism to test whether the microclimate of AgriPV favors its colonization in the soil.

Backtracking: A control algorithm used in single-axis solar tracker structures. In conventional power plants, their function is to prevent a row of panels from shading the back row during dawn and dusk. In AgriPV, *backtracking* takes on a vital agronomic function: the algorithm can be programmed to adjust the angle of the panels to allow direct light to pass through to crops at critical moments, or to protect plants from excess radiation at midday by actively managing the microclimate.

Beauveria bassiana: Entomopathogenic fungus (which causes disease in insects) widely used in the biological control of agricultural pests. In addition to fighting insects directly, it can penetrate the plant and activate natural defenses and growth hormones. It is highly sensitive to ultraviolet (UV) radiation, being an ideal candidate to validate the hypothesis that shading solar panels extends the useful life of bioinputs applied to leaves.

Bioinputs Law (Law No. 15,070/2024): Brazilian federal legislation approved in December 2024 that regulates the production, registration, and use of biological inputs in agriculture. The law institutionalizes the sector, facilitating the registration of new products and encouraging *on-farm production* (within the property). The article uses this legal framework as a justification for the urgency of research that integrates bioinputs and infrastructure.

CAPEX (*Capital Expenditure*): This refers to the initial investment required for the construction of the AgriPV system, which is typically higher than that of a conventional solar plant due to the need for elevated and reinforced structures.

Carbon Footprint: Total measure of greenhouse gas emissions caused directly and indirectly by an activity. In agriculture, the use of synthetic nitrogen fertilizers and deforestation are major emitters. The strategy proposed in the article aims to reduce the carbon footprint of the crop through two ways: the replacement of chemicals with bioinputs (produced with low carbon) and the generation of renewable energy on site to feed agricultural machinery.

Climate Resilience: The ability of an agricultural system to absorb environmental shocks (such as prolonged droughts or heat waves) and recover while maintaining its productive function. Unlike "resistance" (which tries to block the impact), resilience involves adaptation. AgriPV acts as a resilience infrastructure by physically modifying the environment (reducing temperature and evaporation) so that plants and bioinputs survive the climate extremes projected for the Cerrado and Semi-arid regions.

Crop Evapotranspiration (ETc): Total volume of water lost to the atmosphere through soil evaporation and plant transpiration. It is the fundamental metric for calculating water use efficiency (WUE). Studies indicate that AgriPV can reduce ETc by reducing the direct incidence of solar radiation on the soil and the canopy of plants, saving irrigation water.

Data Governance: A set of policies and processes that ensure the quality, integrity, and security of data collected in the field. In AgriPV research, which involves complex soil, climate, and plant sensors, governance defines who "owns" the data, how it is audited, and how it is standardized to allow comparisons between different farms and crops. The lack of governance is pointed out as one of the main gaps that prevent the scientific validation of the technology on a large scale.

DIN SPEC 91434 Technical standard developed in Germany that has become the global reference for the certification of agrivoltaic systems. The document establishes strict criteria to ensure that energy production does not harm agricultural activity. The norm defines, for example, that the loss of arable area due to infrastructure cannot exceed 10 to 15% and that agriculture must remain the main activity of the land ("primary agricultural use"). The adoption of criteria based on the DIN is essential to avoid the mischaracterization of rural property.

Dual *Land Use*: AgriPV's central concept that proposes the synergistic coexistence of two economic activities on the same surface. Unlike traditional competition where one chooses between "planting food" or "generating energy", dual use seeks to increase the total efficiency of the land. For it to be considered legitimate dual use, and not just a solar plant on rural land, agricultural productivity must be maintained or stabilized through microclimate management.

Ecosystem Services: Benefits that nature provides to humans and the economy, often at no direct financial cost. They include pollination, climate regulation, water purification and soil formation. The AgriPV system is designed not only to produce goods (electricity and food), but to amplify these services, for example by increasing water retention in the soil and reducing wind erosion.

Ecovoltaic: A concept distinct from agrivoltaics focused on *commodities*. The ecovoltaic system combines solar energy generation with ecological restoration or biodiversity conservation, rather than commercial food production. It is used, for example, to create habitats for pollinators (such as bees and butterflies) or to restore native grasslands under the panels. Projects that are part of AgriPV in permanent preservation areas or legal reserves may fall into this category.

Intermittency and Variability: Intrinsic characteristics of solar energy generation, which depends on the availability of sunlight and varies according to the climate and the diurnal cycle. In the context of AgriPV, the variability of the light that reaches the ground (caused by the shade of the panels) is not a defect, but a management resource. The design of the system seeks to create a "flashing light" pattern that reduces the thermal stress of plants without compromising their ability to perform photosynthesis.

LCOE (*Levelized Cost of Electricity*): A metric used to calculate the average cost of generation for each megawatt-hour (MWh) over the entire life of the project (usually 25 to 30 years). In AgriPV, the calculation of the LCOE is more complex, as it must incorporate not only energy costs, but also possible losses or gains in agricultural productivity resulting from infrastructure. A competitive LCOE is what makes the technology attractive to investors and farmers.

Metarhizium anisopliae: A genus of fungi used in the biological control of pests, such as leafhoppers and stink bugs. Like *Beauveria*, its effectiveness depends on favorable environmental conditions, such as high humidity and protection from intense solar radiation. It is one of the bioindicators proposed to monitor the "biological health" of the environment under photovoltaic panels.

On-Farm Production: Model of manufacturing biological inputs (bioinputs) carried out within the farm itself by the rural producer. Law No. 15,070/2024 regulated and facilitated this practice in Brazil. The integration with AgriPV is strategic for this model, as the solar plant provides the cheap energy needed to maintain the bioreactors and the air conditioning of the bacteria and fungi multiplication laboratories on the property.

OPEX (*Operating Expenditure*): This refers to the recurring costs of operation and maintenance. In AgriPV, OPEX includes the complex management of the integration between agricultural machinery and electrical structures. The feasibility of the project depends on the balance between these costs and the double revenues (energy + food).

Partial and Dynamic Shading: Unlike the fixed shading of a tree or building, shading in AgriPV systems is designed and predictable. The "transparency rate" of the modules and the spacing between the rows determine the amount of Photosynthetically Active Radiation (PAR) that reaches the crop. The goal of engineering is to find the optimal spot where shading reduces water evaporation and soil temperature but still provides enough light for the plant's bioeconomy.

Photosynthetically Active Radiation (PAR): Range of the sunlight spectrum (between 400 and 700 nanometers) that plants effectively use to perform photosynthesis. When designing an AgriPV system, it is crucial to measure the available PAR under the panels to ensure that even with shading, the plant receives enough light for its full development.

Pollinators: Insects and animals responsible for the reproduction of many flowering plants. The global decline of pollinators is a threat to food security. Conventional solar structures often remove vegetation, harming these agents. Well-planned AgriPV, by contrast, can create thermal and floral refuges between the rows of the panels, providing a vital ecosystem service for neighboring crops that depend on pollination.

Primary Agricultural Use: Normative principle (present in the DIN SPEC 91434 standard) that determines that, in an agrivoltaic system, agricultural production must be the main and priority activity, while energy generation is secondary. If the installation of the panels causes a loss of agricultural productivity above a tolerable limit (e.g. 20-30%), the project ceases to be classified as AgriPV and becomes a conventional solar plant, losing potential rural incentives.

Pseudo-Agrivoltaic (*Greenwashing*): A critical term used to describe projects that call themselves "agrivoltaic" to obtain environmental permits or tax benefits, but which, in practice, make agriculture unfeasible due to excessive shading or inadequate layout. The research proposed by nMentors aims to establish rigorous metrics to identify and avoid pseudo-agrivoltaic, ensuring the legitimacy of the sector.

Rhizosphere Microbiome: Set of microorganisms (bacteria, fungi, viruses) that live in the soil region in direct contact with plant roots. It works as the first line of defense against disease. The research investigates whether the physical protection of AgriPV helps maintain the diversity of this microbiome, enhancing the effect of the inoculants introduced.

Technology Readiness Level (TRL): Global scale used to classify the maturity stage of a technology, ranging from 1 (basic idea) to 9 (proven commercial operation). The research strategy is to raise the AgriPV-Bioinputs integration from TRL level 3-4 (validation in a laboratory or controlled environment) to TRL 6-7 (demonstration in a relevant operational environment), a necessary step to attract large-scale funding.

Vapor Pressure Deficit (VPD): Meteorological indicator that combines temperature and relative humidity of the air to measure the "drying power" of the atmosphere. A high VPD indicates dry air, which forces the plant to close its stomata and stop growth so as not to lose water. The AgriPV system seeks to maintain VPD at lower levels under the panels, reducing the crop's water demand.

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