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ICAR-National Institute of Abiotic Stress Management
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PREFACE

Agroforestry has emerged as a pivotal nature-based solution in addressing some of the most pressing challenges of our time—climate change, food and nutritional security, and land degradation. The Government of India's ambitious GROW initiative (Greening and Restoration of Wastelands with Agroforestry), which targets the restoration of 26 million hectares of degraded land by 2030, reflects this recognition at the policy level. Yet, despite the ecological and economic promise of agroforestry systems, a critical knowledge gap persists in understanding the nuanced tree-crop interactions, particularly the influence of natural shade on crop performance.

This technical bulletin is the outcome of a rigorous field-based investigation aimed at developing a standardized and scalable methodology for assessing natural shade impacts in agroforestry. By leveraging digital lux meters and a novel Crop Status Index (CSI), the study offers a realistic, cost-effective, and scientifically robust framework for quantifying shade and evaluating crop health under actual field conditions—beyond the limitations of artificial shade nets.

The bulletin presents a detailed protocol for measuring light intensity gradients, categorizing shade levels, and applying CSI through Principal Component Analysis (PCA) to interpret physiological, biochemical, and yield-related crop responses. The methodology was validated using the soybean–*Emblica officinalis* agroforestry model system in semi-arid, degraded lands, offering valuable insights into optimal shade thresholds for sustaining productivity.

Intended for researchers, agroforestry practitioners, policy planners, and field technicians, this publication not only bridges a critical methodological gap but also informs practical tree-crop management strategies to enhance system resilience and land restoration outcomes. We hope this bulletin will serve as a useful reference and inspire further innovations in the science and practice of climate-smart agroforestry.

Authors

CONTENT

1. Background

Agroforestry is increasingly recognized as a nature-based solution to address climate change, food security, and land degradation. The integration of trees with crops not only enhances biodiversity and carbon sequestration but also improves soil health and water use efficiency. India's ambitious GROW initiative (Greening and Restoration of Wastelands with Agroforestry), aiming to restore 26 million hectares of degraded land by 2030, underscores the need to optimize such systems for maximum ecological and economic benefits.

Among the challenges in agroforestry, understanding tree-crop interactions—particularly the role of shade—is critical. While tree canopies can create favorable microclimates that reduce evapotranspiration and improve crop resilience under heat stress, they also reduce light availability, directly affecting photosynthesis and crop yield. This duality necessitates the identification of a **critical shade threshold** that maintains the balance between beneficial microclimate moderation and harmful light limitation.

Traditional approaches of studying tree shade impact on crop performance is often rely on **artificial shade netting** to simulate tree cover. However, these controlled environments fail to capture the dynamic nature of natural shade, which includes fluctuating light intensities, root interactions, and real microclimatic changes such as humidity and temperature variations. Such setups limit the translational relevance of results to real agroforestry conditions. The intensity of shade varies based on canopy density, growth patterns, and microclimate, raising the critical question: what is the acceptable shade threshold in agroforestry?

Therefore, there is an urgent need for in-situ, field-based studies under natural tree canopies to assess shade gradients and their effects on crop physiology and yield. Further, standard indices to assess crop performance under shade are lacking. The **Crop Status Index (CSI)**—a composite index integrating physiological, biochemical, and biophysical parameters—offers a promising tool to evaluate crop health and shade tolerance under natural agroforestry conditions. This study evaluates the soybean-aonla (*Emblica officinalis*) agroforestry system in degraded lands, aiming to quantify natural shade using cost-effective methods and develop a CSI-based approach to determine the optimal shade levels for sustaining productivity.

Figure 1: A view of *Emblica offcinalis*-based agroforestry systems in degraded land in semi-arid region

2. Why a New Methodology Is Needed?

To address the above-mentioned limitations, the current study introduces a novel, field-based methodology that:

- Quantifies real-time natural shade using a Digital Lux meter (HTC LX-101A) across tree-crop interfaces at weekly intervals, avoiding biased readings during cloudy conditions.
- Measures light intensity at a standard height (waist level) under tree canopies and in open (control) conditions to calculate percentage light reduction—a proxy for effective shade.
- Develops shade gradients based on actual field conditions, not artificial nets, thereby ensuring higher relevance and accuracy to real world.
- Introduces a first-of-its-kind Crop Status Index (CSI) for agroforestry, integrating multiple biophysical indicators—based on physiological, morphological, biochemical and yield parameters—to comprehensively assess crop performance under different shade levels.
- Enables determination of the critical shade threshold—the point beyond which crop health and yield decline significantly—allowing informed decisions on tree management (spacing, pruning) and crop selection.
- Offers a scalable, cost-effective, and replicable framework for evaluating and optimizing tree-crop interactions under natural agroforestry conditions.

3. Quantification of Shade in Agroforestry

- To quantify shade intensity in agroforestry systems, researchers should use a digital lux meter (e.g., HTC LX-101A) to measure natural light levels under tree canopies and in open, unshaded areas (Figure 2 & 3).
- Measurements must be taken on clear, sunny days to avoid errors due to cloud cover. Light readings should be recorded hourly from 9:00 AM to 4:00 PM, covering the main daylight hours critical for crop photosynthesis.
- Observations should be conducted weekly throughout the crop growth period to track changes in light availability over time.
- Measurements must be taken at a consistent height—about 1.0 meter above ground (waist height)—to maintain uniformity.
- At each selected tree site, the researcher should first measure light intensity in a nearby open space (control) and then immediately under the tree canopy. This paired approach ensures accurate comparison.
- It is advisable to take multiple readings under the canopy, especially in areas where tree shade is cast (usually within a 3-meter radius from the trunk), as this better reflects the actual growing conditions for crops beneath.
- The percentage of shade is calculated by comparing the difference in light intensity between the open and shaded areas using the formula of Qiao et al. (2019).

$$Shade\ intensity\ (\%) = \frac{Light\ intensity_{\ (Open)} - Light\ intensity_{\ (Under\ tree)}}{Light\ intensity_{\ (Open)}} \times 100$$

- Hourly shade percentages should be averaged to get a daily shade value, and then these daily values can be averaged over several weeks (e.g., 12 weeks) to determine the mean shade level for each tree.

- Based on the average shade percentage, trees are grouped into defined shade categories. For instance, trees showing 36–45% shade are classified under 40% shade. This categorization is essential for designing experiments with multiple shade levels and allows for consistent comparisons across treatments.
- To create shade gradients, researchers should consider pruning tree branches to manipulate the canopy structure and control the shade pattern effectively.
- Shade readings should be regularly monitored during the entire crop season. If changes in tree canopy, leaf shedding, or sun orientation cause a shift in shade levels, such trees should be reassigned to the appropriate category or excluded from the study.
- Unlike methods that record light at fixed distances from the trunk (e.g., 2 or 3 meters), this approach focuses on the actual shaded zone defined by the crown shadow, which better represents crop exposure.

The following table's present field-generated light intensity data, analyzed and categorized based on different shade gradients.

Table1. Grouping of shade treatments based on mean hourly lux data into various shade levels

Shade levels (Factor A)	Number of trees (numbers)	Shade levels (%)	Hourly lux data
S1-0% shade (Open)	0 (No tree)	0% (No trees)	281-1981
S2 – 40% shade	22 (V1: 12 & V2: 10)	35% - 45%	456-590
S3- 50% shade	22 (V1: 14 & V2: 18)	46%- 55%	361-461
S4-60% shade	21 (V1: 13 & V2: 8)	56%- 65%	265-360

(S: shade levels; V= Kharif soybean varieties (V1-KDS-726 and V2-MACS-1188)

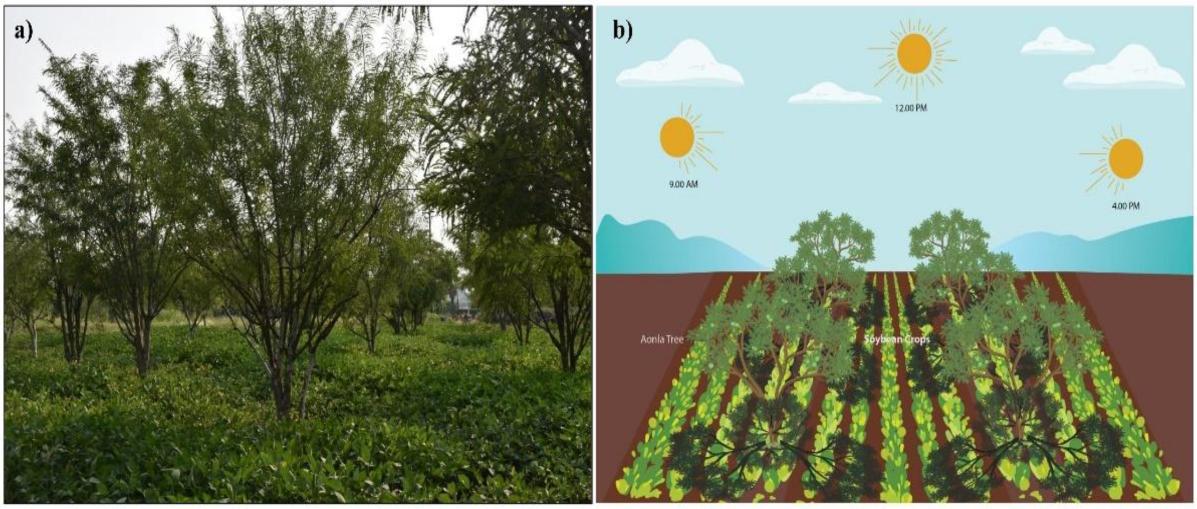

Figure 2: View of tree shade on understorey crop i.e., soybean with *Emblica officinalis*-based agroforestry system (a); Representation of tree shade during different periods of the day under tree canopy (b)

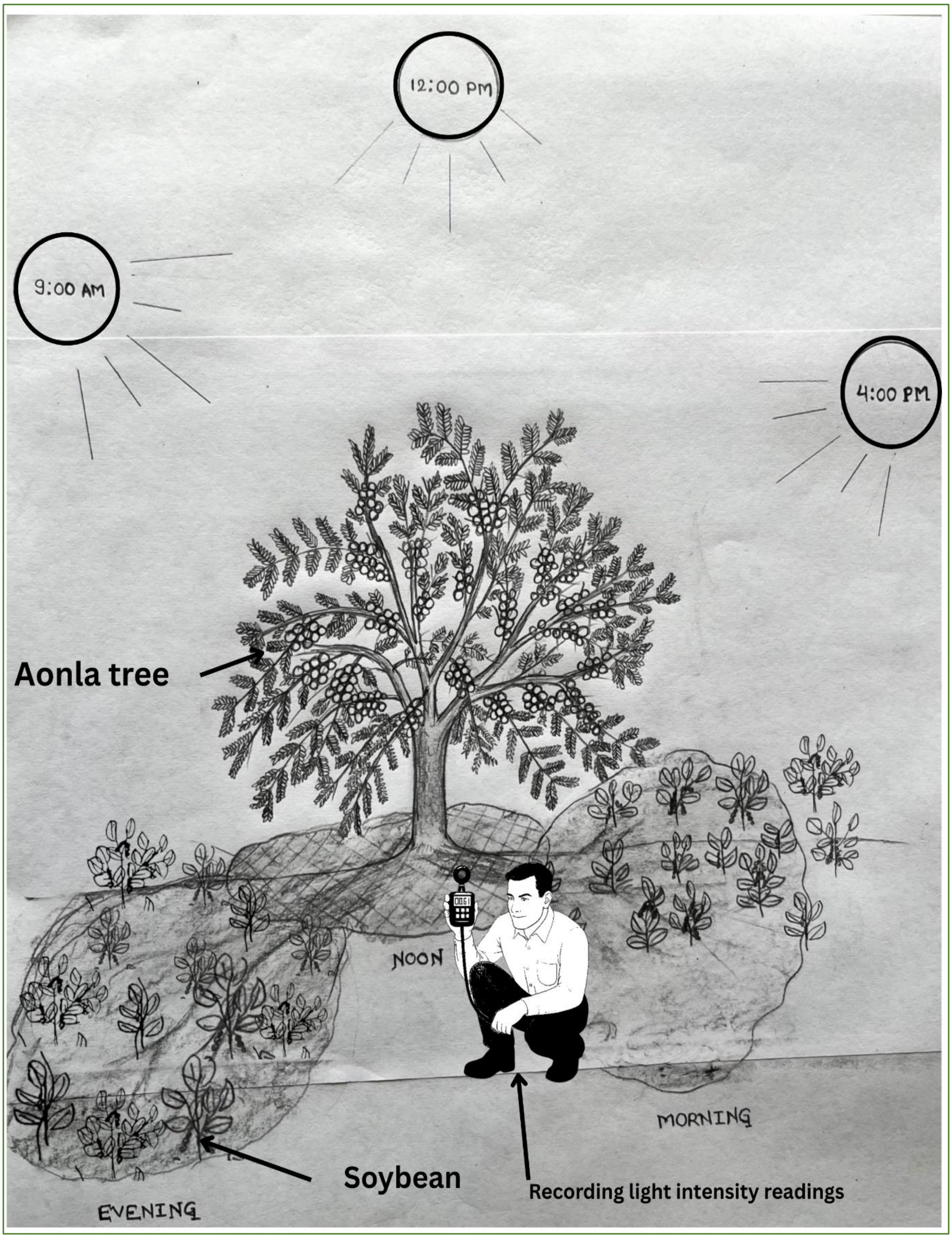

Figure 3: Schematic diagram for quantifying shade in natural conditions of aonla-based agroforestry systems

4. Challenges

Although this method involves more effort and frequent data collection, it provides a realistic and accurate representation of natural shade patterns. In contrast, artificial shading using nets or plastic covers may be easier but fails to capture the complexity of tree-generated shade. For example, in *Emblica officinalis*-based agroforestry systems during the kharif season, weekly light intensity readings were taken from 9:00 AM to 4:00 PM under varying cloudy and rainy conditions. Such field-based observation is feasible in rainfed regions with average annual rainfall between 500–1000 mm. This approach is recommended for researchers seeking to evaluate actual light conditions in agroforestry systems and their effects on intercrop performance (Figure 4).

5. Methodology for Crop Status Index (CSI) Calculation

To calculate the Crop Status Index (CSI), multiple physiological, biochemical, and biophysical crop parameters are measured. Since there are many variables, Principal Component Analysis (PCA) is used first to simplify and summarize the data by identifying key factors that explain most of the variation (Figure3).

1. **Principal Component Analysis (PCA):**
   - PCA reduces the complexity of the dataset by transforming many correlated variables into a smaller number of uncorrelated variables called Principal Components (PCs).
   - Each PC represents a combination of the original variables and explains a certain percentage of the total variation in the data. The first PC explains the most variation, the second PC the next most, and so on.
   - Only PCs with eigenvalues greater than or equal to 1 and explaining more than 5% of variation are retained.
2. **Selecting Variables for the Minimum Data Set (MDS):**
   - Within each retained PC, variables with the highest contributions (loadings) are considered important.
   - Variables that have very high correlation ($r > |0.75|$) with each other are filtered to avoid redundancy, keeping only one representative variable among them.
   - This results in a reduced set of key indicators—the MDS—that effectively represent crop status without duplication.
3. **Data Normalization:**
   - The selected indicators are normalized so their values can be compared on the same scale.
   - For each variable, the observed value is transformed into a score between 0 and 1, where 1 indicates the best condition and 0 the worst, depending on whether “more is better” or “less is better” for that parameter.

$$S_i = \frac{(X_o - X_{min})}{(X_{max} - X_{min})} \text{ for more is better properties}$$

$$S_i = 1 - \frac{(X_o - X_{min})}{(X_{max} - X_{min})} \text{ for less is better properties}$$

Where X_{max}, X_{min} and X_o are the maximum, minimum and observed values of the attribute i, respectively.

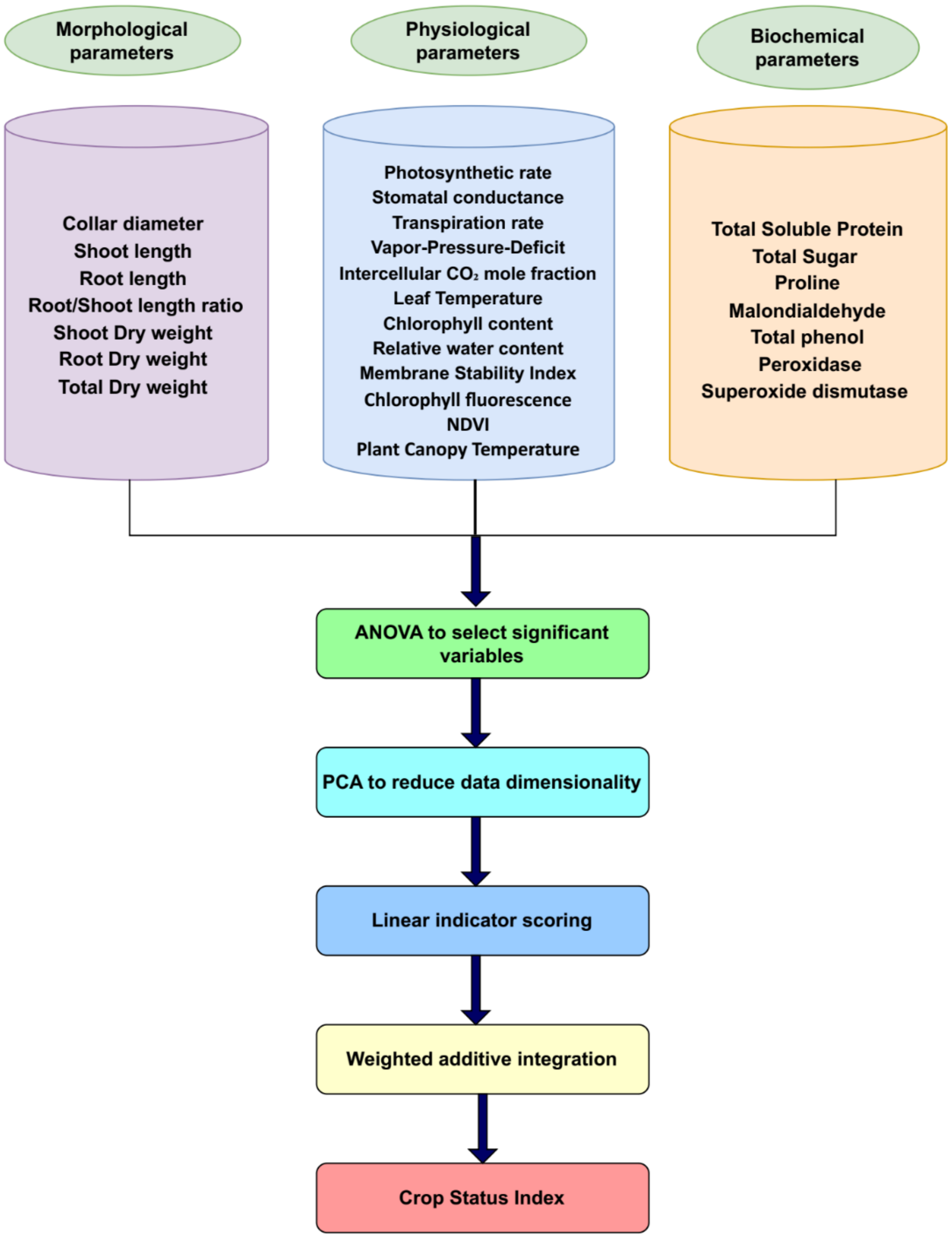

Figure 4: Flow chart depicting the methodology for Crop Status Index (CSI)

4. **Weighting Indicators and Calculating CSI:**
    - Each PC's contribution to total variability is used to assign weights to the indicators derived from that PC.
    - These weights reflect the relative importance of each indicator in determining crop status.
    - The normalized scores of the indicators are multiplied by their respective weights and summed to give a single Crop Status Index (CSI) value.

- A higher CSI indicates better overall crop health and performance.
- The weighted CSI is computed as:

$$\mathrm{CSI} = \sum_{i=1}^{n} (W_i \times S_i)$$

where S_i is the normalized score and Wi is the weight of the i^{th} indicator.

6. Applications of the Methodology

Crop Status Index (CSI) for Soybean under Different Shade Levels

Principal Component Analysis (PCA) identified four key components (PC1 to PC4) explaining 68.45% of the total variation in crop health indicators. From these, a Minimum Data Set (MDS) was selected including stomatal conductance, total soluble protein, superoxide dismutase activity (SOD), chlorophyll a and b, malondialdehyde (MDA), peroxidase activity (POD), and root-to-shoot dry weight ratio. Variables with strong inter-correlation were carefully filtered to avoid redundancy, ensuring the MDS captures essential physiological and biochemical traits related to soybean health.

The MDS variables were normalized and weighted based on PCA eigenvalues to compute the Crop Status Index (CSI), a comprehensive indicator of crop health. Statistical analysis revealed significant differences in CSI across shade levels but no significant variation between the two tested soybean varieties. The highest CSI was recorded under full sunlight (S1-0%, CSI=0.80), followed closely by moderate shade conditions S2-40% (0.77) and S3-50% (0.75). The lowest CSI was observed at the highest shade level S4-60% (0.53), indicating substantial stress under dense shade.

A strong positive correlation ($R^2 = 0.667$) between CSI and soybean seed yield demonstrated that improved physiological and biochemical status directly translates into higher productivity (Figure 5). This confirms CSI as a reliable integrative metric for assessing crop performance under varying environmental stresses.

The results indicate that moderate shading up to 50% does not adversely affect soybean growth or yield significantly, while shade beyond this threshold imposes stress through reduced photosynthetic activity and altered physiological functions. These insights provide practical guidance for managing shade in agroforestry, intercropping, and emerging agrivoltaic systems, where up to 50% shading can be optimized to balance crop health and renewable energy generation on degraded lands.

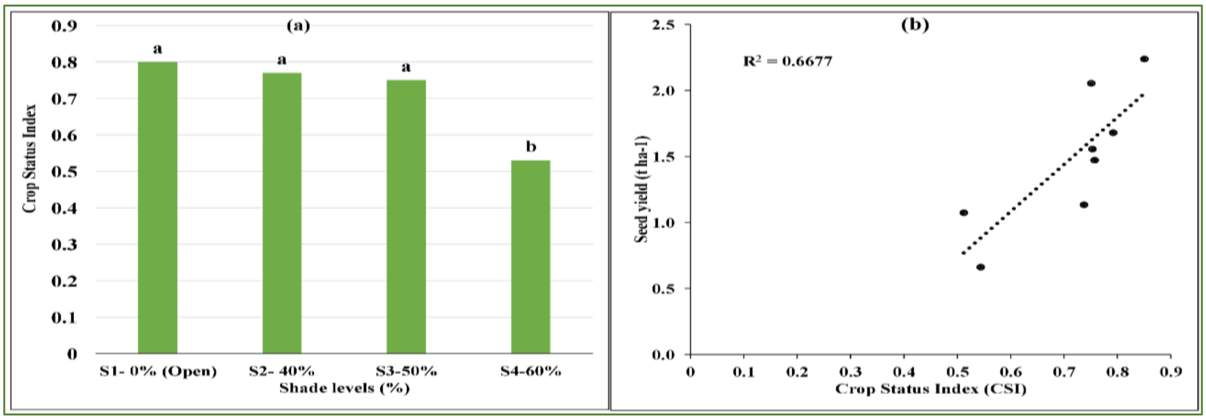

Figure 5: Influence of shade levels on Crop Status Index (CSI) under *Emblica officinalis*- based agroforestry systems (a); Fig 2: Scatter plot showing the relationship between crop status index and soybean seed yield (t ha^{-1})

7. Uniqueness of Methodology

- Provided practical methodology to quantify tree shade under in-situ natural agroforestry conditions using a simple digital lux meter, rather than relying on artificial shade nets or costly instruments.
- This study is the first to develop and apply a composite Crop Status Index in agroforestry systems, integrating physiological, biochemical, and yield traits into a single, actionable metric—unlike traditional methods that assess parameters separately.
- Unlike conventional agroforestry approaches that rely on trial-and-error or general recommendations, CSI provides a quantifiable threshold for tree shade tolerance, allowing for precise management of canopy cover without compromising crop productivity.
- Existing models rarely consider site-specific stress conditions like degraded soils. This study's CSI-guided framework is tailored for resource-poor environments, making it a unique tool for climate-resilient and resource-efficient farming.

8. Practical Implications and Scalable Applications of CSI-Based Shade Optimization in Agroforestry Systems

- Defines optimal shade threshold (≤50%) using a quantifiable Crop Status Index (CSI), enabling evidence-based management of tree canopy in agroforestry systems.
- Provides a low-cost, field-adaptable method for measuring natural shade using digital lux meters, suitable for resource-constrained and degraded landscapes.
- Enables precise crop selection and varietal screening by integrating physiological and biochemical indicators into a single composite index (CSI) for shade tolerance assessment.
- Supports the design of climate-resilient intercropping systems, including agroforestry and agrivoltaics, by identifying shade levels that maintain productivity without inducing stress.
- Bridges the gap between research and on-farm practice by eliminating reliance on artificial shade nets and capturing real-time environmental interactions.
- Offers a standardized framework for policy and extension programs, allowing for scalable, data-driven recommendations in agroforestry development and land restoration projects.

9. Conclusion

This study introduces a novel, field-based methodology for quantifying natural shade and assessing crop performance in agroforestry systems using a scientifically grounded Crop Status Index (CSI). By replacing artificial shade nets with real-time lux meter readings, the method offers a more ecologically relevant approach to understanding tree-crop interactions. The development and application of the CSI allow for a comprehensive assessment of crop health under varying shade intensities. This approach moves beyond generalized shade management advice by offering a quantifiable, evidence-based threshold for shade optimization. The methodology bridges the gap between controlled experimental designs and the complexities of real-world agroforestry systems, making it both practical and scalable for farmers, researchers, and policymakers.

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