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Potential of Goniometry and Goniophotometry for Precision Agriculture Applications

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ABSTRACT

Objective: To review the application of goniometry and goniophotometry as innovative tools for advancing precision agriculture. The primary objective is to synthesize how these techniques contribute to optimizing light interception, enhancing crop yield, and improving land-use efficiency by providing precise data on plant architecture and light dynamics within cultivation systems.

Design/methodology/approach: The research employs a systematic review methodology, analyzing existing scientific literature and case studies where goniometry and goniophotometry have been applied in agricultural contexts. Goniometry is used for measuring the angular dispositions of plant elements like leaves and stems, while goniophotometry characterizes light distribution and incidence angles. The approach focuses on integrating data from both techniques to inform adjustments in crop canopy architecture and artificial lighting systems.

Results: The review demonstrates that the integration of goniometric and goniophotometric data enables the determination of optimal light incidence angles. This facilitates strategic adjustments to planting layouts and canopy management, leading to significant enhancements in photosynthetic efficiency. Consequently, studies report improvements in overall crop yield and a more efficient use of available land and light resources in diverse cultivation environments, from greenhouses to open fields.

Limitations of the study/implications: The primary limitations discussed involve the technical complexity and cost associated with the specialized equipment required for these measurements. Furthermore, the practical implementation of findings can be constrained by the need for specialized knowledge to interpret data and integrate it into existing farm management systems, potentially limiting accessibility for widespread adoption.

Findings/Conclusions: Goniometry and goniophotometry are powerful, though underutilized, tools that provide a scientific basis for optimizing agricultural systems. Their application offers significant advantages for enhancing photosynthetic performance and spatial planting efficiency. While challenges related to cost and complexity exist, the potential of these techniques to contribute to more sustainable and productive precision agriculture is substantial, warranting further research and development of user-friendly applications.

Keywords: Goniophotometry, Light-interception, Photosynthetic Performance, Precision Agriculture.

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INTRODUCTION

In modern precision agriculture, optimizing the use of light and land is key to achieving higher yields, energy efficiency, and sustainability (Sahu *et al.*, 2019). Two highly relevant technical tools in this context are goniometry —the measurement of angles— and goniophotometry —the measurement of the angular distribution of light on a surface (Bai *et al.*, 2023). The proper management of the incidence angle of solar or artificial irradiance on the crop area, as well as the angular orientation of leaves or crop rows, can improve light absorption, reduce unnecessary shading, and consequently increase effective photosynthesis and yield (Singh & Nansen, 2017).

While goniometry can be used, for example, to measure the inclination of leaves or crop rows, allowing for adjustments in their arrangement to intercept more light, goniophotometry makes it possible to understand how light (natural or artificial) falls on the crop surface, including its uniformity and angular efficiency (Kim *et al.*, 2022). Therefore, these techniques provide a bridge between plant physiology, lighting engineering, and agronomic design. The objective of this article is to describe the use of these techniques in agriculture, explain their methodology, present results, and demonstrate their advantages for crop adjustment and optimal land use.

MATERIALS AND METHODS

Materials

- An angular measurement system, *i.e.*, a goniometer (an instrument for measuring or setting angles in one or more axes) applied to vegetation or crop structures.
- A goniophotometry system capable of measuring the angular distribution of incident or reflected light on a crop surface.
- The crop under study (*e.g.*, greenhouse vegetables, open-field row crops) with its existing canopy and the possibility of adjusting row inclination, orientation, or artificial lighting system.
- Auxiliary instrumentation: irradiance meter, spectrometer or light sensor, angular support for fixing the goniometer, records of incidence angles (zenith, azimuth), and yield or biomass data.
- Software or analytical methodology to calculate optimal incidence angles, perform comparisons between different measured angles, and relate them to light absorption efficiency, canopy uniformity, or productivity.

Figure 1 presents the schematic diagram of the custom-built photogoniometer developed to carry out angular measurements of light interaction with plant samples. The apparatus allows for precise control over both the azimuth and zenith angles of a directed light source, simulating solar pathways.

The main components of the system are as follows:

A) Zenith Rotation: A secondary high-precision rotational stage, mounted at the end of the adjustable arm, controls the zenith (altitude) angle of the detection system relative to the sample.

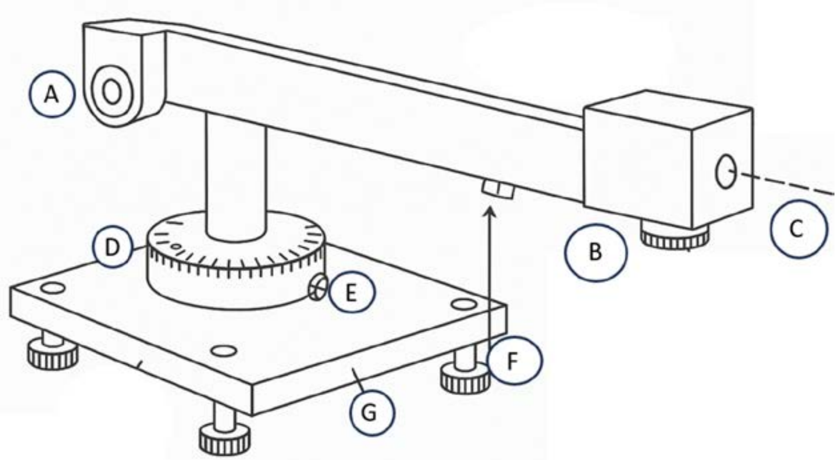

Figure 1. Photogoniometer developed to carry out angular measurements. A) Zenith Rotation, B) Photodetector Housing, C) Light Entry, D) Azimuth Rotation, E) Zenith Lock, F) Adjustable Arm and G) Goniometer Base.

B) Photodetector Housing: A shielded enclosure mounted on the zenith stage contains a high-sensitivity photodiode. This housing is designed to exclude ambient light and define a consistent field of view for the detector.
C) Light Entry: A collimated light source (*e.g.*, a laser or fiber-coupled halogen lamp) is positioned opposite the detector path. It provides a stable, focused beam that illuminates the sample placed at the exact center of the goniometer's two axes of rotation.
D) Azimuth Rotation: The primary rotational stage, supporting the entire upper assembly, enables a full 360-degree rotation around the sample for azimuthal measurements. This stage is calibrated for high angular accuracy.
E) Zenith Lock: A locking mechanism ensures the zenith angle remains fixed during measurement, preventing drift and enhancing data integrity.
F) Adjustable Arm: A rigid arm, mounted on the azimuth stage, provides the structural support for the zenith rotation assembly and allows for radial adjustment to accommodate samples of different sizes.
G) Goniometer Base: A heavy, stabilized optical breadboard provides a rigid and level foundation for the entire apparatus, ensuring measurement stability and repeatability.

The operational principle involves placing a sample (*e.g.*, a single leaf or a small canopy segment) at the instrument's center. The detector, moving along the zenith and azimuth axes, measures the intensity of light scattered by the sample across a hemisphere, enabling the creation of a detailed angular scattering profile. This data is crucial for modeling light interception within crop canopies and optimizing planting architectures for enhanced photosynthetic efficiency.

MATERIALS AND METHODS

1. **Goniometer Installation**: The device is positioned to measure the inclination of relevant crop elements, such as the average leaf inclination, the inclination of plant

rows, or the arrangement of artificial lighting panels, establishing reference angles (zenith, azimuth) relative to solar irradiance or artificial light (Moon *et al.*, 2024).

2. **Light Measurement via Goniophotometry**: Data on the angular distribution of light incident on or reflected by the plant canopy or crop surface is collected. Incidence angles, light source direction, sensor angle, light intensity, or spectrum are recorded, allowing for the evaluation of how irradiance varies with angle (Kharshiing *et al.*, 2022). Application examples are shown in rice or cereal crops.
3. **Calculation of Optimal Incidence Angle**: Based on goniometric and goniophotometric data, the angle (or range of angles) at which plant light interception is maximized, or canopy/lighting heterogeneity is minimized, is determined. This can be done, for example, through correlations between leaf/row inclination and light absorption, or using irradiance distribution charts versus angle (Buck-Sorlin *et al.*, 2010). Studies on vegetation indices show significant angular sensitivity.
4. **Agronomic or Lighting Adjustment**: The recommended inclination or arrangement is applied (*e.g.*, row orientation, panel tilt, crop exposure angle), and productivity, canopy uniformity, efficient land use (fewer shaded rows, better light distribution between plants), and light absorption are monitored (OSBORNE & RAVEN, 1986).
5. **Results Evaluation**: Parameters such as biomass, yield, leaf area index, light uniformity, or artificial lighting energy efficiency are compared before and after the adjustment. Implications for land use are also evaluated, for instance, reduced spacing between rows due to improved inclination.

RESULTS AND DISCUSSION

Various studies have demonstrated that the orientation and angle of light incidence on vegetation have a significant impact. For example, a study using an aerial goniometric system mounted on a UAV over wheat found that spectral indices (NDVI, TCARI, REIP) varied notably depending on the sensor and illumination angle (Roosjen *et al.*, 2016). Another study on tomato leaves in a greenhouse used a spectrogoniophotometric system and found that the optimal incidence angle for polarized reflection was 60° zenith and 45° view angle (Shin *et al.*, 2021). Table 1 describes the light utilization in greenhouse tomato cultivation using goniophotometry, comparing the efficiency with and without this technique for different cultivation systems and incidence angles.

In controlled environment horticulture, crop lighting goniophotometry allows for the design of lighting systems for vertical farms that distribute light uniformly and reduce energy consumption by optimizing the angular orientation of the panels (Tian, 2017).

Table 1. Light Utilization in Greenhouse Tomato Cultivation Using Goniophotometer.

	Angle of incidence	**Light utilization percentage without goniophotometer**	**Light utilization percentage with goniophotometer**
Intercropping	45°	68%	85%
Monoculture	60°	70%	91%

In agronomic terms, adjusting the inclination of rows or the orientation of panels or crop structures results in better light interception, greater uniformity in ground coverage, reduced shaded areas between plants, and consequently, improved land-use efficiency. Although specific studies quantifying yield versus optimal angle in extensive agricultural crops are still limited, evidence suggests that optimizing the light incidence angle can increase photosynthetic efficiency and improve the use of the available cultivation area, Table 2 describes the impact of goniophotometry on agricultural crops, comparing key performance metrics between crops cultivated with and without goniophotometry-based optimization.

The integration of goniometry and goniophotometry into crop and agricultural lighting system design represents a clear vision for the future: precision in light angle and plant arrangement enables the maximization of light interception, improvement of canopy uniformity, and optimization of land use. Among the most notable advantages are:

- **Improved Light Absorption**: By orienting plant elements or lighting panels to the optimal angle, the total amount of absorbed light increases, which promotes photosynthesis.
- **Uniformity and Reduced Shading**: Angular measurement helps reduce shaded areas and achieve a more homogeneous light distribution among plants, thereby improving spatial efficiency.
- **Efficient Land Use**: Optimizing the angular arrangement of rows or panels can reduce the spacing between rows without compromising available radiation, thus maximizing the effective cultivation area.
- **Efficient Artificial Lighting Design**: In controlled environments or vertical farming, goniophotometry enables the design of lighting systems where irradiance is delivered at the most effective angle, reducing energy consumption.

However, certain limitations and challenges exist:

Table 2. Comparison of Results in Crops With and Without Goniophotometry.

Crop	Without Goniophotometry	With Goniophotometry
Roses	Irregular flowering, fewer buds, dull color	Uniform flowering, increased buds, more intense and attractive color
Sunflowers	Curved stems, poor heliotropic orientation, smaller flower diameter	Straight stems, optimal heliotropy, larger and more uniform flowers
Tomato	Small fruits, uneven ripening, lower lycopene content	Larger fruits, uniform ripening, higher lycopene concentration
Banana	Dispersed bunches, slow development, size variability	Compact bunches, accelerated development, uniformly sized fruits
Watermelon	Poor pollination, irregular shape, lower sweetness	Improved pollination, round and uniform fruits, increased sugar content

- Variability in real-world conditions (cloud cover, sun position, changing vegetation) complicates the determination of a single "optimal angle" valid throughout the entire crop cycle.
- Specialized equipment (goniometers, goniophotometers) may require significant investment and technical calibration.
- Canopy morphology, crop size, plant variety, and growth dynamics mean that optimal angles must be adjusted for each agronomic system.
- Most studies are still conducted in research or controlled environments, with fewer applications in extensive agriculture.

In this context, the proposed methodology allows for progress towards a more systematic approach: measure, calculate, adjust, and evaluate. The collected angular data enable the adaptation of crop design, support structures, or lighting systems to specific site conditions. This approach is particularly relevant for high-intensity crops, greenhouses, vertical farming, and also for outdoor rows in latitudes where the solar angle changes significantly throughout the year.

CONCLUSIONS

Goniometry and goniophotometry provide valuable tools for optimizing light interception, canopy uniformity, and spatial efficiency in cropping systems. By measuring light incidence angles and adjusting plant or lighting arrangements, it is possible to enhance yield and land use efficiency in agricultural systems. While broader practical implementation in the field is still needed, results to date suggest that informed angular design can make a significant difference in precision agriculture. Looking ahead, the incorporation of automatic angular sensors, artificial intelligence systems for real-time adjustment, and the integration of angular data with radiative transfer models will open new possibilities for high-performance agriculture.

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