AgriVoltaics World Conference 2022
Agrivoltaics Systems
https://doi.org/10.52825/agripv.v1i.632

Published: 06 Feb. 2024

Agri-Horti-PV Research System in North Rhine-Westphalia Including PV Trackers and Integrated Rainwater Harvesting

Matthias Meier-Grüll[1][https://orcid.org/0009-0002-1296-3720], Christoph Jedmowski[1][https://orcid.org/0000-0003-4647-4896], Kathrin Hoelscher[1][https://orcid.org/0009-0006-1055-9985], Christin Müller[1][https://orcid.org/0009-0009-2338-045X], Leonard Raumann[2][https://orcid.org/0000-0001-6043-7093], Bart Pieters[2][https://orcid.org/0000-0001-6533-2098], Andreas Gerber[2][https://orcid.org/0000-0001-9102-5227], Maximilian Trommsdorff[3,4][https://orcid.org/0000-0003-2330-5168], Matthew Berwind[3][https://orcid.org/0009-0003-0988-0817], and Onno Muller[1][https://orcid.org/0000-0002-0473-5632]

[1] Institute of Bio- and Geosciences (IBG-2, Plantsciences), Forschungszentrum Jülich GmbH, Germany

[2] Institute of Climate and Energy Research (IEK-5, Photovoltaics), Forschungszentrum Jülich GmbH, Germany

[3] Fraunhofer Institute of Solar Energy Systems (ISE), Freiburg, Germany

[4] Wilfried Guth Chair, Department of Economics, University of Freiburg, Freiburg, Germany

Abstract. We present a new Agri-Horti-PV system installed at the end of 2021 in the brown coal area of North Rhine-Westphalia near Jülich, Germany. The system contains different PV installations: Standard south oriented PV modules with a rainwater harvesting set up and east-west tracker modules, of which one is equipped with a rainwater harvesting setup. For the investigation of plant growth under the PV panels and on the reference areas without PV installations a novel rail system allowing for automatic camera movement is integrated in the Agri-Horti-PV park. Using the camera setup plant growth measurements with high spatio-temporal resolution will be possible. The scientific investigations of crop growth and the influence of variable shading conditions controlled by the tracking system started in the growth season of 2022. Here we present the technical details of the system as well as first results of an experiment carried out with faba beans, assessing impact of the Horti-PV system on growth dynamics and leaf morphology.

Keywords: Agri-Horti-PV, PV Tracker, Field Phenotyping, Faba Beans

1. Technical Details

1.1 Agri-Horti-PV system

Figure 1a shows a schematic map of the Agri-Horti-PV system. Figure 1b shows a top view photo image of the Agri-Horti-PV system. There are four different PV systems, with three control areas without PV panels in between. Starting in the south (the bottom of figure 1a), the first system has south oriented PV modules, with a tilting angle of 20°. The construction contains different roof configurations between the PV panels (hail nets and acrylic glass cover) such that the influence of different roof top covers e.g. on the water management in the system can be studied. The height of the south oriented system is 4.30 m at the highest roof point. The construction in general allows a drive through height of 2.50 m. The drive through width is

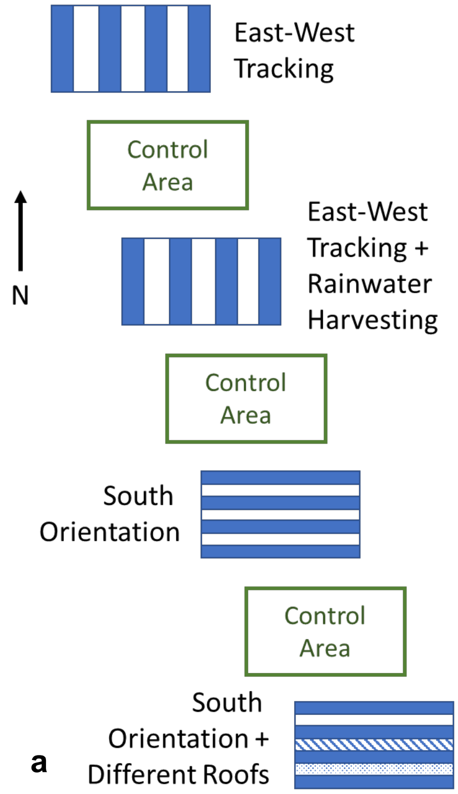

Figure 1a+b. Schematic map of the Agri-Horti-PV system installed in Morschenich-alt in the brown coal area of North Rhine-Westphalia (a, left) and top view photo of the Agri-Horti-PV system (b, right).

4.0 m. These geometries allow the use of machineries applied in horticultural practice to produce e.g. berries, apples, and lettuce. Thus, we call our south oriented setups Horti-PV.

In the north of the first Horti-PV system, a control area without PV panels is placed followed by the second Horti-PV system with south oriented panels. Here, the area between the panels is fully open such that the rainwater reaches the ground directly. Further north the east-west tracker with rainwater harvesting and the second control area south is located. The rainwater harvesting consists of a gutter between the PV modules to collect the rain flowing over the PV tables (details see figure 3). The rainwater is collected in a central tank for the controlled drop irrigation in all systems. The height of the PV tracker system is 6 m allowing for a drive through height 4.0 m. The distance between the steel poles and thus the drive through width is 11 m. The geometries of the PV-tracker system allow the use of machineries applied in agricultural practice to produce e.g. potatoes, wheat or maize. Thus, we call our PV tracker setups: Agri-PV.

At the most north side of the field the Agri-PV east-west tracker without rainwater harvesting and the third control area south of it is installed. The whole fenced area is roughly 1.8 ha in size. The single systems as well as the control areas have dimensions of about 40 x 25 m^2.

The whole Agri-Horti-PV system carries 896 PV panels, generating a total PV power of 295 kW$_{peak}$. Bifacial silicon-based PV modules with a dimension of 1 x 2 m^2 are installed. A battery pack with a capacity of 35 kWh is connected to one PV table of 25 kW$_{peak}$ of the Horti-PV system. The electricity generated and stored using that stand alone PV-battery system is used for the measurement equipment, the irrigation and the PV tracker control in the field.

1.2 Phenotyping setup

The Agri-Horti-PV system is unique in its kind to combine photovoltaics with high throughput non-invasive quantification of plant performance in the field. To determine the so-called phenotype of plants we make use of state-of-the art sensors that can be mounted on a custom-made carriage moving along a rail system. The rail system is mounted under the photovoltaics and in the open field 'control' area for comparison to growth conditions without photovoltaics.

a **b**

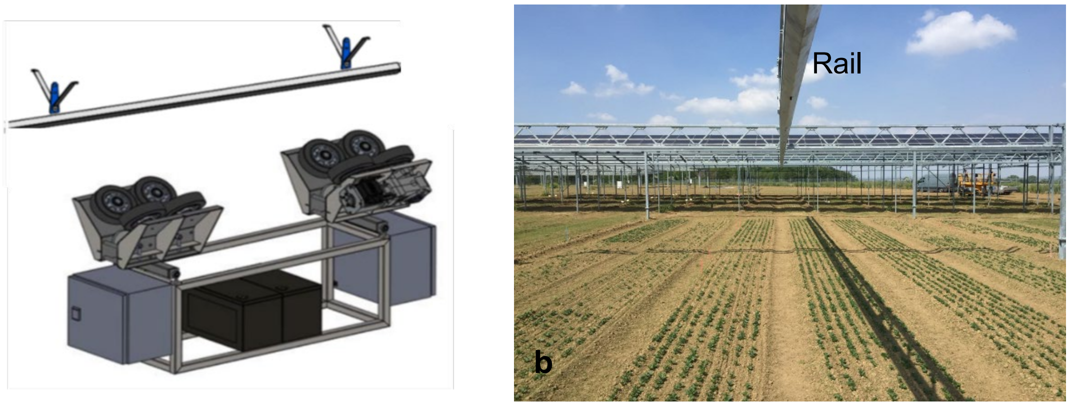

Figure 2a+b Technical drawing of the rail system (top) to carry the camera wagon (bottom) for high resolution plant growth and performance measurements (a, left) and photo of the rail system installed in the Agri-Horti-PV system (b, right).

Figure 2 shows the design of the rail system with carriages for mounting sensors in figure 2a. The carriage location has an accuracy of 2 cm and is battery powered. The carriage has a universal mounting platform that can carry sensors up to about 50 kg. The total length of the rail through the whole Agri-Horti-PV system including the control area (figure 2b) is ~1200 m with minimal two tracks under the PV modules and in the control fields. The rails are perpendicular to the orientation of the panels as such in the south oriented PV the carriage will drive from north to south (or vice versa). This allows to capture plant performances along the environmental gradient under the panels. To quantify plant performance, we will first attach RGB cameras followed by sensors for field phenotyping [1]. The system is expected to be fully operational in summer 2023. In 2022, phenotypical data was acquired by ground measurements and first data is presented in section 2.

1.3 PV Tracker system and control unit

As shown in figure 1b) mentioned above, two pilots equipped with horizontal single-axis trackers (HSAT) were installed in the northern portion of the test site, both containing four 2P bifacial module rows. The first tracking sub-system includes an internal V-shaped module angle to allow the tables to harvest rainwater for irrigation purposes, shown in figure 3. The second system has a traditional flat module orientation. The two module rows in the V-shaped arrangement are stringed individually to improve charge controller performance. Each system has a ground clearance of roughly 5.50 m and a ground coverage ratio of roughly 33 %. Light heterogeneity and edge effects play an important role in the growth characteristics of plants beneath such a system, and for that reason, the analysis is spatially divided into varying light treatment zones so that phenotypical measurements across the field can be better compared to one another.

Figure 3. Side view of module V-shaped row with internal angle for rainwater harvesting capabilities. During rain events, the modules change to a zenith orientation for collection.

The systems serve as testbeds for custom tracking algorithms that consider plant and photovoltaic yield in a combined system logic, also possessing the ability to switch between target modes dependent on season, crop, or manual override. The tracking algorithm's core is based on two performance indicator calculations, one for light and PV yield, and one for crop yield. The PV performance calculation uses the Radiance ray-tracer at its core and is coupled with the Fraunhofer ISE's validated PV yield calculation software Zenit^{TM}. For agricultural performance quantification in the algorithm, crop growth models (selection depends on practice typically WOFOST, Expert-n, STICS, DSSAT) calibrated for the site and by phenotypic measurements are utilized. This novel combined PV and plant yield calculation software is referred to as APyV, providing the basis for dual yield tracking algorithms schematically depicted in figure 4. In this scheme, three-day weather forecasts are utilized in a cloud-based

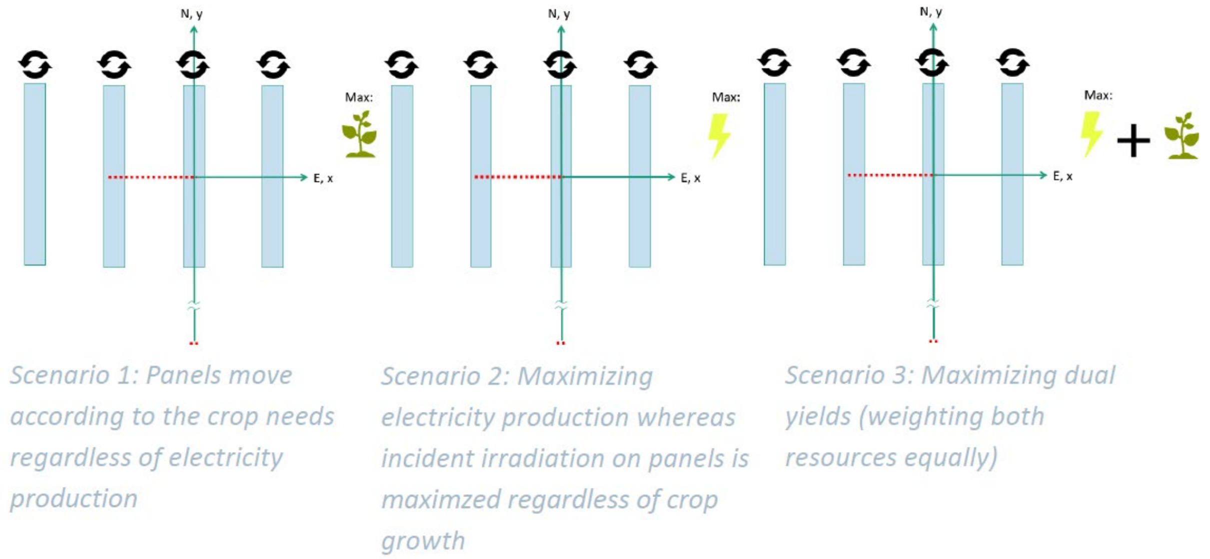

Figure 4. Three example modes for the Agri-PV tracking algorithms to be deployed at the site, each capable of time-dependent activation.

digital twin of the system to upload tracking profiles for that consider predicted weather, with real-time in-situ monitoring of irradiation, wind speed, and rainfall events allowing the system to adapt to local meteorological variabilities.

1.4 PV analytics

For all subsystems, we installed PV monitoring setups from the Laboratory of Photovoltaics and Optoelectronics of the University of Ljubljana (Figure 5) to measure the current/voltage characteristics of selected modules (two modules per module orientation and subsystem). The modules are measured sequentially. The duration of a single I/V measurement is approximately 10 seconds with a repetition rate of 1 measurement per minute. Between I/V measurements, the modules are kept at the maximum power point (MPP). We also measure the temperature of the modules as well as the ambient temperature (sensor type SHT75 from AMES), wind speed (sensor type VMT-107A from AMES), irradiance in the horizontal plane and in the plane of array using reference cells from ISE Freiburg and the University of Ljubljana.

Figure 5. PV monitoring cabinet from University of Ljubljana with 4 MPP tracker units (upper black boxes) and the IV measure unit (lower black box).

In addition, we installed a sky camera (model SONA 502U) from Sieltec to monitor the sky dome (180° field of view) and two pyranometers (CMP11) from Kipp & Zonen pointed at the ground and sky to calculate the ground albedo. On system level we collect performance data from each sub-string as well as the performance data from the different systems.

2. First experiments in 2022

The installation of Agri-Horti-PV systems affects the microclimatic conditions for plants grown within the system in multiple ways [2]–[4]. Two important factors that are altered by the presence of solar panels are light and water availability: Directly under the panels of the second Horti-PV system, plants are partly shaded and shielded from direct rainfall, whereas plants in the open area between the panels experience full rain and more shade during the day.

In order to analyse plant growth in an Agri-Horti-PV system, we have grown faba beans (*Vicia faba*) of the variety Tiffany in the second Horti-PV system, shown in figure 6, and the adjacent control area. Plots were orientated perpendicular to the solar panels and span from the open area (“APV-open”) up to the area directly under the panels (“APV-closed). Different densities were planted to study the influence of density stress in addition to effects of varieties of shadow and water in the system (please note that density effects will not be presented in this paper as data analysis is still ongoing) We used our light simulation model (see proceedings paper of L. Raumann *et al*. for more details) such that one ‘plot’ on area with faba beans planted at the same density included the full range of light conditions.

Figure 6. First experimental design of faba beans of different densities grown under the Horti-PV system.

We sampled in all three locations (control, APV-open and APV-closed) and observed a response of plants in terms of plant height, as shown in Fig. 7 for plants grown with a density of 40 plants m^{-2}, a standard density for faba beans in agricultural practice in Germany. Daily growth rate was highest for control plants until 55 days after sowing (DAS) and dropped significantly afterwards when plants were close to their maximum height. Up to 49 DAS, there was only a small difference between experimental groups, with growth rates being the lowest for APV-open initially. After 49 DAS, the differences in growth rate became larger and plants in APV-closed developed much slower compared to the other two groups. Overall, this pattern can be explained by differences in water and light availability. During early growth in spring, water was still sufficiently accessible for plants in the covered parts of the system, as the system was not completed before end of 2021 and consequently there was still high enough soil humidity. Under these conditions, APV-closed plants initially developed faster in comparison to APV-open, as they received more light per day. As soon as the soil water content under the panels decreased due to evapotranspiration and lack of replenishment by rainfall, plant growth in APV-closed was slowed down. Also, a difference in development is apparent in APV-open in comparison to control plants, as control plants show a distinct peak in daily growth rate 55 DAS, which is not visible for APV-open plants. We assume that this effect is attributed to a delayed plant development caused by different light conditions. Light availability also has an impact on leaf morphology [5], resulting in differences in area-to-mass ratio, also known as specific leaf area (SLA). Changes in SLA of faba beans are presented in Fig. 8. Here, control plants had the lowest SLA, also SLA of leaves from the top segment of

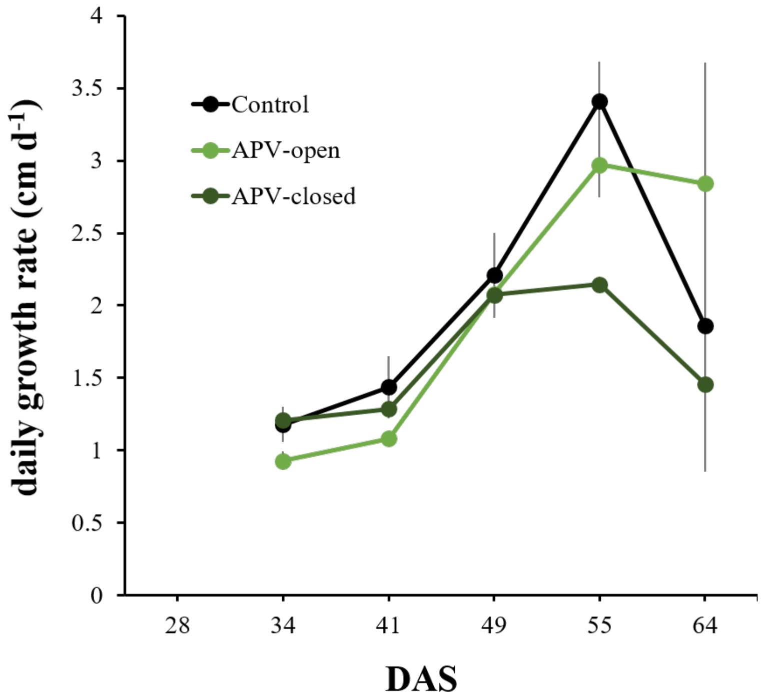

Figure 7. Daily growth rate of faba bean plants grown under the covered (APV-closed) or uncovered (APV-open) part of the Horti-PV system or the adjacent control area; DAS = days after sowing, mean ± SD, n=5.

the plants was lower compared to the middle segment. The same pattern can be observed for APV-open plants, however overall values for SLA are higher than in the control. Interestingly, the segment effect was inverted for APV-closed group, and in total SLA values of APV-open and APV-closed were comparable. It was shown before that SLA is negatively correlated with light intensity during growth [6], which is line with the observed differences between control and APV plants, as well as between top and middle leaves in control and APV-open. Since SLA is a complex trait which is also affected by water availability and temperature [7], it is

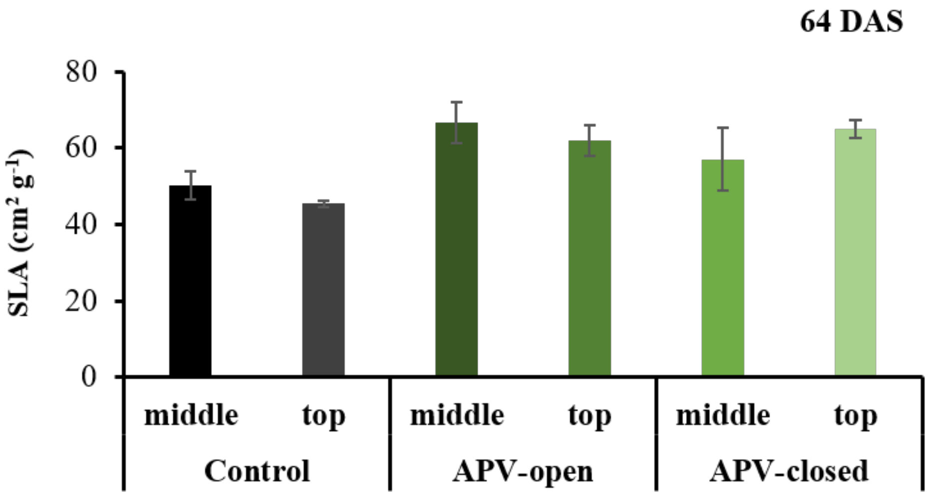

Figure 8. Specific leaf area (SLA) of of faba bean plants grown under the covered (APV-closed) or uncovered (APV-open) part of the Horti-PV system or the adjacent control area; middle = leaves of the middle section of plants, top = leaves of the top section of plants DAS = days after sowing, mean ± SD, n=5.

difficult to draw comparisons between APV-open and APV-closed due to the multifactorial origin of the observed SLA values. The remarkable increase of SLA in top leaves of APV-closed will be an interesting feature to be investigated in future trials in the Agri-Horti-PV system.

3. Summary and Outlook

This paper gives a technical overview of our Agri-Horti-PV system containing various options for different scientific experiments investigating plant growth and performance, PV-tracking optimization and PV-yield analysis. With this highly flexible tool we expect important insights and results for the whole Agri-PV community and possibilities for further joint research projects to combine results from different Agri-PV systems. First experiments already show the influence of inhomogeneous light and water distribution on the growth performance of faba beans in the Horti-PV setup.In upcoming experiments, plant growth and performance in response to Agri-Horti-PVs and the associated alterations in microclimate will be analysed in more detail. The use of the automated rail system covering the whole Agri-Horti-PV system will provide phenotypical data in high spatio-temporal resolution, helping to reveal the potential and the challenges of crop production within the Agri-Horti-PV systems and providing optimization measures for future implementations in agricultural practice.

Data availability statement

Physiological data presented in Figs. 7 and 8 will be published as part of Christin Müller's master's thesis.

Author contributions

0: Conceptualization, 1: Methodology, 2: Software, 3: Formal Analysis, 4: Investigation, 5: Visualization, 6: Writing – original draft, 7: Writing – review & editing 8: Supervision, 9: Resources, 10: Funding acquisition, 11: Project administration

Matthias Meier-Grüll: 0,1,6,7,8,9,10,11 -- Christoph Jedmowski: 0,1,2,4,7,8 -- Kathrin Hoelscher: 0,1,3,4,6 -- Christin Müller: 4, Leonard Raumann: 2,4,7 -- Bart Pieters: 2,4,7 -- Andreas Gerber: 1,6,7,8,11 -- Maximilian Trommsdorff: 0,1,3,4,7,8,9,10,11 -- Matthew Berwind: 0,1,2,3,4,6,8,10,11 and Onno Muller: 0,1,3,4,6,7,8,9,10,11

The authors declare no competing interests.

Competing interests

The authors declare no competing interests.

Funding

This work was carried out in the framework of projects funded by the Federal Ministry of Education and Research in Germany: YESPV-NIGBEN (03SF0576A), Bioökonomie-REVIER (APV 2.0 (031B0918A) and Agri FEe (031B1137DX))

Acknowledgement

We thank our colleagues for the technical support at the installations and especially: Michael Quarten, Angelina Steier and Christina Kuchendorf from IBG-2 Forschungszentrum Jülich; Jonas Noll and Dirk Erdweg from IEK-5 Forschungszentrum Jülich. We thank the SUNFarming GmbH for the engineering and the technology delivery of the Agri-Horti-PV system.

References

1. Morisse, M., D. M. Wells, E. J. Millet, M. Lillemo, S. Fahrner, F. Cellini, P. Lootens, O. Muller, J. M. Herrera, A. R. Bentley and M. Janni (2022). "A European perspective on opportunities and demands for field-based crop phenotyping." Field Crops Research 276: 108371. https://doi.org/10.1016/j.fcr.2021.108371
2. E. H. Adeh, J. S. Selker, and C. W. Higgins, “Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency,” PLoS ONE, vol. 13, no. 11, Nov. 2018, doi: https://doi.org/10.1371/journal.pone.0203256.
3. Y. Elamri, B. Cheviron, A. Mange, C. Dejean, F. Liron, and G. Belaud, “Rain concentration and sheltering effect of solar panels on cultivated plots,” Hydrology and Earth System Sciences, vol. 22, no. 2, pp. 1285–1298, Feb. 2018, doi: https://doi.org/10.5194/hess-22-1285-2018.
4. H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, and J. Wery, “Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?,” Agricultural and Forest Meteorology, vol. 177, pp. 117–132, Aug. 2013, doi: https://doi.org/10.1016/j.agrformet.2013.04.012.
5. Xu, F., Guo, W., Xu, W., Wei, Y., Wang, R. (2009). Leaf morphology correlates with water and light availability: What consequences for simple and compound leaves? Progress in Natural Science, 10: 1789-1798, https://doi.org/10.1016/j.pnsc.2009.10.001
6. Evans, J.R. and Poorter, H. (2001). Photosynthetic acclimation of plants to growth irradiance: the relative importance of specific leaf area and nitrogen partitioning in maximizing carbon gain. Plant, Cell & Environment, 24: 755-767. https://doi.org/10.1046/j.1365-3040.2001.00724.x
7. Zhou, H., Zhou, G., He, Q., Zhou, L., Ji, Y., Zhou, M. (2020). Environmental explanation of maize specific leaf area under varying water stress regimes. Environmental and Experimental Botany 171: 103932. https://doi.org/10.1016/j.envexpbot.2019.103932