

Light Thresholds and Shading Effects on Strawberry and Raspberry Yields and Quality Under Agrivoltaics Systems in Switzerland

Jocelyn Widmer^{1,*} , André Ançay¹, Mathilde Duchemin², Gaël Nardin² ,
Mathieu Ackermann², and Louis Sutter¹ 

¹Agroscope, Conthey, Switzerland

²Insolight, Lausanne, Switzerland

*Correspondence: Jocelyn Widmer, jocelyn.widmer@agroscope.admin.ch

Abstract. In Switzerland, a large proportion of strawberries (*Fragaria × ananassa* Duch.) and raspberries (*Rubus idaeus* L.) are cultivated under protective covers such as rain covers, tunnels, and greenhouses to safeguard against adverse weather. However, rising summer temperatures increasingly threaten fruit yield and quality, prompting interest in agrivoltaic (AgriPV) systems as a climate-smart solution. AgriPV enables dual land use by combining photovoltaic energy production with crop cultivation, though shading from solar panels may impact crop performance. This four-year study assessed the effects of shading on yield and quality of strawberries and raspberries grown in substrate systems with fertigation across 21 case studies in Switzerland, including 13 AgriPV configurations at three sites. Light availability was measured as daily light integral (DLI), and its influence on yield, fruit weight, firmness, sugar content, and acidity were analysed using linear mixed-effects models. We report slopes with standard errors and p-values to quantify effect sizes. Results show a positive linear relationship between DLI and both yield and sugar content in both species, with stronger effects observed in strawberries. Based on the DLI at which the standardized yield regression crosses zero, we recommend minimum DLIs of 25 mol m⁻² d⁻¹ for strawberries and 15 mol m⁻² d⁻¹ for raspberries to avoid disproportionate yield loss. Strawberry firmness also declined at low DLI, likely due to reduced UV exposure. Fruit weight and acidity were unaffected. Our findings inform the design of AgriPV systems that balance renewable energy production with high-quality berry yields, emphasizing the importance of species-specific light requirements.

Keywords: Daily Light Integral, Berry Production, Strawberry, Raspberry, Shading

1. Introduction

1.1 Climate change and protected berry crops

Strawberry (*Fragaria × ananassa* Duch.) and raspberry (*Rubus idaeus* L.) production is a high-value agricultural sector, with approximately one-third of strawberries and three-quarters of raspberries grown under protective structures, such as rain covers, plastic tunnels, or greenhouses in Switzerland [1]. Berry crops are mainly grown under protective covers to shield them from adverse weather conditions such as heavy rainfall, hail, and excessive solar radiation, which can damage fruit and reduce marketable yield. These covers help extend the growing season and improve fruit quality. They typically allow a high level of light transmission, with a shading level between 15% and 35% when using single-layer polyethylene films [2], to ensure

sufficient photosynthesis. Different types of covers vary in their structure and material: rain covers are generally open-sided and use clear plastic sheeting, tunnels provide more enclosure and environmental control, while greenhouses may offer the most protection but also generate higher temperatures. The choice of cover depends on the crop, production system, and climatic conditions, but all aim to balance protection with adequate light availability.

1.2 Agrivoltaics: dual use for food and energy

Agrivoltaics (AgriPV) integrates photovoltaic panels with crop production, enabling simultaneous generation of renewable energy and agricultural yield on the same land. This dual-use concept increases land-use efficiency, enhances farm resilience by diversifying income streams, and can mitigate crop temperature and evapotranspiration stress. AgriPV systems, depending on configuration (e.g., static tilted, single-axis tracking), modulate microclimates beneath panels—reducing heat, moderating soil moisture, and altering light distribution [3].

1.3 Berry crops and shade tolerance: the need for quantifying thresholds

Berry species naturally evolved in semi-shaded environments (e.g., forest understory), leading to a generally higher shade tolerance compared to many field crops. A meta-analysis of AgriPV shading studies show variable yield responses across berry species [4]. Strawberries exhibit sensitivity to increased shade, with yield losses scaling with light reduction. Berries like blueberry tolerate up to ~35–50% shade without yield decline, while others (e.g., raspberry, blackberry) show moderate shade tolerance. Aggregated berry group analysis suggests yield may even be boosted under up to ~60% shade in some contexts [5], though species- and environment-specific thresholds are critical. Despite promising indications, there remains a lack of crop-specific shading response curves—especially for strawberries and raspberries—that delineate the thresholds where yield and quality begin to decline. Optimal AgriPV design requires balancing trade-offs between energy generation and crop performance. Irradiance reduction of 15–30% has been shown to moderately reduce yields in berry crops under uniform shade. However, complex factors—such as panel density, annual and seasonal variation in solar irradiance, cultivar-specific light response, and localized microclimate conditions—affect outcomes. Currently, there is no consensus on the maximum shading levels (percentage of light attenuation) that strawberries and raspberries can tolerate without economically significant yield or quality losses.

This four-year, multi-site Swiss study addresses these knowledge gaps by:

Providing species specific daily light integral (DLI) recommendations for strawberries and raspberries.

Evaluating impacts on key agronomic performance metrics, including yield, average fruit weight, and quality traits (firmness, sugar, acidity).

Integrating DLI thresholds into practical agrivoltaic design guidelines (panel spacing and coverage) for Swiss conditions

These data will enable the definition of design parameters for AgriPV that optimize crop productivity while harnessing renewable energy.

2. Material and Methods

2.1 Study design and experimental setup

This study is based on 21 distinct case studies, each defined as a unique combination of crop species (strawberry or raspberry), site, and year. Data were collected over four consecutive

years from 2021 across three sites located in the major berry-producing regions in Switzerland, each representing different climatic zones and environmental conditions. At all sites, crops were cultivated in substrate systems using fertigation, which reflects the standard horticultural practice in intensive berry production in Switzerland. Across all sites and years, 6 raspberry varieties were cultivated, whereas the analysis of strawberries was restricted to summer varieties (single annual flowering), comprising 5 varieties. However, due to the limited replication per variety, the analyses were conducted at the species level, distinguishing only between strawberries and raspberries. The 21 case studies covered a broad range of shading structures, both solar and conventional. Non-AgriPV shading systems included four commonly used protective structures in commercial berry farming: rain covers (simple plastic roofs with open sides), polytunnels (low-height structures providing moderate enclosure), large polytunnels (higher and wider constructions), and greenhouses (fully enclosed structures that offer maximum environmental control). In parallel, 13 different types of AgriPV installations were tested. These varied in their design, particularly in terms of solar panel spacing, orientation, and density, which influenced the shading levels experienced by the crops. For a given study site, several AgriPV and conventional systems may be present and evaluated. As this study aims at identifying the effect of shading, results obtained in open field case studies were excluded from the analysis. Indeed, the absence of cover mixes in other factors such as exposure of the crops to adverse weather conditions. Within each case study, all other cultivation parameters—such as variety, substrate, nutrition, irrigation regime, crop protection, and general crop management—were standardized. The only experimental variables were the type and intensity of shading and, indirectly, the local climatic conditions.

2.2 Light measurements

Light availability was quantified using the DLI, expressed in moles of photosynthetically active radiation (PAR) per square meter per day ($\text{mol m}^{-2} \text{d}^{-1}$). DLI was measured using quantum PAR sensors (SQ-500-SS; Apogee Instruments, Logan, USA or RK200-02 Type A; Hunan Rika Electronic Tech Co., Ltd, Changsha, China) installed just above the crop canopy within each shading treatment. For each case study, the DLI was averaged over the entire crop cycle, from planting to the last harvest, and served as the principal explanatory variable for assessing shading impacts on crop performance. The data were cleaned by removing all extreme values ($\text{DLI} < 0$ or $> 65 \text{ mol m}^{-2} \text{d}^{-1}$) or erroneous measurements.

2.3 Crop measurements

For all case studies, several agronomic and quality-related parameters were measured. Total fruit yield was recorded by summing the weight of picked fruit over the entire harvest period, and average fruit weight was calculated as the total fruit weight divided by the number of harvested fruits. Raspberry firmness was measured on 24 fresh fruits using a Firmtech 7 FT7 berry firmness meter (UP Umweltanalytische Produkte GmbH, Ibbenbüren, Germany) whereas strawberries firmness was measured on 25 fruits with a Durofel (Setop Giraud-Technologie and Copa technologie S.A. / Ctifl, Cavaillon, France) according to the manufacturer's recommendations. Around 400g of fruit was blended and juice samples were analysed to measure soluble solids content ($^{\circ}\text{Brix}$) using an Atago pocket refractometer PAL-1 (ATAGO Co., Ltd, Tokyo, Japan), while titratable acidity ($\text{g citric acid L}^{-1}$) was determined by acid–base titration with an Omnis Titrator (Metrohm Schweiz AG, Zofingen, Switzerland) using sodium hydroxide solution (0.1M NaOH) as the titrant. Each case studies included at least 3 replicates.

2.4 Statistical analysis

To allow direct comparison across species, years, and case studies, all measured parameters—yield, average fruit weight, firmness, sugar content, and acidity—were standardized within each crop using Z-scores. Each Z-score value was obtained by subtracting the species-specific mean (across all case studies) from the raw value and then dividing by the species-

specific standard deviation. This standardization enabled a relative performance sensitivity assessment across diverse environmental and shading conditions [6]. For each of the five standardized response variables, a linear mixed-effect model was fitted. Fixed effects in all models included crop species (strawberry or raspberry), DLI (as a continuous variable), and the interaction between species and DLI. The model also included a random intercept for case study, accounting for site- and year-specific variability. The DLI value at which the yield Z-score regression line crosses zero corresponds to the point where crop yield drops below the average yield of the case studies included in the analysis. This value is used as the minimal DLI recommendation in this study, as we believe that AgriPV systems should not negatively impact crop yields. Model validation followed standard procedures, including checks for normality, homoscedasticity, and independence of residuals using diagnostic plots. P-values were calculated based on Kenward–Roger approximation of degrees of freedom [7]. All analyses were conducted in R, using the packages lme4 for mixed-effects modelling [8].

3. Results

Daily light integral had a significant positive effect on yield across all case studies, indicating that increasing light availability under the different shading systems was associated with higher fruit yield (Table 1). Importantly, a significant interaction was found between species and DLI, suggesting that the response of yield to increasing DLI differed between the two species. Specifically, strawberries showed a steeper increase in yield with rising DLI values, indicating greater sensitivity to shading than raspberries (Table 1). On average, yield increased by 2.4% per additional $\text{mol m}^{-2} \text{d}^{-1}$ of DLI in strawberries, compared to 1.8% in raspberries. (Figure 1A). Based on the point where the standardized regression line crosses zero, the minimal DLI recommendation for maintaining average yield was $15 \text{ mol m}^{-2} \text{d}^{-1}$ for raspberry and $25 \text{ mol m}^{-2} \text{d}^{-1}$ for strawberries. No significant effects of DLI, species, or their interaction were observed for average fruit weight. This suggests that while shading reduced total yield, it did not significantly alter the average size of individual fruits in either species. Sugar content followed a similar trend to yield, with a significant positive effect of DLI on sugar content (Table 1). The interaction between DLI and species was also significant, indicating that sugar levels in strawberries were more strongly affected by light availability than in raspberries (Figure 1B). No significant effects of DLI, species, or their interaction were found for titratable acidity. This suggests that acidity was stable across shading treatments and not significantly influenced by light conditions for either crop. Fruit firmness was significantly affected by the interaction between species and DLI, despite the absence of a significant main effect of DLI across all species (Table 1). Stratified interpretation showed that firmness increased with higher DLI in strawberries, whereas there was no significant effect in raspberries (Figure 1C).

Table 1. Results of linear mixed-effects models for statistical inference of fixed effects with shown denominator degrees of freedom (*df*), and *p* values from *T*-test. Significant *p* values ($p < .05$) are displayed in bold

Response	Fixed effects	<i>df</i>	T-value	<i>p</i> value
Berry Yield	DLI	43.32	5.294	< 0.001
	Species	42.219	-2.64	0.012
	DLI : Species	45.294	2.098	0.042
Fruit Weight	DLI	42.973	-0.612	0.544
	Species	40.084	-0.236	0.815
	DLI : Species	44.696	-0.03	0.976
Sugar	DLI	43.678	3.082	0.004
	Species	46.988	-2.642	0.011
	DLI : Species	44.6	3.2	0.003
Acidity	DLI	47.709	-0.306	0.761
	Species	53.542	-0.614	0.542
	DLI : Species	49.277	1.068	0.291
Firmness	DLI	40.561	1.228	0.226
	Species	33.123	-2.313	0.027
	DLI : Species	40.969	3.17	0.003

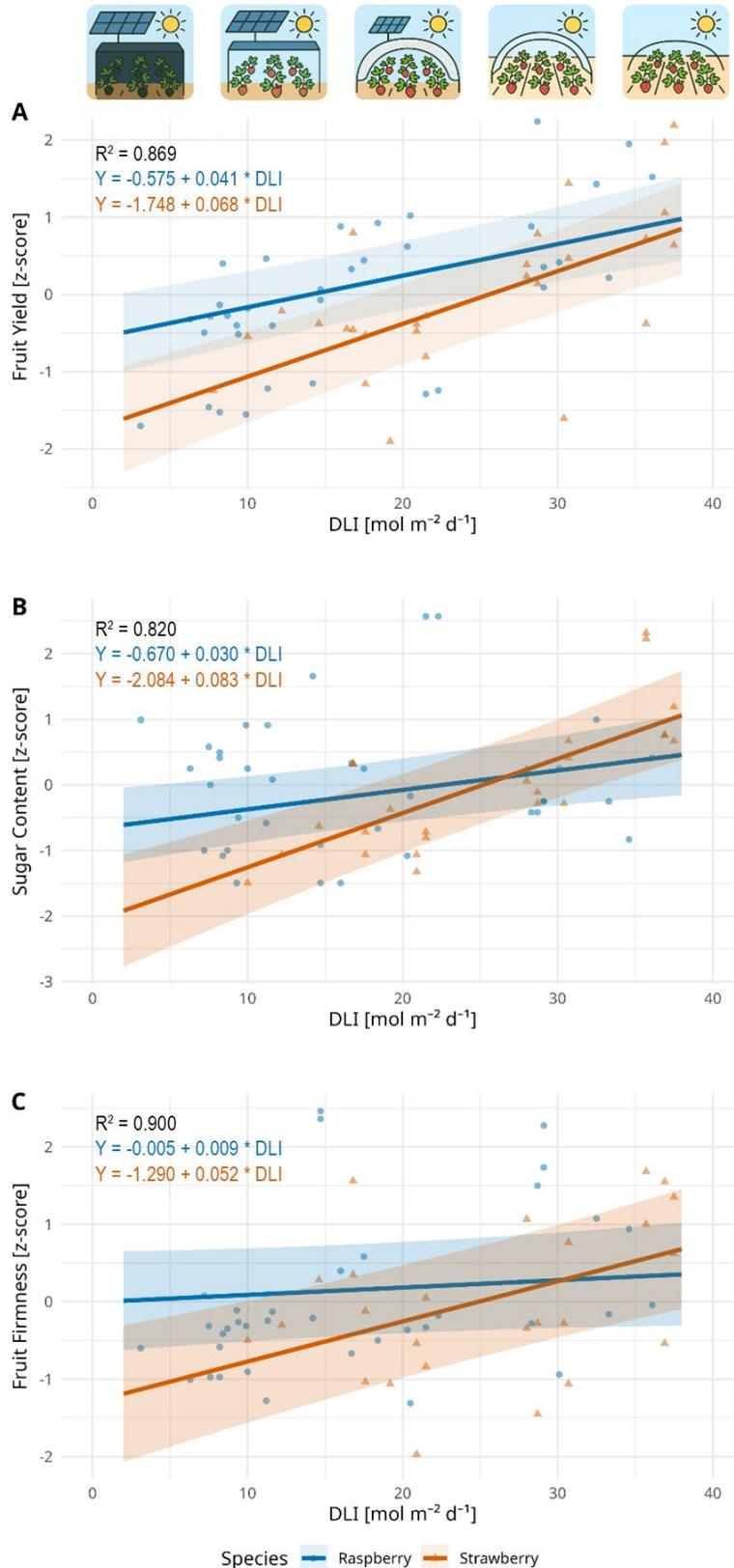


Figure 1. Relationship between Daily Light Integral (DLI) in $\text{mol m}^{-2} \text{d}^{-1}$ and measures (A) berry yield, (B) sugar content and (C) fruit firmness for strawberries (red triangles and lines) and raspberries (blue dots and lines). In the top left corner of each panel, the conditional R^2 of the model is indicated, along with the linear equations calculated for each species. The illustration above the figure shows a schematic gradient from left to right, where light transmission to the crop increases. It ranges from very dark AgriPV systems to light AgriPV or old plastic covers, then to bright polytunnels, and finally open-field conditions

4. Discussion

The response of berry crops to shading under protective structures and AgriPV systems differs markedly between species. Our results show that the response to light availability is stronger on strawberries than raspberries, confirming earlier assumptions about species-specific shade tolerance. In the following section, we discuss these results in detail, first for strawberries and then for raspberries, before briefly addressing traits that were not significantly affected by light.

4.1 Strawberries: high sensitivity to shading

In strawberries, fruit yield showed a strong positive linear relationship with DLI, underlining the crop's high light requirement. Yield decreased consistently across all covered systems as shading increased. Based on our findings, we recommend a minimum DLI of $25 \text{ mol m}^{-2} \text{ d}^{-1}$ over the cropping period for maintaining average yield levels. In our experimental settings, this corresponded to an estimated total shading of 10–30%, depending on the type of cover. These results align with previous findings by [4], who also reported that increased shading leads to significant yield reductions in strawberry crops.

Sugar content followed a similar pattern, with a decrease in sugar level as shading increased, further supporting the critical role of light in maintaining fruit quality. These results reinforce our recommendation of $25 \text{ mol m}^{-2} \text{ d}^{-1}$ as an absolute minimum threshold not only for yield but also for fruit sweetness. As previously shown [9], sugar accumulation in strawberry fruits is tightly linked to photosynthetic activity during the maturation phase. Lower light availability under dense covers or AgriPV systems can impair photosynthesis, which is expected to lead to reduced carbohydrate accumulation in the fruit.

In addition to yield and sugar content, fruit firmness was also negatively affected by shading in strawberries. Firmer berries are a key quality attribute for retail, especially for long-distance transport and shelf life. We hypothesize that this decline in firmness is at least partially due to reduced ultraviolet (UV) radiation under shading structures. Supporting this, studies such as those by [10] have shown that UV exposure can enhance epidermal thickness and firmness in strawberry fruits. Our own variety trials conducted under identical growing conditions consistently show higher firmness in open-field strawberries compared to those grown under cover, further suggesting a role of UV light in maintaining structural fruit integrity.

Collectively, these findings underline the importance of light—both in quantity (DLI) and quality (spectrum)—for optimal strawberry production under protected systems. As AgriPV systems are scaled up, careful attention must be paid to their design to avoid yield and quality losses due to insufficient light.

4.2 Raspberries: greater shade tolerance

Raspberries also showed a decline in yield under increasing shading, but the effect was less pronounced than for strawberries. This confirms some shade tolerance of raspberries, likely due to their evolutionary origin in woodland environments [11]. Based on our analysis, we propose a minimum DLI of $15 \text{ mol m}^{-2} \text{ d}^{-1}$ for maintaining acceptable yields in raspberry production. This threshold allows greater flexibility for integrating AgriPV systems or shade structures in raspberry cropping systems. Also, yields under AgriPV covers tended to be higher in most case studies where a direct comparison with open-field (uncovered) cultivation was made.

In contrast to strawberries, sugar content in raspberries was only slightly reduced by lower DLI. This suggests that raspberries may have a more stable sugar metabolism or greater capacity to compensate under low light. Fruit firmness in raspberries showed no significant relationship with shading level, highlighting their robustness in maintaining textural quality even under suboptimal light conditions.

4.3 Traits unaffected by light availability

Interestingly, some key traits were unaffected by shading in both species. Neither fruit weight nor titratable acidity responded significantly to DLI in our models. This indicates that the size and acid profile of fruits are relatively stable traits across shading conditions, possibly regulated more by genetic factors and water status than by light levels. These findings are consistent with other studies in berry crops that report stability of these traits under variable light [12].

4.4 Implications for AgriPV design

Our study highlights the importance of species-specific light requirements in the context of AgriPV system design. For strawberries, ensuring a minimum average DLI of $25 \text{ mol m}^{-2} \text{ d}^{-1}$ is recommended to maintain both yield and fruit quality, while raspberries can tolerate considerably lower light levels. In practice, these minimal DLI recommendations should be considered when designing and simulating an AgriPV system to optimize the transparency, spacing, tilt and height of the panels. This would ensure sufficient light levels for the crops while optimizing electricity production. While our analysis focuses solely on the effects of DLI—without considering other factors such as cultivation practices or air temperature—it clearly highlights the species-specific light sensitivity and differing yield and quality responses of strawberries and raspberries. Plant-level DLI has the advantage over shading percentage or coverage ratio to take into account solar radiation levels and is therefore proposed as more universal design parameter for AgriPV systems. Additionally, light spectrum management—including the transmission of UV light—may offer opportunities to preserve quality traits such as firmness, particularly in strawberries. Further research should focus on dynamic shading strategies, spectral manipulation using semi-transparent photovoltaic materials, and varietal selection for improved shade tolerance. Understanding genotype-by-environment interactions under AgriPV systems will be key for developing resilient berry production systems in the face of climate change.

5. Conclusions

This study demonstrates that light availability, measured as DLI, is a critical factor influencing both yield and fruit quality in strawberry and raspberry production under protective and AgriPV systems. Strawberries showed high sensitivity to shading, with significant reductions in yield, sugar content, and firmness as DLI decreased. Based on our results, we recommend a minimum average DLI of $25 \text{ mol m}^{-2} \text{ d}^{-1}$ on the crop during the strawberry cultivation cycle, corresponding to a maximum shading level of approximately 10–30%, depending on the system and region. Raspberries exhibited greater shade tolerance, with yield only moderately affected and quality parameters—particularly firmness—remaining largely stable. For this crop, a minimum average DLI of $15 \text{ mol m}^{-2} \text{ d}^{-1}$ appears sufficient to maintain average performance. Due to limited cultivar replication and Switzerland's specific climate, the DLI thresholds may vary depending on cultivars or regions.

Across both species, fruit weight and acidity were not significantly influenced by shading, suggesting these traits are relatively robust to light variation. Our findings provide practical thresholds for the design and implementation of AgriPV systems in berry production and underscore the importance of crop-specific strategies to balance energy generation and agricultural output. Canopy DLI should be monitored, targeting $\geq 25 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for strawberries and $\geq 15 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for raspberries, and UV-transmitting materials should be used where possible. Optimizing light transmission quantity and quality will be essential to ensure sustainable berry yields and quality in future climate-smart systems.

Data availability statement

Parts of the data are private and not publicly available. Please contact the corresponding author if you would like to access the dataset underlying the study.

Author contributions

Conceptualization: JW, MD, MA, GN, LS; Investigation: JW, MD, GN; Formal analysis & Methodology: JW, LS; Writing – original draft: JW, LS; Writing – review & editing: JW, LS, GN

Competing interests

MD, MA and GN are employees of Insolight, a company that develops and commercializes agrivoltaic solutions. All other authors declare that they have no competing interests.

Funding

The authors acknowledge support by the Swiss Federal Office for Energy, the Swiss Innovation Agency (Innosuisse), the Federal Office for Energy FOEN, the Valéry Foundation, the Fondation Sur la Croix. The authors bear sole responsibility for the content and conclusions of the article.

Acknowledgement

The authors would like to acknowledge the support of the Berry production partners Beerenland AG, Bioschmid gmbh and Pitteloud Fruits SA.

References

- [1] Schweizer Obstverband (Fruit-Union Suisse). Bericht 2024 – Surfaces cultivées de petits fruits (Beeren-Anbauflächen 2024). Zoug: Schweizer Obstverband, 2024. <https://www.swissfruit.ch/wp-content/uploads/2024/05/2024-Beerenanbauflaechen.pdf>
- [2] B. Cemek and Y. Demir, "Testing of the condensation characteristics and light transmissions of different plastic film covering materials", *Polymer Testing*, vol. 24, no. 3, pp. 284-289, 2005, doi: [10.1016/j.polymertesting.2004.11.007](https://doi.org/10.1016/j.polymertesting.2004.11.007)
- [3] S. A. Asa'a et al., "A multidisciplinary view on agrivoltaics: Future of energy and agriculture", *Renewable and Sustainable Energy Reviews*, vol. 200, p. 114515, 2024, doi: [10.1016/j.rser.2024.114515](https://doi.org/10.1016/j.rser.2024.114515)
- [4] M. I. Hermelink, B. Maestrini, and F. J. de Ruijter, "Berry shade tolerance for agrivoltaics systems: A meta-analysis", *Scientia Horticulturae*, vol. 330, p. 113062, 2024, doi: [10.1016/j.scienta.2024.113062](https://doi.org/10.1016/j.scienta.2024.113062)
- [5] M. Laub, L. Pataczek, A. Feuerbacher, S. Zikeli, and P. Högy, "Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis", *Agronomy for Sustainable Development*, vol. 42, p. 51, 2022, doi: [10.1007/s13593-022-00783-7](https://doi.org/10.1007/s13593-022-00783-7)
- [6] H. Schielzeth, "Simple means to improve the interpretability of regression coefficients", *Methods in Ecology and Evolution*, vol. 1, no. 2, pp. 103–113, 2010, doi: [10.1111/j.2041-210X.2010.00012.x](https://doi.org/10.1111/j.2041-210X.2010.00012.x)
- [7] M. Kenward and J. H. Roger, "Small sample inference for fixed effects from restricted maximum likelihood", *Biometrics*, vol. 53, no. 3, pp. 983–997, 1997, doi: [10.2307/2533558](https://doi.org/10.2307/2533558)

- [8] R Core Team, R: A Language and Environment for Statistical Computing, Version 4.5.0, R Foundation for Statistical Computing, Vienna, Austria, 2024. [Online]. Available: <https://www.R-project.org/>
- [9] S. Choi, S. Lim, H. R. Kim, and Y. Kim, "Correlation Among Phenotypic Parameters Related to the Growth and Photosynthesis of Strawberry (*Fragaria × ananassa* Duch.) Grown Under Various Light Intensity Conditions", *Frontiers in Plant Science*, vol. 12, p. 647585, 2021, doi: [10.3389/fpls.2021.647585](https://doi.org/10.3389/fpls.2021.647585).
- [10] X. Zhu, F. J. Trough, and T. Yang, "Preharvest UV-B Treatment Improves Strawberry Quality and Extends Shelf Life", *Horticulturae*, vol. 9, no. 2, p. 211, 2023, doi: [10.3390/horticulturae9020211](https://doi.org/10.3390/horticulturae9020211)
- [11] D. L. Jennings, *Raspberries and Blackberries: Their Breeding, Diseases and Growth*. London, UK: Academic Press, 1988.
- [12] S. Kadir, E. Carey, and S. Ennahli, "Influence of high tunnel and field conditions on strawberry growth and development", *HortScience*, vol. 41, no. 2, pp. 329–335, 2006