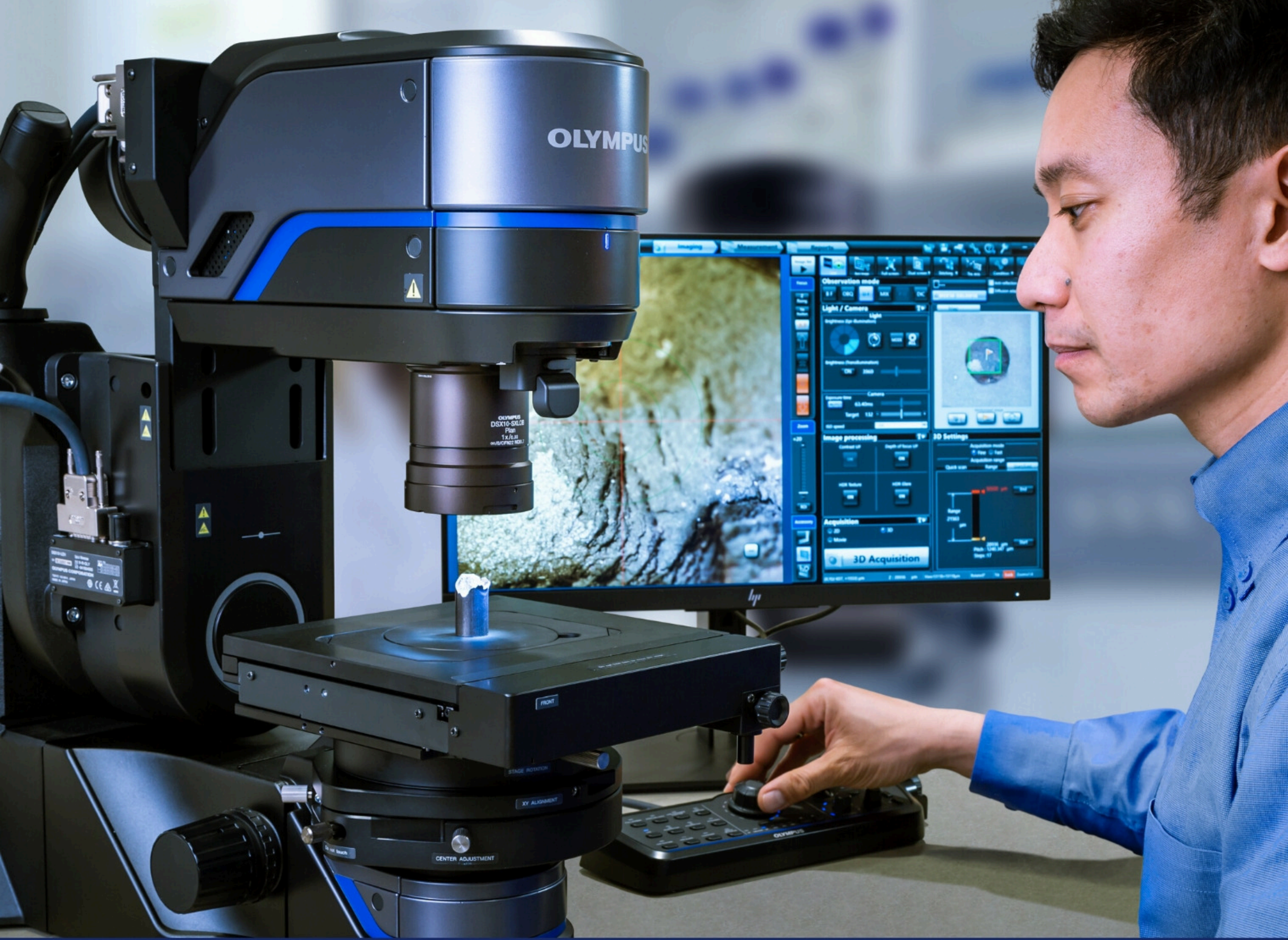
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Tinted Semi-Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland

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Agrivoltaics describes concurrent agricultural production of crops and photovoltaic generation of electricity on the same cropland. By using tinted semi-transparent solar panels, this study introduces a novel element to transform the concept of agrivoltaics from just solar-sharing to selective utilization of different light wavelengths. Agrivoltaic growth of basil and spinach is tested. When compared with classical agriculture, and based on the feed-in-tariff of the experimental location, agrivoltaic co-generation of biomass and electricity is calculated to result in an estimated financial gross gain up to +2.5% for basil and +35% for spinach. Marketable biomass yields do not change significantly for basil, while a statistically significant loss is observed for spinach. This is accompanied by a relative increase in the protein content for both plants grown under agrivoltaic conditions. Agrivoltaics implemented with tinted solar panels improve the biomass production per unit amount of solar radiation up to 68%, with up to 63% increase in the ratio of leaf and stem biomass to root. Agrivoltaics can enrich the portfolio of farmers, mitigate risks associated with climate, and vastly enhance global photovoltaics capacity without compromising agricultural production.

1. Introduction

Plants and photovoltaic (PV) panels both harness solar light (**Figure 1**A),[1] using photosynthesis to produce biomass, and the photovoltaic effect to generate electricity. Apart from both needing sunlight, photosynthetic and photovoltaic systems have distinct requirements in light quality and quantity. The quality of light absorbed by photovoltaic panels can be customized to harness the entire solar spectrum (e.g., opaque panels[2]) or, for tinted semi-transparent panels, specific portions (Figure 1B). For plants, absorption spectra depend on their photosynthetic pigments (Figure 1C). The quantity of light absorbed and used to generate products further differentiates plants and solar panels. For solar panels, electrical output typically correlates linearly with intensity of incident light.[3] For plants, generation of biomass necessarily requires light energy but this does not correlate linearly above a certain intensity, as numerous linked, complex metabolic steps limit the rate.[4]

Plants can be grown to produce biomass or food whereas photovoltaic panels generate electricity cooperatively on the same plot of land. This is termed agrivoltaics or solar sharing.[5–13]

Agrivoltaics has been reported to bring several positive benefits to agricultural activity under appropriate circumstances. Protection provided by the solar canopy has been reported to create favorable microclimatic conditions.[14] Plants grown under the canopy of solar panels benefit from more effective water/rain redistribution,[15] wind mitigation, moderation of

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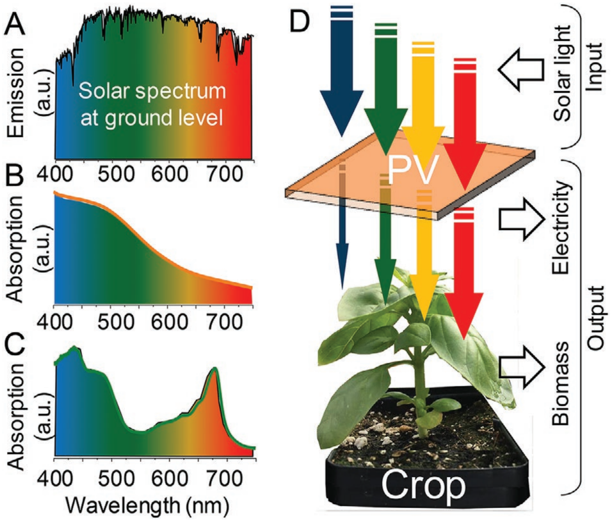

Figure 1. Agrivoltaics for food and energy double-generation implemented with tinted semi-transparent solar panel. A) Solar radiation spectrum in the visible range at the ground level. B) Absorption spectrum for the tinted semi-transparent solar PV panel (a-Si single-junction) used in this study. C) Absorption spectrum for a basil plant leaf. D) Schematic representation of the input (solar energy) and the two contextual outputs of agrivoltaics (i.e., electricity and biomass).

temperature variation,[16] reduction in evapotranspiration, improvement in soil humidity, protection against climatic uncertainty and extreme events such as hailstones.[17] Additionally, implementation of agrivoltaics on soil-less vertical farming technologies could intensify food production, while avoiding widespread natural ecosystem disruption caused by conventional agriculture.[18] Agrivoltaics can also offer a direct financial advantage compared with classical farming.[19,20] Several studies have modelled performance and benefits of agrivoltaics[15,19,21–27] and tested its effect with experiments on plant growth (e.g., lettuce,[28–30] cucumber,[17] wheat,[16,31] onion,[32] tomato,[6,14,33–36] and pepper).[14] By creating opportunities for sustainable dual land usage, agrivoltaics may alleviate the risk of competition between solar panels and agriculture for land with suitable climatic conditions. As discussed recently[37] the climatic conditions that are favorable for agricultural land (e.g., air temperature, humidity, etc.) are also ideal for operation of solar panels.

Until now, agrivoltaics has been implemented using opaque and neutral semi-transparent solar panels.[6,38,39] Those panels attenuate the solar radiation uniformly across the entire visible spectrum. Using tinted semi-transparent solar panels for agrivoltaic applications has been suggested before[9] but no experimental data on the effects on plant growth have been published. Here we show the combination of tinted semi-transparent solar panels with growth of two crops of major commercial significance, basil and spinach (Figure 1D). The tinted semi-transparent solar panels used in the study were manufactured by Polysolar in Taiwan (further details are given in the Experimental Section "Solar PV Panel"). Basil and spinach are particularly appropriate crops as they are frequently farmed in protected agricultural systems (e.g., greenhouses) where implementation of agrivoltaics can be facilitated readily using existing infrastructure. In this case, plants and solar panels not only share the amount of solar radiation falling on the agrivoltaics installation, but selectively harness different portions of the electromagnetic spectrum. Physiological/metabolic variation was analyzed for agrivoltaic growth versus conventional agricultural growth. Based on real field data, energetic, practical and financial implications of agrivoltaics tinted semi-transparent panels were determined. Also, for both basil and spinach, the relative contents of carbohydrate, lipid and protein from plants grown under agrivoltaic conditions were compared versus control plants.

2. Results

2.1. Effect of Agrivoltaics on Basil Growth

Ocimum basilicum, subsequently referred to as basil (cultivar: Italiano Classico, Figure S1, Supporting Information) was grown during the Spring/Summer season. Basil seeds were sown in 12 growth units (GU), six of them built using clear glass (i.e., GU-C) and six of them built using tinted semi-transparent solar panels (i.e., GU-PV) (Figures S2 and S3, Supporting Information). The combination of tinted semi-transparent PV glass and borosilicate clear glass resulted in a solar radiation intensity in the GU-PV ≈43% of that in the GU-C as described in the Experimental Section. During the experimental run (71 days), the mean temperature was 18.7 ± 5.6 °C with a daily mean solar radiation of ≈233 W m^{-2}, which equates to a total solar energy input of 397 kWh m^{-2} (Figure S4, Supporting Information).

Figure 2 shows the collected data on basil plants grown in GU-Cs (Figure 2A) compared with the plants grown in GU-PVs (Figure 2B) at day 71. The mean dry weight (DW) for leaf, stem and root accumulated over the entire experimental run was 627 ± 92 gDW m^{-2} for the plants grown in the GU-Cs. For the plants grown in the GU-PVs the mean was ≈30% less (441 ± 43 gDW m^{-2}, Figure 2C). An even more dramatic reduction (≈48%) was observed when only the tissue below ground (root) was considered, with 236 ± 23 and 121 ± 23 gDW m^{-2} for plants grown in GU-C and GU-PV, respectively (Figure 2D). In contrast, when the biomass for tissues above ground (leaf+stem) was considered separately, plants grown in the GU-PVs accumulated a dry weight biomass of 319 ± 31 gDW m^{-2}, which is only ≈18% less than those grown in GU-C (391 ± 82 gDW m^{-2}) (Figure 2E). This reduction was not statistically significant ($p = 0.078$) (Table S1, Supporting Information). The yields of biomass observed are in line with those reported for commercial basil production (Tables 2 and 3, Supporting Information).

2.2. Effect of Agrivoltaics on Spinach Growth

Spinacia oleracea, subsequently referred to as spinach (cultivar: Spinacio America, Figure S1B, Supporting Information) was grown in two Autumn/Winter seasons (first season 2016; second season 2019, Figure S5, Supporting Information). For the first season (2016), spinach seeds were sown in 12 GUs, six of them built using clear glass (i.e., GU-C) and six of them built using tinted semi-transparent solar panels (i.e., GU-PV). For the second season (2019), spinach seeds were sown in 6 GUs, three

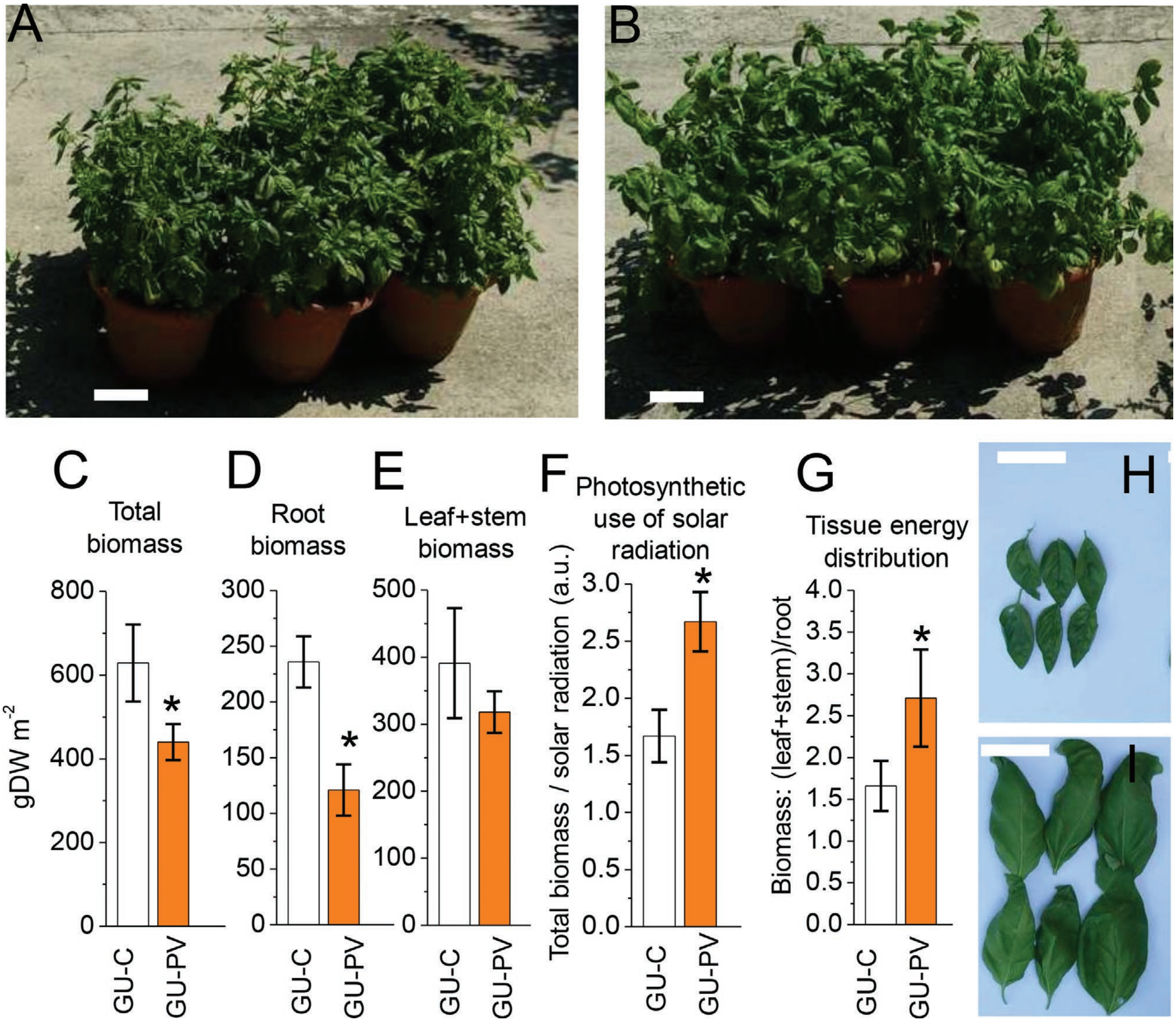

Figure 2. A,B) Overview of the pots of basil plants grown in the GU equipped with clear glass (GU-C) (A) and GU equipped with tinted semi-transparent solar panels (GU-PV) (B) respectively at the completion of the experimental run (day 71). The white horizontal bar represents 100 mm. C–E) Total biomass accumulation (C), root (D) and leaf + stem (E) for basil plants at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). F) Ratio of the total biomass accumulated to the solar radiation. G) Ratio of the biomass above ground (leaf+stem) to the biomass below ground (root) for basil plants at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). The error bar represents ±SD and the asterisk represents statistically significant difference ($p < 0.05$) (*T*-test: Table S1, Supporting Information). H,I) Representative examples of leaves of basil from plants grown in the (H) GU-C and (I) GU-PV. The white horizontal bar represents 50 mm.

of them built using clear glass (i.e., GU-C) and three of them built using tinted semi-transparent solar panels (i.e., GU-PV). The mean temperature was 11.7 ± 7.7 and 13.6 ± 6.4 °C for the first and second season respectively. The daily mean solar radiation for the season 2016 was ≈95 W m^{-2}, which equates to a total energy input of 253 kWh m^{-2}. The daily mean solar radiation for the season 2019 was ≈94 W m^{-2}, which equates to a total energy input of 250 kWh m^{-2} (Figure S5, Supporting Information).

Figure 3 shows the collected data on spinach plants grown during both seasons in the GU-Cs (Figure 3A) compared with the plants grown in the GU-PVs (Figure 3B) at day 111. The mean dry weight (DW) for leaf, stem and root accumulated over the entire experimental run was 218 ± 42 gDW m^{-2} for the plants grown in the GU-Cs. For the plants grown in the GU-PVs the mean was ≈28% lower (158 ± 29 gDW m^{2}, Figure 3C). For the tissue below ground (root) the accumulated biomass was 22.6 ± 3.5 and 12.4 ± 3.1 gDW m^{-2} for plants grown in GU-C and GU-PV, respectively (Figure 3D). For the tissue above ground (leaf+stem), the accumulated biomass was 196 ± 57 and 145 ± 40 gDW m^{-2} for plants grown in GU-C and GU-PV, respectively (Figure 3E). For all those comparisons, the differences between the plants grown in the GU-C and those in the GU-PV were statistically significant ($p < 0.05$) (Table S4, Supporting Information). The yields of biomass observed are in line with those reported for commercial spinach production (Tables 5 and 6, Supporting Information).

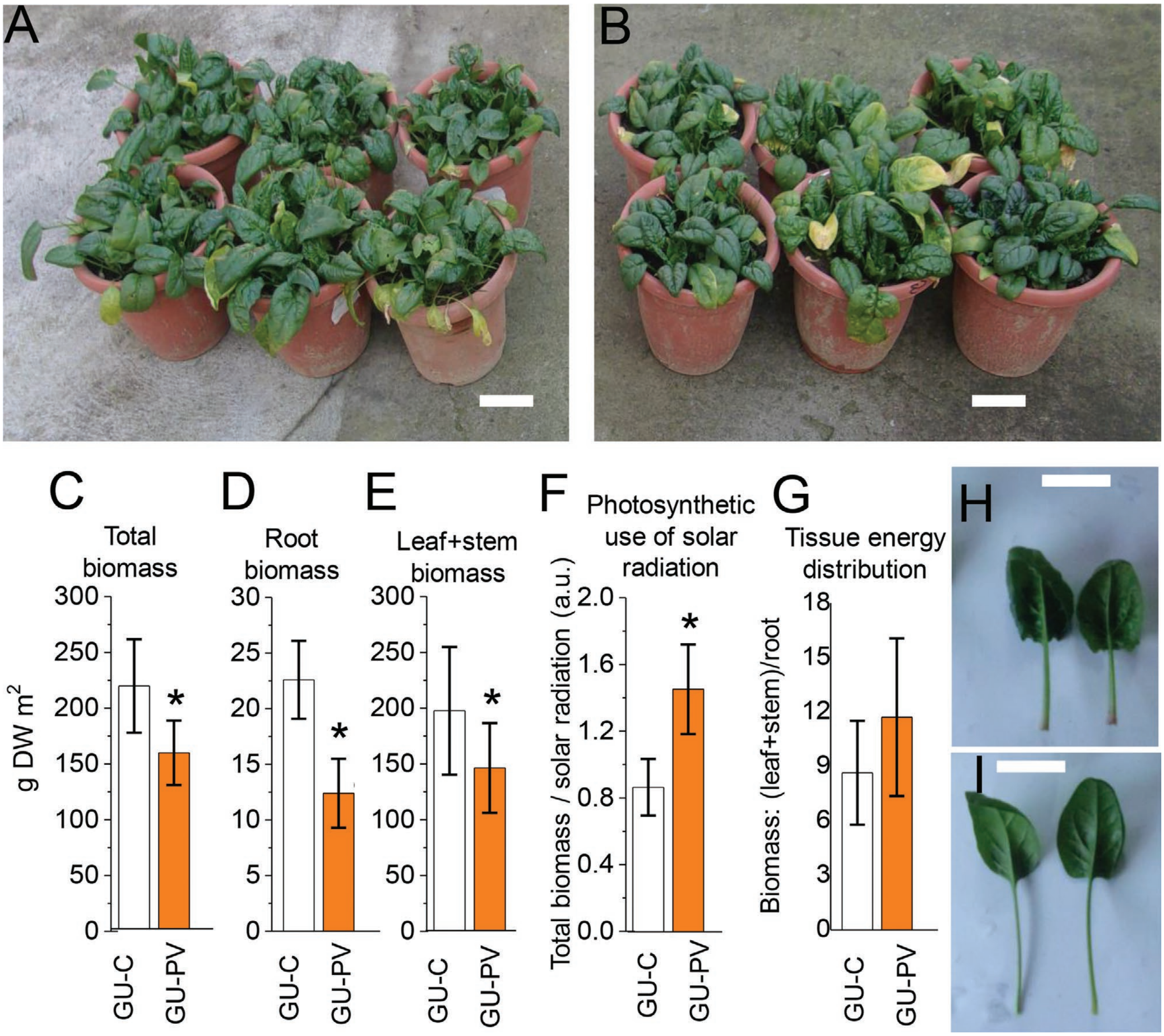

Figure 3. A,B) Overview of the pots of spinach plants grown during the first season in the GU equipped with clear glass (GU-C) (A) and GU equipped with tinted semi-transparent solar panels (GU-PV) (B) respectively at the completion of the experimental run (day 111). The white horizontal bar represents 100 mm. C–E) Total biomass accumulation (C), root (D) and leaf+stem (E) for spinach plants grown during both seasons at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). F) Ratio of the total biomass accumulated to the solar radiation. G) Ratio of the biomass above ground (leaf+stem) to the biomass below ground (root) for spinach plants at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). The error bar represents ±SD and the asterisk represents statistically significant difference ($p < 0.05$) (*T*-test: Table S4, Supporting Information). H,I) Representative examples of leaves and stems of spinach from plants grown in the (H) GU-C and (I) GU-PV. The white horizontal bar represents 50 mm.

2.3. Effect of Agrivoltaics on Plant Metabolism and Phenotype

The use of tinted semi-transparent solar panels resulted in basil and spinach grown in the GU-PVs receiving ≈57% less solar radiation compared with the control (GU-Cs) (Figure S3A,B, Supporting Information). Nevertheless, the total biomass (leaf+stem+root) accumulated per land unit by those crops decreased only by ≈30% for basil and ≈28% for spinach, relative to the control plants grown in the GU-Cs. Plants responded to the depletion of solar energy with a more efficient photosynthetic use of light. This can be quantified by dividing the total biomass (DW) accumulated by the total solar energy falling on the growth area during the experimental trial. For both basil (Figure 2F) and spinach (Figure 3F), the ratio increased by 63% and 68% respectively, for plants grown in GU-PV compared the control plants (Tables 1 and 4, Supporting Information).

In addition, plants redistributed metabolic energy so that more was dedicated to the tissues above the ground (leaf and stems), at the expense of the tissue below ground (root). The distribution of the metabolic energy caused by agrivoltaics can be quantified by calculating the ratio of the biomass (DW) accumulated in leaf+stem by the biomass accumulated in root.

For basil and spinach, this ratio increased by 63% and 35% respectively for the plants grown under an agrivoltaic regime compared to the control plants (Figures 2G and 3G) (Tables 1 and 4, Supporting Information). For this reason, agrivoltaics is probably more beneficial when the edible/marketable biomass is not developed below ground.

Morphological changes were also observed for basil and spinach plants grown under the agrivoltaic regime compared with control plants. Leaves of basil were larger (Figure 2H,I) and the stems of spinach longer in the GU-PV plants (Figure 3H,I and Figure S6, Supporting Information). Both morphological changes are in line with the above discussed changes in the photosynthetic use of light and metabolic energy redistribution.

2.4. Effect of Agrivoltaics on Protein Content

When the carbohydrate and lipid extracted from tissues of plants grown under agrivoltaics condition (GU-PV) were compared with plants grown under clear glass (GU-Cs), the data did not reveal any consistent differences. By contrast, agrivoltaic growth caused a consistent trend in the amount of protein extracted from tissues of both basil and spinach. For basil, there was an increase in the protein extracted from the leaf of plants grown in GU-PVs of +14.1% ($p = 0.056$) compared with leaf from plants grown in GU-Cs. This rise was statistically significant in stem (+37.6%, $p = 0.004$) and root (+9.6%, $p = 0.010$) (**Figure 4**A).

For spinach, when both seasons of growth were considered, the protein extracted from leaf, stem, and root of plants grown in GU-PV was respectively +53.1% ($p = 0.005$), +67.9% ($p = 0.006$) and +13.8% ($p = 0.198$) compared with the equivalent tissues obtained from plants grown in GU-C (Figure 4B and Tables 7 and 8, Supporting Information).

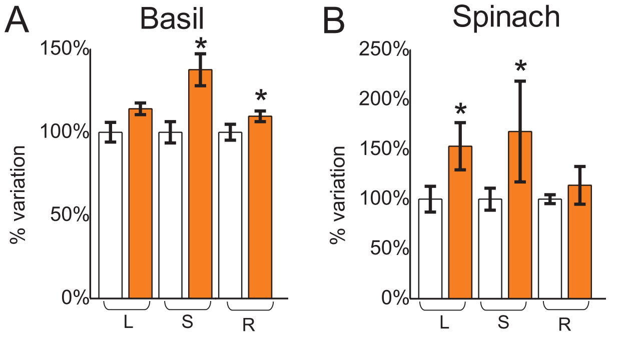

Figure 4. Protein extracted from basil plants A) and spinach plants B) at the completion of the experimental run for both seasons. The protein extracted for each tissue, leaf(L), stem(S), and root(R) for the plants grown in the GU-C (white histogram) is used as reference and given an arbitrary value of 100%. The protein extracted for each tissue, leaf (L), stem(S), and root(R) for the plants grown in the GU-PV (orange histogram) is normalized against its reference. The error bar represents ±SD and the asterisk represents statistically significant difference (*T*-test, $p < 0.05$) (*T*-Test: Tables 7 and 8, Supporting Information).

2.5. Financial Impact of Agrivoltaics

Given the total recorded solar radiation available (Figures S4B and S5B,D, Supporting Information) and the actual electrical efficiency measured for the tinted semi-transparent solar panel (Figure S7, Supporting Information), we estimated the integrated financial balance of the agrivoltaic system. This calculation takes into account the measured yields of marketable biomass for basil and spinach, their actual wholesale global market price, and the actual feed-in-tariff available for electrical energy generated by large photovoltaic installations (>5 MW) for the geographical location where the experimental run was conducted (i.e., Italy). For basil, our data showed a decrease in the yield of marketable biomass (leaf) by ≈15% for plants grown in GU-PV compared with the control plants grown in the GU-C. This loss in plant productivity was compensated by a generation of 27.8 kWh m^{-2} of electrical energy during the 71 days of the experimental run. Overall, the implementation of agrivoltaics with a tinted semi-transparent solar panel combined with the growth of basil was calculated to give a gross financial gain of about +2.5% compared with growth of basil without the solar panel (**Table 1** and Appendix S1, Supporting Information).

For spinach, when both seasons of growth were considered, the yield of marketable biomass (leaf+stem) for plants grown in GU-PV decreased by ≈26% compared with the control plants grown in the GU-C. This was compensated for by a generation of 17.6 kWh m^{-2} of electrical energy. Overall, the implementation of agrivoltaics with tinted semi-transparent solar panel combined with the growth of spinach was calculated to give a gross financial gain of about +35% compared with growth without the solar panel (Table 1 and Appendix S2, Supporting Information). The substantial difference in the gross financial gain between basil and spinach is explained by the market price of those crops, which is about fivefold larger for basil than for spinach at the time of writing.

Table 1. Financial impact of agrivoltaics.

Crop (cultivar)[a]	Growth condition	Mean of the accumulated marketable biomass		Value of the marketable biomass	Expected electrical output	Value of the expected electrical output	Total gross value (biomass + electrical output)
		[gDW m^{-2}]	[kgFW m^{-2}]	[USD m^{-2}]	[kWh m^{-2}]	[USD m^{-2}]	[USD m^{-2}]
Basil (Italiano Classico)	GU-C	245	3.43	22.8	–	–	22.8
	GU-PV	208	2.91	19.4	27.8	4.03	23.4
Spinach (Spinacio America)	GU-C	196	3.32	4.18	–	–	4.18
	GU-PV	145	2.47	3.11	17.6	2.55	5.66

[a] The table shows the biomass production, the electrical output and their equivalent value in USD for conventional agriculture (GU-C) and agrivoltaic (GU-PV, orange shadowed) over the entire experimental run for basil and spinach (Appendices S1 and S2, Supporting Information).

3. Discussion

Agrivoltaics offers the strategic value of generating biomass together with electricity on the same piece of land.[5,7–13,20,38–41] With conventional agrivoltaics, opaque solar panels are used to cover a certain proportion of the agricultural land casting a shadow on the underlying plants. Maximizing the generation of electricity is a desirable goal, but might be at the expense of biomass production. For example, for lettuce, the total biomass yield under agrivoltaic installation in Montpellier (France) was 15–30% less than the control conditions (i.e., full-sun conditions).[28,29] When growth of tomato was tested in Japan, the yield in an agrivoltaic regime was about 10% lower than for conventional agriculture.[36] When the same crop was tested in Morocco, the yield in an agrivoltaic modified greenhouse was substantially the same as in an unmodified greenhouse.[35]

With the use of tinted semi-transparent solar panels, photosynthetic organisms and photovoltaic systems can harness different parts of the visible spectrum. The advantage of that could be understood by examining how the light is absorbed and processed by photosynthetic organisms and photovoltaic panels. Chlorophylls, the main photosynthetic pigments in plants, have absorbance peaks in the blue (≈400–500 nm) and red (≈600–700 nm), and a trough in the green (≈500–600 nm) (Figure 1C). Pigments such as carotenoids and anthocyanins have absorbance peaks in the blue (≈400–500 nm) and green (≈500–600 nm) respectively. However, those pigments function in absorbance and dissipation of excess/harmful solar energy (e.g., UV) to protect the photosynthetic apparatus from light stress.[42–45] Therefore, part of the solar energy absorbed in the blue and green portions of the electromagnetic spectrum is dissipated without contributing to photosynthesis. Customizing the absorption spectra of photovoltaic panels allows them to harness light in the region of the solar spectrum where plants are less effective[2]. For example, the tinted semi-transparent solar panels used in this study absorb preferentially blue and green light, leaving most of the red for photosynthesis (Figure 1B). Therefore, the solar radiation falling in the GU-PV GUs is relatively red enriched (blue and green impoverished), permitting a more efficient photosynthetic use of light, as actually observed in this study (Figures 2F and 3F).

Growth under the tinted semi-transparent solar panels increases the proportion of red light reaching the plants, which may alter the balance of red-absorbing phytochrome and far-red absorbing phytochrome, and reduce the proportion of blue light that moderates the deleterious effects of too much red.[46] Under the normal outdoor spectrum, changes in carbon allocation occur when the far-red phytochrome is activated by far-red-enriched light reflected from overhanging vegetation near the plant, prompting the shade-avoidance response and promoting stem elongation at expense of leaf tissue.[47] Thus, the altered architecture and chemical composition for the plants grown in the GU-PV might be a stress response.

The work described in our study was based on 6 measurements with basil and 9 with spinach. Our work shows that agrivoltaic growth under tinted semi-transparent solar panels affect the accumulation of protein in the tissues of the plants. The amount of protein extracted from leaf, stem and root in both crops grown under agrivoltaic conditions was consistently increased (Figure 4). Accumulating more protein is of particular interest in view of the need for alternative sustainable protein sources to substitute animal proteins,[48] for example, in plant-based artificial meats and protein-rich ingredients.[49] Our study does not allow us to draw conclusions on the effect of agrivoltaics on plants where underground tissues might have different functions, e.g., storage in tubers. Further experimental trials using semi-transparent solar panels with specific, targeted optical properties might permit the development of novel methods for tailoring the content of specific nutrients in crops. In photosynthetic microorganisms this is already an objective of the biotechnology sector.[50,51] The morphological changes observed in the marketable biomass (leaf+stem) of spinach grown in the GU-PV could have additional economic benefits. For example, having longer stems on spinach (Figure 3H,I and Figure S6, Supporting Information) will facilitate harvesting by mechanical tools.

Although agrivoltaics may offer a direct financial advantage compared with classical farming, this advantage depends on many variables (i.e., the local level of solar radiation, the type of crop, the costs for installing the solar panels, the costs associated with farming under canopy, the global/local market price for crops and electricity and also eventual public subsidy available for renewable energy). It is quite challenging to make an absolute algorithm for calculating the financial value of agrivoltaics, based on the interactions and variability of all these factors. However, a range of projections have been published. In 2011 Dupraz et al. predicted that agrivoltaic systems could increase global land productivity up to 73%.[21] Dinesh et al. computed that the value of co-generation of electricity and lettuce in US could reach over 30% when compared with conventional agriculture.[19] More recently, the revenue for farming grape under an agrivoltaic regime in India was foreseen to be several fold that of conventional grape farming.[25] This present study finds that the growth of basil and spinach combined with tinted semi-transparent solar panels could give a gross financial gain estimated at +2.5% and +35% for basil and spinach respectively compared with classical agriculture. These figures were based on the actual feed-in-tariff for electrical energy generated by large photovoltaic installations (>5 MW) for the geographical location where the experimental run was conducted (i.e., Italy) (Appendices S1 and S2, Supporting Information). Calculations based on the cost to the consumer for the electricity produced would give greater predicted benefits of agrivoltaics. If the feed-in-tariff available for electrical energy and/or the price for agricultural products were substantially different from those assumed here (Appendices S1 and S2, Supporting Information), the financial impact of agrivoltaics would clearly need to be reassessed.

Agrivoltaics allows further substantial practical benefits. First, this system permits the diversification of the portfolio of farmers, mitigating the risks associated with climatic and economical uncertainty. Second, the protection provided by the solar canopy creates favorable microclimate conditions. Indeed, the use of water could also be influenced by agrivoltaic practice because the latter allows more effective water-rain redistribution, mitigation of wind and temperature and evapotranspiration, and management of soil humidity. The deployment of large PV solar installations in arid areas might require regular water inputs for cleaning the surface of solar panels. This water could also be used for crop irrigation, maximizing the efficiency of land and water use.[22] The positive effect of agrivoltaics on the use of water has been demonstrated by work on lettuce and cucumber.[17] For unirrigated pasture soil, implementation of agrivoltaics was found to maintain higher soil moisture and causing a significant increase of the yield of biomass.[52]

Agrivoltaic production is in principle applicable to any agricultural land. Having said that, the installation of solar panels will be facilitated if an existing physical infrastructure is already in place. This is the case in protected agriculture, which uses a confined environment in which to grow crops (e.g., greenhouses). Therefore, the global potential impact of agrivoltaics on the PV expansion could be inferred based on the land area in use for protected agriculture. Farming with protected agriculture is a growing reality throughout the world with an estimated global vegetable area of 5 630 000 ha.[53] Implementing the tinted semi-transparent solar panels tested in this study, on the area currently in use for protected agriculture, would permit a vast expansion of the installed PV capacity to ≈3547 GWp (Appendix S3, Supporting Information). This figure is about fivefold that of the current PV installed capacity.[54,55] This estimate does not take account of installation of agrivoltaics on soil-less vertical/indoor farming, which promises to be one of the main solutions to avoid increasing the use of arable land and therefore limiting agriculture's contribution to climate change.[56–58]

As this study suggests, the use of agrivoltaics depends on a multitude of variables, some of those associated with local and perhaps transitory conditions (e.g., public subsidy). Nevertheless, in order to offer a practical guideline for the implementation of agrivoltaic systems on cropland, we have compiled a repository table to summarize the key factual elements characterizing agrivoltaic installations as available in published studies, but excluding geo-economical elements (Table S9, Supporting Information).[59,60] The database includes: a) the location where the agrivoltaic is installed; b) the chosen crop; c) the growth season during which the agrivoltaic was tested; d) and e) the yield of marketable biomass without and with agrivoltaic regime; f) the model of solar panel installed; g) the proportion shade level (%) caused by agrivoltaic use on the incident solar radiation at level of the growth area; and h) the mean of the electrical output during the experimental run.

4. Conclusion

This paper provides an important advance in the field of agrivoltaics. For the first time, the results of using tinted semi-transparent solar panels tested with crops of global value (basil and spinach) are presented. Agrivoltaic growth produced four measurable effects on the physiology of basil and spinach: i) plants demonstrated a more efficient photosynthetic use of light (up to 68% for spinach); ii) the metabolic energy of plants was preferentially redirected toward tissues above ground (up to 63% for basil); iii) the phenotype of plant parts above ground was different from the control plants; iv) the amount of protein extracted from both plants was increased in leaf (basil: +14.1%, spinach: +53.1%), stem (basil: +37.6%, spinach: +67.9%) and root (basil: +9.6%, spinach: +15.5%).

Even with a loss in the yield of marketable biomass for both basil (15%) and spinach (26%), projection of our experimental data has shown that agrivoltaics could give a substantial overall financial gain calculated to be +2.5% for basil and +35% for spinach compared with classical agriculture. Finally, by compiling the available published data on agrivoltaics (Table S9, Supporting Information), we have defined a list of key minimum parameters required for the characterization of published installations. With this, we aim to introduce clarity in the field and facilitate the expansion of agrivoltaics and permitting growth of the global PV capacity without compromising the use of arable land for food production.

5. Experimental Section

The GU: The experimental runs were conducted in GUs. Each one was formed by a timber frame (the overall dimensions were 500 mm height × 350 mm × 350 mm) as shown in Figure S2 (Supporting Information). The GUs were divided in two groups designated GU-C or GU-PV. In the GU-Cs the timber frames were covered with borosilicate clean glass, one glass sheet on the top (350 mm × 350 mm) and 4 glass sheets on the sides (350 mm × 200 mm) (Figure S2A,B, Supporting Information).

In the GU-PVs the timber frames were covered with tinted semi-transparent PV glass, one PV glass sheet on the top (350 mm × 350 mm), 2 PV glass sheets on the sides (350 mm × 200 mm) and 2 borosilicate clean glass sheets on the other sides (350 mm × 200 mm) (Figure S2C,D, Supporting Information). The combination of tinted semi-transparent PV glass and borosilicate clear glass resulted in a solar radiation in the GU-PV ≈43% of the solar radiation falling in the GU-C (Figure S3A,B, Supporting Information).

The lower part of each GU (250 mm height) was left open to permit ventilation and prevent overheating. One plastic pot (260 mm diameter, 250 mm height, 11 L internal volume) was placed in each GU at the center of the frame (Figure S3C, Supporting Information). The top edge of the pot placed inside the GU reached approximately the lower edge of the lateral glass sheets. The soil used was commercial compost, Levington Professional Growing Medium–M3, and was not autoclaved.

Experimental Set-Up: The GUs were arranged in three lines and four rows in a plot of land located 45°21' N 9°19' E (Melegano, Italy). The GU-Cs and GU-PVs were arranged alternately and placed on the ground leaving a gap of ≈0.50 m in between each GU (Figure S8, Supporting Information).

Seed Sowing: For the Spring/Summer run (from April 2016 to June 2016) basil (*Ocimum basilicum* L.) was used. Seeds were obtained from an Italian seed supplier (http://www.franchisementi.it/) (Figure S1A, Supporting Information). The cultivar chosen was Italiano Classico. Each pot was sown with ≈100 mg of seeds (≈105 seeds). Seeds were placed in the ground on the 21st of April (2016) and plants left in place until the end of June for a total of 71 days. Decanted tap water was dispensed in a quantity of ≈1.0 L per pot every other day for the entire duration of the experimental run. The percentage of germination for the plants grown in the six GU-Cs and the plants grown in the six GU-PVs were 42.7 ± 7.3% and 38.3 ± 8.6% respectively (Figure S1C, Supporting Information).

For the Autumn/Winter run (season 1: from September 2016 to December 2016; season 2: from September 2019 to December 2019) spinach (*Spinacia oleracea* L.) was used. Seeds were obtained from an Italian seed supplier (http://www.franchisementi.it/) (Figure S1B, Supporting Information). The cultivar chosen was Spinacio America. Each pot was sown with 20 seeds. Seeds were placed in the ground at the beginning of September (season 1: 3rd, 2016; season 2: 1st, 2019) and plants left in place until the third week of December (season 1: 23rd, 2016; season 2: 21st, 2019) for a total of 111 days. After germination (≈10 days), the numbers of seedlings were adjusted to 7 per pot in each GU. This was done to avoid an unequal plant distribution and excessive crowding in the growing area. The percentage of germination for the plants grown in the six GU-Cs and the plants grown in the six GU-PVs were 70.8 ± 15.3% and 77.5 ± 15.1% respectively (Figure S1D, Supporting Information). Decanted tap water was dispensed in a quantity of ≈0.5 L per pot every other day until the end of October, and then the quantity was reduced to ≈0.25 L per pot every other day.

Plant Tissues Harvesting and Mass Determination: Plant tissues were harvested at the end of each experimental run. Leaf, stem and root were separately stored in paper bags. Leaf and stem were dried in a 45 °C oven for 15 days. Soil was carefully removed from the radical system. Then roots were washed in tap water three times and finally stored in paper bags to be dried in a 45 °C oven for 15 days. Dry weight (DW) of the dried biomass was determined using a Precision 100M-300C balance (JOHNSON PRECISA).

Protein Determination: For basil and spinach (season 1), protein quantification was carried out on dried plant tissues by applying Kjeldahl's factor (http://www.fao.org/fao-who-codexalimentarius) to the proportion of nitrogen in samples subjected to elemental analysis [Flash EA1112, Thermo Scientific, Loughborough, UK] according to the manufacturer's instructions.

For spinach (season 2), protein quantification was carried out on dried plant tissues using the Dumas technique (Method 990.03) (AOAC 2006) using Nitrogen analyzer Rapid MAX N Exceed–ELEMENTAR – Langenselbold (Germany) as described.[61]

Solar PV Panel: The photovoltaic technology used is thin-film amorphous silicon with a transparent zinc oxide back conductive layer and clear front glass coated with Fluorine Tin Oxide. The PV panels are a glass laminate with the PV layers sandwiched between. They absorb light in the blue and green part of spectrum and let through light in the red part of the spectrum, which gives them an orange tint (transmission spectrum and data points are shown in Figure S9 and Table S10 (Supporting Information) respectively). The panels have a nominal efficiency and power output of 8% and 66 W m^{-2} respectively.[62]

The solar module data used in this study is taken from a test bed run by the Sheffield Solar group, at the University of Sheffield, where the test modules are short circuited and the current is sampled every two minutes. Module power output is calculated by the Equation (1)

$$P_{\text{out}} = \left(J_{\text{scob}} \times P_{\max}\right) / J_{\text{sc}} \tag{1}$$

Where P_{out} is output power, J_{scob} is the observed short circuit current, $P_{\max}$ is the module maximum rated power, and J_{sc} is the short circuit current at $P_{\max}$.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

HW and Polysolar provided the tinted semi-transparent solar panel.

Keywords

agrivoltaics, bio-energy, crops, photovoltaics

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