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SOILLESS PRODUCTION OF WILD ROCKET AS AFFECTED BY GREENHOUSE COVERAGE WITH PHOTOVOLTAIC MODULES

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Abstract. Solar photovoltaic greenhouses have become more popular, especially in the countries of southern Europe, due to specific government remuneration policies. However, many agronomic questions need to be addressed. This research was carried out in three types of commercial greenhouses covered with different materials (polycarbonate modules – PCM, traditional – TPM and innovative semi-transparent – IPM photovoltaic modules) with the aim to verify the compatibility of solar energy production with the production of high-quality wild rocket (*Diplotaxis tenuifolia* L.). IPM may satisfy the entire electricity demand of a commercial greenhouse. Yield for rocket grown in TPM was lower than for IPM and PCM. Antioxidant properties and dry weight decreased as a consequence of decreasing cumulative photosynthetic photon flux density. Nitrate content in TPM was higher (about 10.000 $mg \cdot kg^{-1}$ FW) than the maximum limits allowed by EC Regulation No. 1258/2011, whereas it was lower in IPM and PCM (1.805 and 668 $mg \cdot kg^{-1}$ FW, respectively). The results suggest that it is possible to combine solar energy production with high-quality wild rocket production, using innovative semi-transparent PV modules.

Key words: Renewable energy, photovoltaic greenhouses, *Diplotaxis tenuifolia* L., sustainable agriculture, nitrate content

INTRODUCTION

Greenhouses are highly sophisticated structures which seek to provide ideal conditions for plant growth and production throughout the year. The characteristics of green-

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house cladding materials affect the level and quality of the transmitted radiation and are of primary concern for greenhouse plant cultivation [Geoola and Peiper 1994], where growth factors (light, temperature, humidity and air composition) should be delivered and maintained at optimal levels. Ideal greenhouse covers should ensure maximum solar radiation transmittance combined with minimum heating requirements during the cold season. Greenhouses for the cultivation of special crops, or located in zones with high sun radiation, may need shading, particularly during periods of high irradiation [von Elsner et al. 2000] and suggest that these greenhouses could be covered with photovoltaic cells to produce an electrical energy source, by converting light energy into electrical energy [Yano et al. 2009]. In recent years, solar photovoltaic (PV) greenhouses have spread across Southern Europe, especially in Spain and Italy, due to the abundance of solar energy and the advantageous public policy support for renewable electricity generation [Sarasa-Maestro et al. 2013, Cossu et al. 2014]. The introduction of PV greenhouses helps reduce energy consumption from traditional fossil fuels, which is partly compensated by renewable energy sources [Yano et al. 2009]. During summer periods, integrated semi-transparent PV panels could also provide a better thermal balance in the greenhouse, since they reduce internal solar heat gain and air cooling demands [Yano et al. 2010, Yano et al. 2014]. However, the shading caused by the PV module limits photosynthetically active radiation (PAR), thus reducing plant photosynthesis, quality and productivity. Therefore, there is a need to achieve the optimal balance between shade reduction (in order to maintain optimal levels of photosynthesis) and energy production. In order to avoid high percentages of coverage, local laws require shaded areas to be ≤ 25% [Regione Sardegna 2010, Regione Puglia 2012, Castellano 2014]. To the best of our knowledge, little information on yield and quality has been reported in literature regarding vegetables grown in greenhouses covered with PV modules [Minuto et al. 2009, Kadowaki et al. 2012, Cossu et al. 2014]. It has been reported that low levels of solar radiation can affect some quality parameters in vegetables, such as nitrate content [Santamaria et al. 1997, Santamaria 2006, Weiguo et al. 2012].

Rocket is an important leafy vegetable crop that has become very popular and widely cultivated, even in greenhouses using hydroponic systems. This leafy vegetable, much appreciated by consumers, is a good source of nutrients and antioxidant molecules, especially glucosinolates [Bennett et al. 2002, Durazzo et al. 2013, Nurzyńska-Wierdak 2015] but is also a hyper-accumulator of nitrates, as are celery, chervil, cress, lamb's lettuce, lettuce, radish, red beetroot, spinach, and Swiss chard [Santamaria et al. 1999]. If present in high amounts, nitrates may have negative effects on human health, which raises several issues in the sector of leafy vegetable production and commercialization [Santamaria 2006]. To our knowledge, there is no information in the scientific literature on the quality of rocket grown in PV greenhouses. Bearing these remarks in mind and considering the economic and nutritional importance of wild rocket, this study aimed to verify the compatibility of sustainable energy production by PV greenhouses with high-quality rocket production. In particular, in greenhouses covered with either conventional polycarbonate, traditional or innovative photovoltaic modules, the trials aimed: i) to evaluate environmental growing conditions and energy productivity; ii) to compare the yield and quality of rocket grown in soilless systems.

MATERIALD AND METHODS

Greenhouses. The experiments were carried out in Avetrana (Apulia Region, Southern Italy) (40º20'N, 17º43'E) during 2013, in three types of commercial greenhouses, each with a different cover material: traditional photovoltaic modules (TPM), polycarbonate modules (PCM) and innovative photovoltaic modules (IPM) (fig. 1). The structure specifications and cover material properties are shown in Table 1. PV output terminals were connected to an inverter to supply the photovoltaic-produced electricity for alternating current appliances. Greenhouses were located along an east-west axis 5 m apart, consisting of a single sloping roof with a pitch of 19º and south-facing. Ventilation was provided by manually opened front windows and automatic lateral and roof windows, depending on the temperature and relative humidity inside the greenhouse.

TPM **PCM** **IPM**

Fig. 1. Details of greenhouse cover material: (TPM) traditional photovoltaic modules; (PCM) polycarbonate modules; (IPM) innovative photovoltaic and polycarbonate modules

Table 1. Structure specifications and cover material properties of the greenhouses

Cover material	Greenhouses		
	TPM	PCM	IPM
	traditional photovoltaic modules	polycarbonate modules	innovative photovoltaic and polycarbonate modules
Cover with PVM(*) (%)	100	0	32
Cover without PVM (%)	0	100	68
Transparency PVM (%)	0	–	20
Shaded area (%)	100	0	25**
PVM model	Solsonica mod. 610	–	V-energy mod. 154PVTT
Solar cell tecnology	polycrystalline silicon	–	polycrystalline silicon
Solar cell per module (n°)	60	–	54
Solar cell format (mm)	156 × 156	–	156 × 156
Solar cell dimensions (mm)	1663 × 998	–	1663 × 998
Solar cell maximum power (Wp)	230	–	200
Solar cell efficiency (%)	13.86	–	12.21

[*] – PVM = photovoltaic modules

[**] – maximum value set by Apulian regional regulations [Regione Puglia 2012]

Experimental set-up. Wild rocket (*Diplotaxis tenuifolia* L.) plants were grown in an ebb and flow hydroponic system. Seeds were sown on 24 October 2013 in polystyrene plug trays (160 cells per tray with diameter of 2.5 cm and volume of 21 mL) filled with a mixture of peat (50% white–50% black peat mixture, Brill 3 Special, Brill Substrates, Georgsdorf, Germany) [Bouchaaba et al. 2015]. On 07 November 2013, when the seedlings reached the three-true-leaf stage, they were transplanted into 0.4 L pots filled with peat. The pots were placed on benches (galvanized sheet iron, 2000 × 800 × 100 mm) containing nutrient solution (NS) with a planting density of 100 plants$\cdot$m^{-2}. Each treatment was replicated three times, thus using 9 benches in all. The NS contained (mmol) 14.4 NO_3^--N, 1.6 NH_4^+-N, 2 $H_2PO_4^-$-P, 6 K^+, 4 Ca^{2+}, and 1 Mg^{2+} as macronutrients, whereas micronutrients were supplied according to Johnson et al. [1957]. The well water used had the following characteristics: pH 7.1, electrical conductivity (EC) 1.1 dS m^{-1} and (mmol): 1 Ca^{2+}, 0.4 Mg^{2+}, 6 Na^+, and 5.7 Cl^-. The chemical composition of the used water was considered for the preparation of the nutrient solution. The NS pH was adjusted to 5.5–6.0 using 1 mol H_2SO_4. During the fertigation flow, the NS was raised to the level of the container base in the benches, maintained for about 1–2 hours according to plant needs (flow phase), and then released by opening the bench plugs.

Physical measurements: photosynthetic photon flux density, yield, dry weight and colour. Photosynthetic photon flux density (PPFD) was measured every 30 minutes throughout the growing cycle using LICOR LI-190 (Li-Cor Inc., USA) quantum sensors connected to WatchDog 1000 Series Micro Stations (Spectrum Technologies Inc., Plainfield, IL). These devices were used to measure PPFD outside the greenhouse and at the centre of each greenhouse type (TPM, PCM, and IPM). All sensors were placed at a height of 2 m near the plants. Thirty days after transplanting, at harvest time, twenty plants per treatment were sampled. Plants were cut at 20 mm above the substrate level. Plant material was dried in a thermo-ventilated oven at 65ºC until constant weight, finely ground through a mill (IKA; Labortechnik, Staufen, Germany) with a 1.0 mm sieve used for quantitative chemical analyses. Colour parameters L^* (lightness), a^* (redness) and b^* (yellowness) were measured on the surface of ten leaves for each replication by a colorimeter (CR-400, Konica Minolta, Osaka, Japan) in reflectance mode using the CIE $L^*a^*b^*$ colour scale. Before the measurements, the colorimeter was calibrated by a standard reference with L^*, a^* and b^* values of 97.55, 1.32 and 1.41, respectively. Hue angle ($h° = \tan^{-1}(b^*/a^*)$) and saturation or chroma ($C = (a^{*2} + b^{*2})^{1/2}$) were then calculated from the primary L^*, a^* and b^* readings.

Chemical analysis

Inorganic anion contents. Inorganic anions (Cl^-, NO_3^-, $H_2PO_4^-$, SO_4^{2-}) were determined by ion exchange chromatography (Dionex DX120, Dionex Corporation, Sunnyvale, CA, USA) as reported by Bonasia et al. [2008]. Briefly, inorganic anions were determined in 0.5 g of dried sample using an IonPac AG14 precolumn and an IonPac AS14 separation column (Dionex Corporation). The eluent consisted of 3.5 mmol$\cdot$L^{-1} of sodium-carbonate and 1.0 mmol$\cdot$L^{-1} of sodium-bicarbonate solution, and 50 mL of the same eluent were used to extract the anions. Results were expressed as mg$\cdot$g^{-1} dry weight (DW) and also as mg$\cdot$kg^{-1} fresh weight (FW) for nitrate content.

ORAC and TEAC assays. Rocket samples were freeze-dried using a Freezone® model 7754030 lyophilizer (Labconco Corp., Kansas City, MO, USA) equipped with a stoppering tray (Freezone® model 7948030, Labconco Corp., Kansas City, MO, USA) and stored at -20ºC until analysis. Hydrophilic extracts were prepared from 0.5 mg of freeze-dried vegetable tissue, ground to a fine powder, added to 5 ml of acetone/water/acetic acid (70:28:2 v/v/v) and centrifuged at 2500 × *g* for 15 min. The supernatant was collected and the procedure was repeated three times and the combined supernatants used for antioxidant chemical assays. Lipophilic extracts were obtained by mixing 1g of finely ground sample with hexane (2 × 10 mL) and centrifuging at 2500 × *g* for 15 min. Supernatants were combined and evaporated to dryness. The lipophilic residue was reconstituted in 10 mL of acetone. Three independent extractions were performed for each sample. For the Oxygen Radical Absorbance Capacity (ORAC) assay, the method of Davalos et al. [2004] was used. The lipophilic ORAC assay [Huang et al. 2002] was based on the procedure outlined above with the exception that the acetone-reconstituted hexane extracts and Trolox standards were appropriately diluted with 7% randomly methylated *β*-cyclodextrins (RMCD; CycloLab, Hungary) solvent (w/v), performed in a 50% acetone-water mixture (v/v). Seven percent RMCD + 2, 2’-Azobis-(2-methylpropionamidine) dihydrochloride (AAPH) was used as the blank. As for the hydrophilic ORAC assay, final results were calculated using the differences of area under the FL decay curves between the blank and a sample. The results were expressed as μmol TE·g^{-1} FW. The Trolox Equivalent Antioxidant Capacity (TEAC) assay was performed as reported in Re et al. [1999].

Statistical analysis. The effect of environmental growing conditions on yield and quality of rocket was tested by performing a one-way analysis of variance (ANOVA). The least significant difference (LSD) test ($P = 0.05$) was used to establish differences between means.

RESULTS AND DISCUSSION

Photosynthetic photon flux density and energy production. Figure 2 shows the photosynthetic photon flux density (PPFD) recorded outside and inside different greenhouses during the crop cycle. The PPFD trend in the TPM greenhouse differed from that found in the other two greenhouses. The PPFD recorded in the greenhouse covered with TPM stayed below 50 μmol m^{-2} s, while the PPFD values recorded in the greenhouses covered with PCM and IPM were 15–30% lower (fig. 2) than outside due to the cover material [Sangpradit 2014]. However, between 10:30 and 12:30, the IPM greenhouse showed a substantial decrease (75%) in PPFD compared with outside, due to the shade from the PV modules on the pyranometer (fig. 2).

Figure 3 shows PPFD accumulation from November 7th to December 6th for TPM, IPM and PCM; PPFD accumulation was about 30% and 35-fold lower, respectively, in IPM and TPM than in PCM.

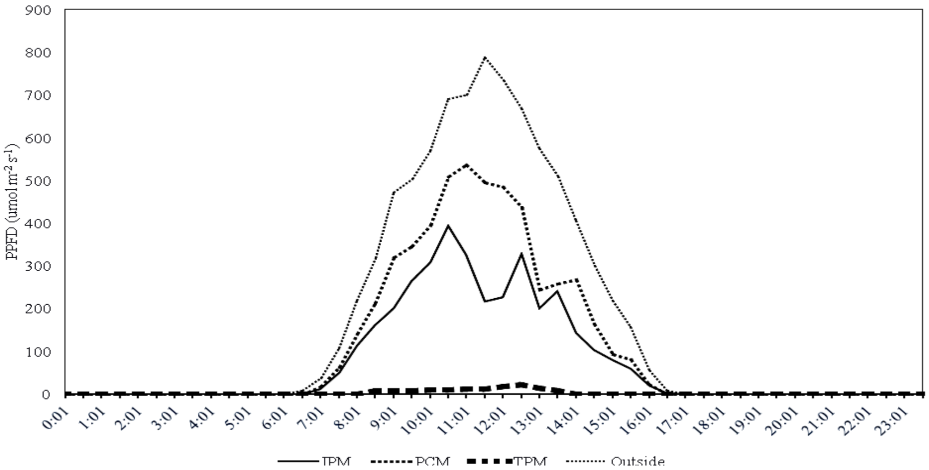

Fig. 2. Hourly average photosynthetic photon flux density (PPFD), outside and inside different greenhouses: TPM = traditional photovoltaic modules; IPM = innovative photovoltaic and polycarbonate modules; PCM = polycarbonate modules

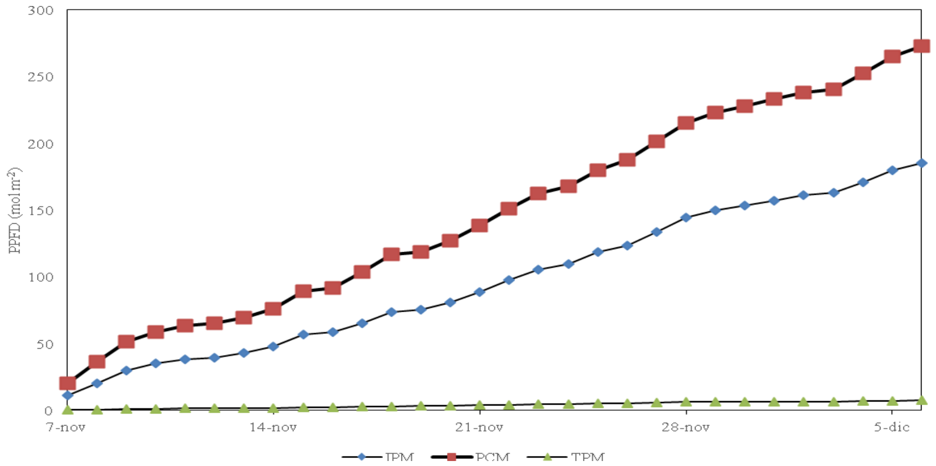

Fig. 3. Photosyntetic photon flux density (PPFD) accumulation from November 7th to December 6th. Comparison among different greenhouses: TPM = traditional photovoltaic modules; IPM = innovative photovoltaic and polycarbonate modules; PCM = polycarbonate modules

Regarding energy production, a yield of 1500 kWh per kWp installed can be estimated from the PV modules, according to the Photovoltaic Geographical Information System at the Joint Research Centre [2015] for the Apulia Region (located in Taranto province). This would indicate estimated electrical energy production of 0, 38 and 161 $kW \cdot m^{-2} \cdot year^{-1}$, respectively, for PCM, IPM and TPM. While the estimated energy production of the greenhouse covered with TPM was about 4-fold higher than that obtained from the greenhouse covered with IPM, it should be pointed out that in the latter greenhouse, the area covered by photovoltaic modules was 3-fold lower than in the greenhouse covered with TPM. At the same time, the number of solar cells per module was 10% lower in the greenhouse covered with IPM (tab. 1). Rocamora and Tripanagnostopoulos [2006] estimated that 24 $MJ \cdot m^{-2} \cdot year^{-1}$ (= 6.66 $kWh \cdot m^{-2} \cdot year^{-1}$) of electrical energy was consumed by electric loads in a greenhouse. Thus, the size of the photovoltaic modules used in our greenhouse covered with IPM can supply a commercial greenhouse's entire demand for electricity. Moreover, there would be a surplus of about 31 $kWh \cdot m^{-2} \cdot year^{-1}$, that would qualify for a government bonus for full architectural integration.

Yield, dry weight and ionic contents. The yield, dry weight and ionic contents of wild rocket grown in greenhouses covered with different modules are reported in Table 2. The lowest yield and dry weight were obtained in the greenhouse covered with TPM, due to the severe reduction in PPFD (figs 2 and 3). On the other hand, the highest dry weight was recorded in rocket plants grown in PCM (+13.8 and +84.6% compared to IPM and TPM, respectively), while the difference in yield between IPM and PCM was not statistically significant (tab. 2). Within certain limits, shading can improve environmental conditions for growth, especially for rocket which is well adapted to growth throughout the year [Hall et al. 2012, Cavaiuolo and Ferrante 2014]. In a previous study on Welsh onions cultivated in a PV greenhouse with a reduction of over 50% in PPFD, fresh and dry-matter weight were lower than those of onions cultivated in the control greenhouse [Kadowaki et al. 2012]. Cossu et al. [2014] showed a reduction in marketable yield in tomatoes grown in a PV greenhouse, in comparison with a plastic covered greenhouse (5.2 *vs.* 6.3 $kg \cdot m^{-2}$, respectively), while no significant reduction in yield for tomato and basil were reported by Minuto et al. [2009] in greenhouses with semi-transparent PV panels and with 20% shading.

Table 2. Effect of greenhouse cover material on yield, dry weight and chloride, nitrate, phosphate and sulfate content in wild rocket (n = 3)

Cover material	Yield	Dry weight	Cl^-	NO_3^-	$H_2PO_4^-$	SO_4^{2-}
	($g \cdot m^{-2}$)	($g \cdot kg^{-1}$ FW)	($mg \cdot g^{-1}$ DW)			
TPM	408 b	74.7 c	15.45 b	132.93 a	10.34 b	29.50 a
IPM	589 a	121.2 b	20.84 a	14.97 b	26.48 a	23.42 b
PCM	540 a	137.9 a	19.60 a	4.85 b	32.03 a	16.43 c
Significance(1)	**	***	*	***	**	**

TPM = traditional photovoltaic modules; IPM = innovative photovoltaic and polycarbonate modules; PCM = polycarbonate modules

(1) – ***, ** and * significant at $P \le 0.001$, $P \le 0.01$ and $P \le 0.05$, respectively. For each parameter, the same letters in the same column indicate that mean values are not significantly different (P = 0.05)

Wild rocket grown under TPM showed the lowest Cl^- and $H_2PO_4^-$ contents, as well as the highest SO_4^{2-} and NO_3^- levels (tab. 2). The SO_4^{2-} content in the leaves grown under TPM modules was about 26 and 80% higher than in the IPM and PCM samples, respectively, while nitrate content in TPM samples was about 13-fold higher than in

IPM and PCM samples (tab. 2). No statistically significant difference was observed for the content of Cl^-, $H_2PO_4^-$ and NO_3^- between IPM and PCM. Thus, a decrease in PPFD may lead to an increase in nitrate content. This is in accordance with several Authors [Steingröver et al. 1986, Blom-Zandstra 1989] who report that nitrate accumulation in vegetables is higher under low light intensity conditions. Similarly, Santamaria [2006] reported light intensity and nitrogen fertilization as the major environmental factors influencing nitrate content in vegetables.

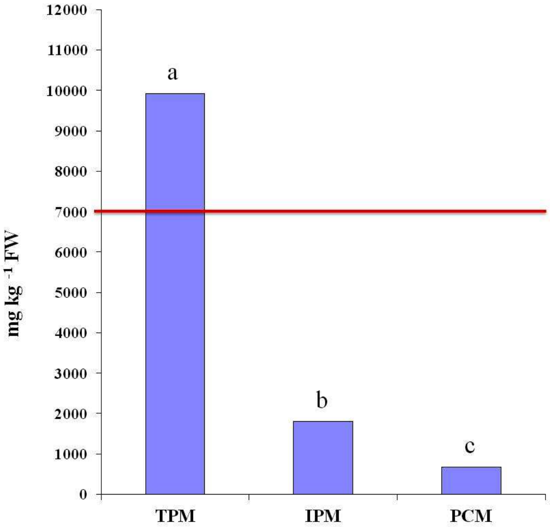

Fig. 4. Nitrate content (as fresh weight basis) in *D. tenuifolia* grown in greenhouses covered with different modules (n = 3): TPM = traditional photovoltaic modules; IPM = innovative photovoltaic and polycarbonate modules; PCM = polycarbonate modules. The horizontal red line represents the nitrate commercial threshold (European Commission Regulation 1258/2011) for *D. tenuifolia* harvested from 1st October to 31st March. Significance: $P \leq 0.001$. Different letters indicate that mean values are significantly different ($P < 0.05$)

Nitrates are very abundant compounds in nature and, among leafy vegetables, rocket is considered to be a hyper-accumulator of these compounds. Although there is emerging evidence that nitrates may play a protective role against cardiovascular diseases [Hord et al. 2009, Weitzberg and Lundberg 2013], up to now nitrates are considered anti-nutrients, and a reduction in their dietary intake is recommended as a preventive health measure [Santamaria 2006]. Strong evidence for either harmful or beneficial effects of dietary nitrates on human health is lacking [Cavaiuolo and Ferrante 2014]. On the other hand, the scientific risk assessment on nitrates in vegetables has led to the setting of a nitrate limit in vegetables [European Food Safety Autority 2008]. Among the leafy vegetables, rocket species can accumulate high amounts of nitrates [Santamaria 2006, Egea-Gilabert et al. 2009], especially during the autumn-winter cycles [Santamaria et al. 2002, Ferrante et al. 2003]. Therefore, European Commission Regulation (EC) No. 1258/2011, amending Regulation (EC) No. 1881/2006 as regards maximum levels for nitrates in foodstuffs [Commission Regulation 2015], for marketing rocket set a nitrate content of below 6.000 and 7.000 mg·kg^{-1} fresh weight, respectively, in summer and winter-grown rocket. Taking into account these limits, the results of the present study show that the nitrate content in wild rocket grown under TPM modules (fig. 4) prevents its sale and cultivation under such environmental conditions. Therefore, growing wild rocket under TPM requires different strategies for reducing the nitrate content: i) removing part of leaf petioles; ii) reducing total content of NO_3-N and NH_4-N in the nutrient solution; iii) removing part or all of the nitrate nitrogen from the nutrient solution a few days before harvesting [Santamaria et al. 2001]. By contrast, rocket production in greenhouses covered with IPM and PCM modules could be legally marketed without using these growing strategies, since the nitrate content was below the limits set out in the current EC Regulation (fig. 4).

ORAC and TEAC assays. As antioxidant molecules are physically classified by their solubility [Arnao et al. 2001], the antioxidant capacity of hydrophilic and lipophilic extracts of wild rocket grown in greenhouses covered with different modules was evaluated and is shown in Table 3. Both ORAC and TEAC values of the hydrophilic extracts were affected by light conditions. The antioxidant capacity of hydrophilic compounds showed a net increase from samples cultivated under TPM to samples grown under IPM and a smaller increment from IPM to PCM rocket samples. As reported above for dry matter (tab. 2), these results show that increasing average light intensity (figs 2 and 3) may also lead to higher accumulation of hydrophilic compounds in wild rocket, according to some Authors [Jin et al. 2009, Bian et al. 2015]. Antioxidant activity values of lipophilic extracts were much lower than those of hydrophilic extracts (tab. 3). Generally L-HORAC are lower than H-ORAC values in fruits and vegetables [Wu et al. 2004]. Moreover, in this study, L-TEAC values were lower than L-ORAC values, probably because, as previously reported [Zulueta et al. 2009], carotenoid antioxidant capacities measured by the TEAC method were lower than the value obtained by the ORAC assay. As shown in Table 3 L-TEAC values of wild rocket grown under TPM were lower than PCM ones. On the other hand, L-ORAC values were highest in rocket samples grown under IPM. Previous studies [Brazaitytė et al. 2015] report that carotenoid concentration increases with increasing irradiance level up to a value of 200–300 μmol·m^{-2} s^{-1}; above these levels carotenoid content starts to decrease. However, remarkable differences among plant species are reported [Bian et al. 2015].

Table 3. Effect of greenhouse cover material on oxygen radical absorbance capacity (ORAC) and trolox equivalent antioxidant capacity (TEAC) assay in *D. tenuifolia* (n = 3)

Cover material	H-ORAC	H-TEAC	L-ORAC	L-TEAC
	(μmol trolox equivalent·g^{-1} FW)			
TPM	4.05 c	4.64 c	0.47 c	0.11 b
IPM	8.27 b	8.89 b	0.72 a	0.15 ab
PCM	9.88 a	11.06 a	0.57 b	0.17 a
Significance ⁽¹⁾	***	***	***	*

TPM = traditional photovoltaic modules; IPM = innovative photovoltaic and polycarbonate modules; PCM = polycarbonate modules; H = hydrophilic extracts; L = lipophilic extracts

(1) – *** and * significant at P ≤ 0.001 and P ≤ 0.05, respectively. For each parameter, the same letters in the same column indicate that mean values are not significantly different (P = 0.05)

Table 4. Effect of greenhouse cover material on D. tenuifolia colour parameters (n = 3)

Cover material	L^*	a^*	b^*	h°	C
TPM	40.9	-15.1 a	20.7 a	126.1	25.6 a
IPM	40.5	-13.8 b	18.5 ab	126.8	23.1 b
PCM	39.5	-12.9 c	17.5 b	126.4	21.7 b
Significance (1)	ns	***	**	ns	**

TPM = traditional photovoltaic modules; IPM = innovative photovoltaic and polycarbonate modules; PCM = polycarbonate modules

(1) – *** and ** significant at $P \leq 0.001$ and $P \leq 0.01$, respectively; ns = not significant. For each parameter, the same letters in the same column indicate that mean values are not significantly different (P = 0.05)

Colour parameters. The values for L^*, a^*, b^*, h^o *and* C of the wild rocket grown in greenhouses covered with different modules are reported in Table 4. As regards L^*, no significant differences were found between all treatments, while a^* and b^* values for TPM samples were, respectively, lower and higher than for PCM samples. On the other hand, similar h^o values were observed for all treatments, as the green colour perceived for the rocket samples grown in greenhouses covered with different modules was similar. By contrast, metric chroma (*C*), which indicates the degree of difference of a hue in comparison to a grey of the same lightness, was highest in the TPM samples. As a consequence, the colour intensity of samples as perceived by humans may be lower in wild rocket grown in greenhouses covered with PCM and IPM than with TPM. These results show that increasing the light intensity (figs 2 and 3) did not affect L^* and h^o values in wild rocket, with only slight changes in metric chroma. Colour and appearance attract a consumer to a food product and can help with impulse purchases. Thus, colour is usually considered the most important attribute of any food's appearance [Francis and Clydescale 1975] and it affects consumer choice and preferences. In any case, as only slight differences in colour parameters were found in this study, we can speculate that it may be possible to obtain wild rocket production in greenhouses covered with different modules, without any remarkable changes in an important quality trait such as colour.

CONCLUSIONS

The greenhouse with 100% coverage with traditional PV panels had the highest electrical energy production, but the yield and quality of the wild rocket obtained in this environment were lower than in the greenhouse covered with innovative PV and polycarbonate modules, especially with regard to nitrate content and antioxidant capacity. The nitrate content in wild rocket grown under greenhouses covered by traditional PV panels is high enough to make the product unmarketable. For both cultivation environments covered with PV panels, the electrical energy produced could be used to satisfy the energy needs of agricultural farms. Nevertheless, the results suggest that it is possible to combine sustainable energy production by PV greenhouses with high-quality rocket production by the use of semi-transparent PV modules obscuring an area of up to 25% Anyway, additional studies would be required for verifying the possibility to increase this limit.

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BEZGLEBOWA PRODUKCJA DZIKIEJ RUKOLI POD WPŁYWEM POKRYCIA SZKLARNI MODUŁAMI FOTOWOLTAICZNYMI

Streszczenie. Słoneczne szklarnie fotowoltaiczne stały się popularne, zwłaszcza w krajach południowej Europy, ze względu na specyficzną politykę rządową zwrotu kosztów. Jednakże należałoby zająć się niektórymi rozwiązaniami agrotechnicznymi. Niniejsze badanie przeprowadzono w trzech typach komercyjnych szklarni pokrytych różnymi materiałami (moduły polikarbonowe – PCM, typowe – TPM oraz innowacyjne półprzezroczyste – IPM moduły fotowoltaiczne) w celu zweryfikowania kompatybilności produkcji energii słonecznej z produkcją dzikiej rukoli o wysokiej jakości (*Diplotaxis tenuifolia* L.). IPM może zaspokoić całość wymagań elektryczności komercyjnej szklarni. Plon rukoli rosnącej w TPM był niższy niż dla IPM i PCM. Właściwości antyoksydacyjne oraz sucha masa obniżyły się w rezultacie zmniejszającego się skumulowanego zagęszczania strumienia fotonów. Zawartość azotanów w TPM była wyższa (około 10 000 mg·kg^{-1} FW) niż maksymalne granice dopuszczane przez Regulację UE Nr 1258/2011, a niższa niż w IPM i PCM (odpowiednio 1805 i 668 mg·kg^{-1} FW). Wyniki sugerują, że możliwe jest połączenie produkcji energii świetlnej z produkcją wysokiej jakości dzikiej rukoli przy użyciu innowacyjnych półprzezroczystych modułów PV.

Słowa kluczowe: energia odnawialna, szklarnie fotowoltaiczne, *Diplotaxis tenuifolia* L., rolnictwo zrównoważone, zawartość azotanów

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