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Assessment of spectrally selective coatings for plastic greenhouses

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Abstract: Spectrally selective coatings were designed to have specific PAR transmittances (namely 40 % and 70 %) and block or limit non-PAR solar radiation. The coatings also have low infra-red emissivity. This means that at night and in winter months, objects (including plants) underneath the coating beneficially lose less heat via radiation. The designed coatings consisted of spectrally functional PVD coatings and protective lacquers. They were commercially manufactured on PET substrates and used in a first-time trial as greenhouse cladding. Three trial tunnel greenhouses (uncoated PET, 70 % PAR and 40 % PAR transmittance coatings) were constructed in Ankara, Turkey and crops of lettuce, tomato and peppers were planted. PAR, temperature, and humidity in the greenhouses were logged and the crop growth analysed. The daytime air temperatures of the coated greenhouses were consistently lower than the reference uncoated greenhouse. The seasonal crop yield is presented as influenced by the greenhouse coating depending on the planting season.

Keywords: greenhouse 1; coating 2; low-emissivity 3; spectrally selective 4; sputtering 5; Turkey 6

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1. Introduction

Greenhouses are used all around the world to cultivate crops under stable conditions. Incident light, temperature and humidity can be adjusted to meet the needs of different crops, extend the local seasonal growth period, and allow the cultivation of non-indigenous crops. Greenhouses heat up due to the greenhouse effect but also due to hot air being trapped inside. The air temperature can be reduced with passive or forced ventilation, evaporation, or air conditioning or conversely increased by heating. Controlling temperature and humidity in a greenhouse can require over 40% of the total crop production cost in the form of energy cost. [1]. The amount of incident sunlight and therefore energy intake can be controlled with shading. The amount of incident radiation can be reduced in the summer months by chalking the cladding or by using reflective curtains. While in central and northern Europe these measures are sufficient to keep a greenhouse at optimal temperatures, cultivation is often discontinued at the height of summer in Mediterranean regions [2]. The shading is currently not selective so that when the energy intake is reduced so is the photosynthetically active radiation, PAR, needed by the plants. Conversely, at night and in winter months curtains may be used to reduce radiative and convective heat losses.

The ideal greenhouse cladding would be spectrally selective allowing sufficient PAR transmittance for optimal growth yet blocking the remaining portion of the solar spectrum to allow a controlled temperature. The optimum selectivity (in this context, the ratio of the PAR transmittance, $T_{PAR,}$ to the solar radiation transmittance, T_{SOL}) is dependent on location, temporal incident radiation, crop-type (and even stage of crop growth e.g., seeding, flowering, fruit-bearing) and season. In high latitudes, and globally during winter months, the availability of PAR limits plant growth whereas excessive radiation in lower latitudes and in summer periods can damage crop growth. Additionally, the cladding

would optimally have a low emissivity and low IR-transmittance to reduce the thermal losses at night and in cooler seasons. Thus, the ultimate cladding would have adaptive spectral properties that are tuned not only to the location but are sensitive to the temporal (time of day, seasonal) solar radiation and fluctuating temperature of the greenhouse but this is technologically challenging. A review of adaptive and novel greenhouse coverings is given by Timmermans [2].

At locations where plants often receive excessive sunlight, as well as reducing the total irradiance, growers can use filters or spray-on coatings that increase the diffuse fraction of sunlight [3] or absorb and reflect in the infra-red region [2]. These type of 'spectral filters' also allow for improvements in the management of temperature in greenhouses.

For glass greenhouses [4], single pane pyrolytic fluorinated tin dioxide coatings, applied during glass manufacturing are produced for solar control and improved low-emissivity. Solar control and low-emissivity coatings are standard in the glazing industry. In multi-glazed windows the sensitive thin film dielectric-metal-dielectric coatings are enclosed in-between the glass panes, which is an inert and protective environment. Applying a similar coating technology to plastic films, which operate in humid, warm and greenhouse environments, is a challenge and additional cover layers such as lacquering are essential to protect the thin-film system.

In this paper solar control and low-e (low emissivity) coatings based on a functional sputtered dielectric-Ag-dielectric layer thin film stack with a lacquered cover layer, were deposited on a commercial substrate PET Melinex 401 CW.

The spectral properties of the coating were designed at the Fraunhofer ISE to allow a maximum PAR transmittance, T_{PAR}, for a specified solar transmittance T_{SOL}. The prototype greenhouses are in Ankara, Turkey. The coating spectral properties were simulated and optimized considering lettuce, tomato and pepper and location with a "thermal insulation" designed coating and a "solar shade" designed coating. The durability of the coated systems was assessed in the damp-heat climate chamber prior to testing.

Three tunnel greenhouses were constructed: a reference, a "thermal insulation" designed coating and a "solar shade" designed coating. The greenhouse temperature, humidity and PAR were monitored and in spring and summer crops of lettuce and in summer to autumn bell pepper and tomato were planted and assessed.

The PET Melinex 401 CW proved to be a sub-optimal substrate for the greenhouses but still a comparison of the coatings on the effect of the climate in the greenhouse and the resulting effect on the crop yield was able to be analysed.

2. Materials and Methods

To protract the PAR and temperature externally and internally in the coated greenhouses in Ankara, Türkiye, the temperature and irradiance data was used from PVGIS-SARAH [5]. Hourly values for direct irradiance, diffuse irradiance, reflected irradiance, sun height, air temperature and wind speed between 2005 and 2016 were retrieved. For the tables displayed in Figure 2 an average day per month was calculated. This meant an average day per hour contains the data of 12 years and all days of the given month. The sum of direct and diffuse irradiance was calculated for an average day and values for PPFD were estimated from the sum. The calculation of the PPFD, here, assumes that the PAR to total solar radiance is an average of 0.45 and it also takes the number of photons in PAR as 4.57 μmol s-1 W-1. This value is derived from the averaged energy of an incoming photons in the PAR wavelengths [6,7].

The daily light integral (DLI) is calculated summing the hourly PPFD across the day and cutting above the photosynthetic saturation point of tomatoes of 800 μmol $m^{-2}s^{-1}$ (i.e., for all hourly periods where PPFD > 800 μmol $m^{-2}s^{-1}$ only 800 μmol $m^{-2}s^{-1}$ was taken to sum the DLI).

The in-house developed simulation tool RAT was used to plan and optimize the spectral properties of the coating system. A thin film layer system based on Ag embedded in dielectric layers can be designed in the software, by setting thicknesses for each layer

and providing the refractive index (n) and extinction coefficient (k). This allows the optical parameters to be simulated and a specific film system to be designed with a specific T_{PAR} and a minimized T_{SOL}.

The "best" coating systems (high T_{PAR} to T_{SOL}) were designed by the Fraunhofer ISE and coated on 100 μm thick PET Melinex 401 CW as a commercial product-in-development by industrial partners ROWO GmbH (roll to roll sputtering) and Dunmore (roll to roll lacquering). The exact material of the coating cannot be digressed as it is a commercial product in development.

The PET was the selected as it is highly compatible to coat in the inline roll-to-roll sputter coater and lacquer-coating system and exhibited highly durable spectral properties after aging in the damp-heat chamber. It was however sub-optimal for mechanical and UV-stability.

Reflectance and transmittance measurements were done with a Bruker Vertex 80 spectrometer with an integrated sphere which measure from 0.3 to 17 μm. The solar hemispherical transmittance, T_{SOL}, is the percentage of the direct and diffuse AM1.5 solar radiance transmitted from the coating system. The transmitted PAR, T_{PAR} , was protracted using the PAR reference given in DIN 5031-10 [8]. The emittance and infra-red transmittance taken as standard Planck black body radiator at 300 K.

The coated samples were placed in a Vötsch VC 4060/L/S climate chamber under temperature of 85°C and 85% humidity for 30 days for accelerated aging testing.

Three 50 m^2 tunnel greenhouses of dimension were constructed in Ankara, Turkey: a reference with the chosen PET substrate as reference, a "thermal insulation" designed coating and a "solar shade" designed coating These are pictured in Figure 1.

The greenhouse humidity and temperature were measured automatically every 15 minutes using an Elitech sensor which can store data for six months. Data for outside temperature and humidity was collected from an onsite weather station.

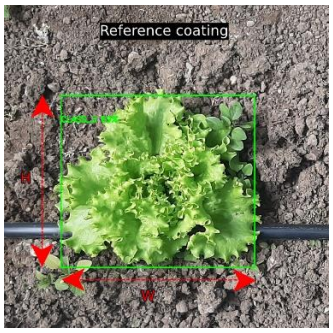
An Apogee MQ-500 Quantum meter with separate sensor was used to manually measure PAR inside and outside of the greenhouses.

Maritima lettuce crops were planted for in April for the spring crop and again in July for the summer crop. Siranzo tomato and sobek pepper were planted only in July.

The growth measurements of the lettuce were measured using photography and image processing (object detection using Region-based Convolutional Neural Networks, R-CNN Algorithms [9]). The average area, width and height of the lettuces were assessed in this way and for the tomatoes and peppers the plant size, fruit size, number of buds, number of flowers and number of fruits were measured manually. After harvesting in July the lettuce crop weight was measured for each greenhouse.

In the case of lettuce, 40 plants were selected as samples in each section, while for each section, 5 plants of tomato and pepper were selected to evaluate and compare their growth.

(a)



(b)

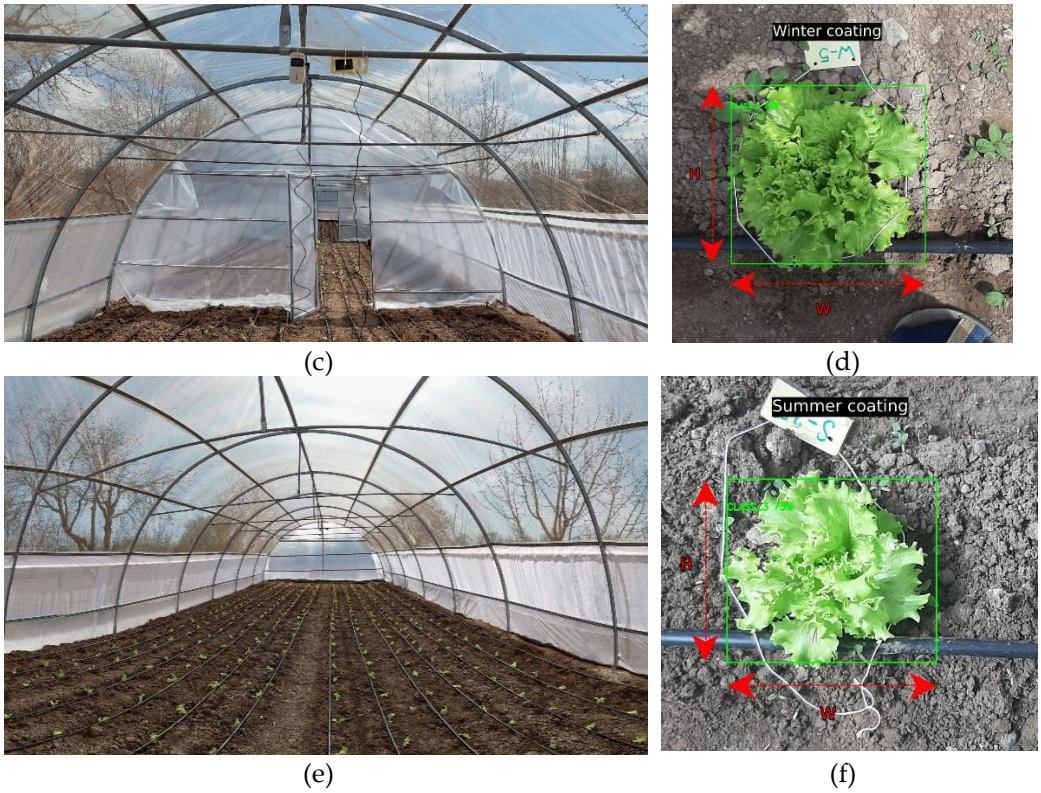


Figure 1: Photographs of (a) reference tunnel greenhouse with PET roof and (b) grown sample lettuce from spring crop, (c) "thermal insulation" coated greenhouse and (d) grown sample lettuce from spring crop (e) "solar shade" coated greenhouse and (f) grown sample lettuce from spring crop.

3. Results

3.1. Coating design and production

The amount of available PAR directly effects plant growth and therefore the yield of crop plants. Past the photosynthetic saturation point any surplus radiation will heat up and may cause damage to the plant. In table 1 is a summary from [10,11] for the ideal PPFD levels for tomatoes, lettuce and pepper. 800 $\mu mol\ m^{-2}\ s^{-1}$ is taken as the photosynthetic saturation point. To achieve maximum yield plants require a specific amount of light each day. This can be expressed by the daily light integral (DLI). Summing up the photosynthetic photon flux density over one day gives the DLI and it is therefore expressed in $mol\ m^{-2}\ d^{-1}$.

Table 1. Succinct overview of critical PAR parameters for tomatoes, lettuce and peppers [10,11]

Plant	Desired PAR dosage in PPFD[1] ($\mu mol\ m^{-2}s^{-1}$)	Photosynthetic saturation point[2] in PPFD ($\mu mol\ m^{-2}s^{-1}$)	Required DLI[3] ($mol\ m^{-2}day^{-1}$)
Lettuce	250-350		14-15
Tomato	400-500	800	22-30
Pepper	350-450		20-40

[1] PPFD = photosynthetic photo-flux density

[2] Above which photosynthesis rate reaches a maximum

[3] DLI = daily light interval.

The average daily PPFD per hour and DLI per day for each month were estimated, as described above in section 2, for the greenhouse's location in Ankara. If the PAR is reduced using a greenhouse covering with a specific T_{PAR} value one can estimate the PPFD the crop inside would be exposed. Using the critical PPFD values in Table 1, the results are presented in charts for different PAR-filters in Figure 2. In the charts, below 300 $\mu mol\ m^{-2}s^{-1}$ (cells coloured blue) represents insufficient PPFD for crop growth whilst over 800 $\mu mol\ m^{-2}s^{-1}$ (cells coloured red) exceeds the photosynthetic saturation point. The green cells lie in the optimum range of PPFD. These charts are shown in Figure 2a where T_{PAR} is set to 100 % (outside the greenhouse) and in Figure 2b T_{PAR} is set to 88 % (exposure under a PET substrate). From this protraction we designed coating to have approximately 70 % and 40 % T_{PAR}. The "DLI" (yellow line) is the daily light integral for a plant taking 800 µmol m^{-2} sec^{-1} as photosynthetic saturation point

A 70 % T_{PAR} was selected for our so-called "thermal insulation" coating, as this is near the maximum PAR achievable with the dielectric-Ag-dielectric sputter system plus lacquer system on PET. The protraction of the influence of a T_{PAR} of 70 % on the PPFD in Ankara is shown in Figure 2(c). The DLI and PPFD levels inside the respective greenhouse decrease compared to the uncoated PET greenhouse. The average PPFD in the summer months of June to August is still much higher than the photosynthetic saturation point (which means a potentially damaging amount of sunlight to the plants). This coating should be optimal in March-May and September-October when the DLI exceeds 20 $mol\ m^{-2}\ day^{-1}$. This thermal insulation coating is also a low-e coating. It has high infra-red reflectance inwards to the greenhouse which minimises energy loss from heat radiation of the plants and soil. This coating should help protect plants by reducing their radiative thermal losses which would help reduce rapid plant cooling on cold, clear nights. The thermal insulation coating was placed on the inner-greenhouse side of the PET substrate.

A T_{PAR} of 40 %, which we call a "solar shade" coating was selected to reduce the sunlight so that even in the high summer months the PPFD is cut to below the photosynthetic saturation point i.e., below 800 $\mu mol\ m^{-2}s^{-1}$. The protraction of this case however highlights that the DLI is sub-sufficient (<20 $mol\ m^{-2}\ day^{-1}$) for the 9 months of the year (see Figure 2 d). Therefore, in Ankara it is clear a solar shading layer which drastically cuts the T_{PAR} by 40 % is could *only* useful in months June, July, and August. The solar-shade coating was placed on the outside facing side of the PET substrate.

Based on this analysis Fraunhofer ISE designed the dielectric-Ag-dielectric based film system to have optical properties where T_{PAR} was 40 and 70 % respectively for the solar shade and thermal insulation coatings and by adjusting the interference film system a T_{SOL} that was minimized (to minimize the non-PAR portion of the solar spectrum) allowing lower day-time temperatures in the greenhouse. The samples were subsequently made on a roll-to-roll sputter production line at ROWO GmbH and an industrial scale lacquering line at Dunmore using the PET Melinex as a substrate (see section 2). They are commercial products which are in development. The optical properties of the coated and uncoated product as well as a standard LDPE (low density polyethylene) greenhouse covering were measured and are shown in Table 1. It should be noted that the actual T_{PAR} was 1 % less than the designed product and thus these are the values used in the charts in Figure 2 (c) and (d). T_{SOL} is then lowered significantly more than the T_{PAR}, to 25 % for the solar shade coating and 51 % for the thermal insulation shading. Both coated products have low-emissivity and low infra-red transmittance.

Time (GMT)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	51	94	56	1	0	0	0	0
4	0	0	10	151	305	408	372	238	115	9	0	0
5	0	38	203	467	654	800	788	651	481	255	87	0
6	143	238	491	816	1020	1178	1191	1074	853	569	341	179
7	320	462	773	1134	1314	1492	1507	1421	1186	855	601	383
8	464	656	967	1328	1480	1694	1764	1659	1417	1053	767	534
9	542	781	1055	1386	1563	1750	1887	1808	1517	1105	849	609
10	524	734	1052	1335	1463	1684	1891	1789	1488	1052	821	580
11	474	695	946	1255	1408	1568	1740	1674	1366	915	720	520
12	379	533	809	1091	1193	1347	1529	1472	1136	708	532	390
13	258	392	625	856	973	1110	1255	1156	863	504	293	214
14	72	203	393	548	683	823	952	810	535	195	44	8
15	0	14	141	273	400	517	611	448	172	4	0	0
16	0	0	0	24	122	214	243	103	0	0	0	0
17	0	0	0	0	0	2	2	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
Sum:	3175	4746	7466	10664	12628	14682	15790	14304	11129	7224	5054	3417
DLI:	11	17	24	28	31	33	33	31	28	22	18	12

(a)

Time (GMT)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	44	83	49	1	0	0	0	0
4	0	0	9	133	268	359	328	209	101	8	0	0
5	0	33	179	411	576	704	694	573	423	224	77	0
6	126	210	432	718	897	1037	1048	945	751	501	300	158
7	281	406	681	998	1156	1313	1327	1250	1044	753	529	337
8	408	577	851	1169	1303	1491	1552	1459	1247	926	675	469
9	477	687	929	1220	1375	1540	1661	1591	1335	973	747	536
10	461	646	926	1175	1288	1482	1664	1574	1309	926	723	511
11	417	612	832	1104	1239	1380	1532	1473	1202	805	633	458
12	333	469	712	960	1049	1185	1346	1296	999	623	468	343
13	227	345	550	753	856	977	1105	1018	759	444	258	188
14	64	179	345	482	601	724	838	713	471	171	38	7
15	0	12	124	240	352	455	538	394	151	3	0	0
16	0	0	0	21	108	188	214	91	0	0	0	0
17	0	0	0	0	0	2	2	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
Sum:	2794	4177	6570	9384	11112	12920	13896	12587	9793	6357	4448	3007
DLI:	10	15	22	27	30	32	32	30	27	21	16	11

(b)

Time (GMT)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	35	65	39	1	0	0	0	0
4	0	0	7	104	210	282	257	164	79	6	0	0
5	0	26	140	322	451	552	544	449	332	176	60	0
6	99	164	339	563	704	813	822	741	589	393	235	124
7	221	319	534	783	907	1030	1040	980	818	590	414	264
8	320	453	667	916	1021	1169	1217	1144	978	726	529	368
9	374	539	728	957	1078	1207	1302	1247	1047	763	586	420
10	361	507	726	921	1010	1162	1305	1234	1027	726	567	400
11	327	480	653	866	971	1082	1201	1155	942	631	496	359
12	261	368	559	753	823	929	1055	1016	784	489	367	269
13	178	271	431	590	671	766	866	798	595	348	202	148
14	50	140	271	378	471	568	657	559	369	134	30	6
15	0	10	97	188	276	357	422	309	119	3	0	0
16	0	0	0	16	84	147	167	71	0	0	0	0
17	0	0	0	0	0	2	1	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
Sum:	2191	3275	5152	7358	8713	10131	10895	9870	7679	4985	3487	2358
DLI:	8	12	19	25	28	30	31	28	25	18	13	8

(c)

Time (GMT)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	20	37	22	0	0	0	0	0
4	0	0	4	59	119	159	145	93	45	4	0	0
5	0	15	79	182	255	312	307	254	188	99	34	0
6	56	93	191	318	398	460	464	419	333	222	133	70
7	125	180	302	442	512	582	588	554	463	334	234	149
8	181	256	377	518	577	661	688	647	553	410	299	208
9	211	305	412	541	609	682	736	705	592	431	331	237
10	204	286	410	521	571	657	737	698	580	410	320	226
11	185	271	369	489	549	611	679	653	533	357	281	203
12	148	208	316	426	465	525	596	574	443	276	207	152
13	100	153	244	334	379	433	490	451	336	197	114	83
14	28	79	153	214	266	321	371	316	209	76	17	3
15	0	5	55	107	156	202	238	175	67	1	0	0
16	0	0	0	9	48	83	95	40	0	0	0	0
17	0	0	0	0	0	1	1	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
Sum:	1238	1851	2912	4159	4925	5726	6158	5579	4340	2818	1971	1333
DLI:	4	7	10	15	18	21	22	20	16	10	7	5

(d)

Figure 2: Charts of the hourly values for photosynthetic photon flux density (PPFD) in $\mu mol\ m^{-2}s^{-1}$ for an average day of the month in Ankara Turkey for (a) outside (b) beneath a PET Melinex covering with T_{PAR} =88 % (c) beneath a thermal insulation coated PET with T_{PAR} = 69 % and (d) beneath a solar shade coated PET with T_{PAR} = 39 %. The blue colour indicates the PPFD values below 300 $\mu mol\ m^{-2}s^{-1}$ which is the desired PAR dosage. The green represents suitable PPFD values and red indicates PPFD which exceeds the photosynthetic saturation point. The "Sum" (orange line) is then the daily sum given as $\mu mol\ m^{-2}\ day^{-1}$. The "DLI" (yellow line) is the daily light integral for a plant taking 800 $\mu mol\ m^{-2}\ sec^{-1}$ as photosynthetic saturation point.

Table 2. Spectral properties of the coated greenhouse PET Melinex used as greenhouse cladding material. Standard and diffuse LDPE included as reference.

Material	T_{PAR}	T_{SOL}	$\frac{T_{PAR}}{T_{SOL}}$	T_{IR}	e_{IR}
PET MELINEX 401 CW (100 µm)	88	88	1	40	49
PET with "thermal insulation" coating	69	51	1.35	2	15
PET with "solar shade" coating	39	25	1.56	2	13

LDPE reference standard (200 μm)	88	88	1	66	26
LDPE reference diffuse (200 μm)	74	74	1	14	80

212

213 *3.2. Coating characterisation and durability*

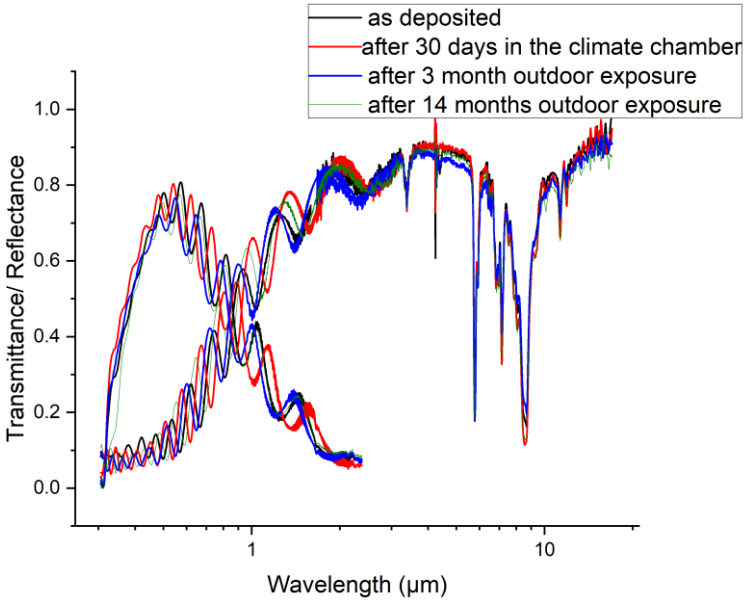
214

215 It was important to assess how durable the coatings were in the humid and warm green-
216 house environment. Firstly, before the greenhouses were constructed, samples from the
217 coated products were exposed for 30 days at 85 ºC and 85 % humidity in a climate chamber.
218 Secondly, samples from the coated products were monitored with time in the actual green-
219 houses. Samples were inspected visually, and their spectral products were measured.

220

221 The transmittance and reflectance data are presented in Figure 3 (for the thermal insulation
222 product) and Figure 4 (for the solar shade product) for samples as deposited, after 30 days
223 in the climate chamber and after 3 months and 14 months greenhouse exposure.

224



225

226 **Figure 3:** Transmittance and reflectance plots for the thermal insulation product (T_{PAR} = 69 %) before
227 and after testing in the climate chamber and greenhouse environment.

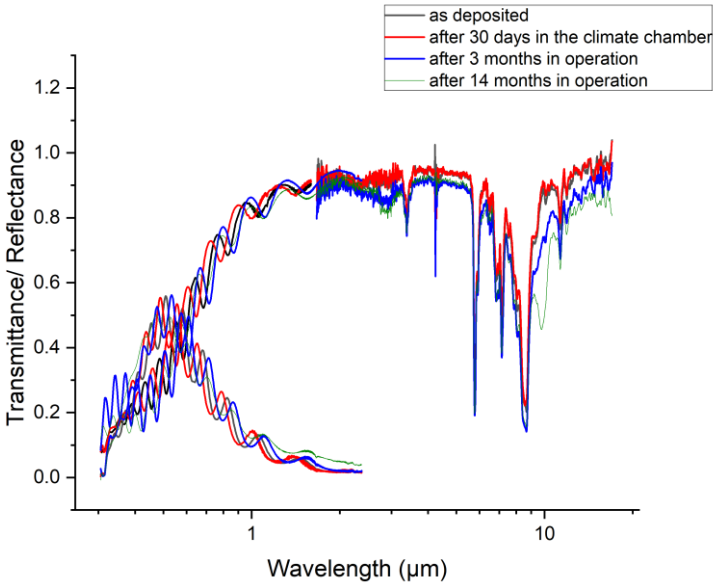


Figure 4: Transmittance and reflectance plots for the solar shade product (T_{PAR} = 39 %) before and after testing in the climate chamber and greenhouse environment.

In the controlled environment of the climate chamber the coatings did not degrade. The spectral parameters were the same before and after exposure and visual degradation was not observable.

When the material was incorporated as greenhouse cladding, it is important to distinguish between damage to the PET substrate and damage to the coating. The PET Melinex 401 CW was chosen for its compatibility with the coating techniques. The PET was not UV-stabilised and the mechanical properties for the greenhouse construction were sub-optimal, for example the PET was more rigid than the standard LDPE covering and thus the greenhouse was more difficult to assemble. And care needed to be taken during the installation of the cover to avoid tearing.

The thermal insulation coating itself, however, although exposed the humid and warm temperatures of the greenhouse for 14 months the emissivity increased from 0.15 to 0.22. The solar shade coating which was exposed to outdoor conditions exhibited an increase in emissivity from 0.13 to 0.25. This increase in emissivity indicates a slight degradation in the functional silver layer. As Figure 4 and Figure 5 testify the spectral parameters remain very similar to the as deposited samples indicating that the protective lacquer had done an excellent job in protection of the dielectric-Ag-dielectric sputtered film system.

The PET Melinex 401 CW substrate itself began to degrade after 6 months in the field. This meant segments of the reference PET greenhouse cladding as well as the coated thermal insulation coated PET greenhouse were ripped (as shown in the photographs in Figure 5 (a) and (b)). The torn PET panels were replaced by fresh panels to allow the crop growth experiment to continue running. Only the reference greenhouse and the thermal insulation coated greenhouse exhibited this behavior. The solar-shade coating which was applied to the outer-side of the greenhouse shielded the PET from UV-damage and thus the solar-shade coated PET did not degrade and survived even high winds in November 2022 and heavy snow in the February 2023 months (see Figure 5 (c)).

The solar-shade coating greenhouse remains currently in use. The other two greenhouses were dismantled 14 months after construction.

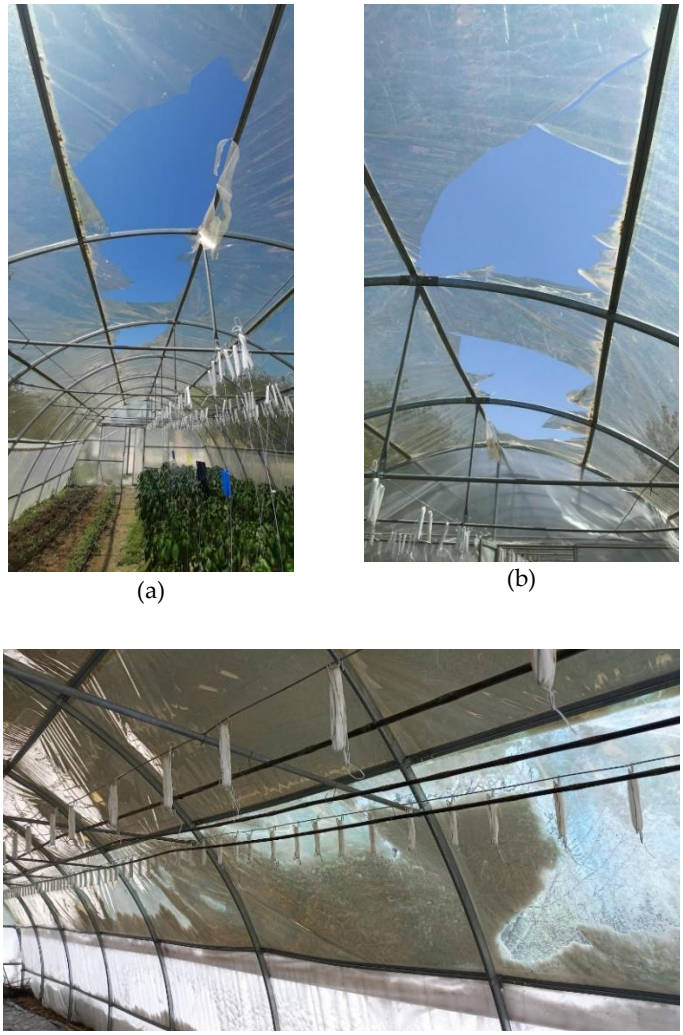


Figure 5: Photographs of the damaged PET Melinex substrates # months after installation following UV exposure and high winds (a) from the reference greenhouse (b) from the thermal insulated coated greenhouse. Photograph (c) shows the solar-shade coated greenhouse remains in good condition, here after 12 months, and despite heavy snow (shown) and previously high winds.

3.3. Coating influence on the PAR; temperature and humidity in the trial greenhouses

After greenhouse construction the PAR was measured periodically with a hand-held measurement system. The PPFD for the three greenhouses as well as the external measurements are shown in Figure 6. On the right-hand axis the percentage of PAR is given (simply the interior measured PPFD divided by the exterior measured PPFD). The measurements were not taken at the exact same moment and thus discrepancies can arise (for example sudden cloud cover). The PAR measurements confirm that in the PET greenhouse the T_{PAR} is approximately 80-90 %, the thermal insulation allows T_{PAR} of 60-70 % and the solar shade allows a T_{PAR} of approximately 30-40 % which corresponds with the spectroscopic measured properties given in Table 2.

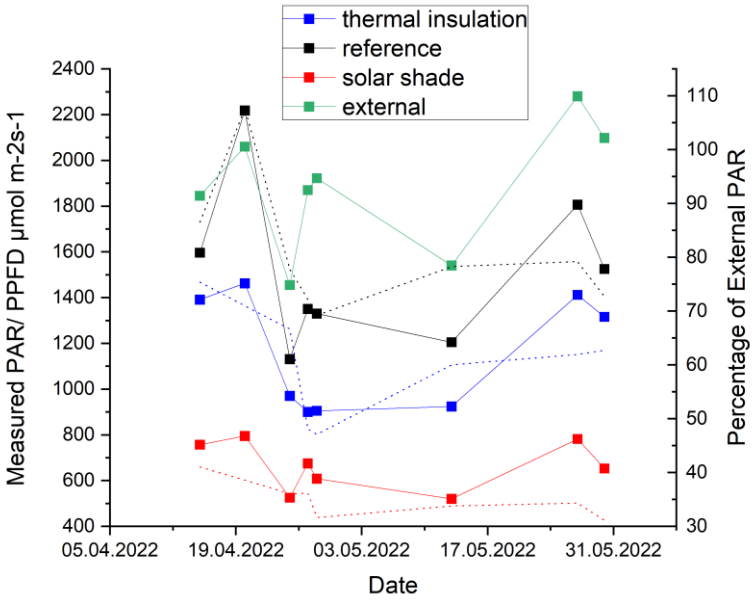


Figure 6: PAR PPFD measured periodically inside the three trial greenhouses and externally. The solid lines correlate to the left axis and the actual PPFD. The dotted lines correlate to the percentage of PAR transmitted in the three trial greenhouse in comparison to the measured exterior PAR.

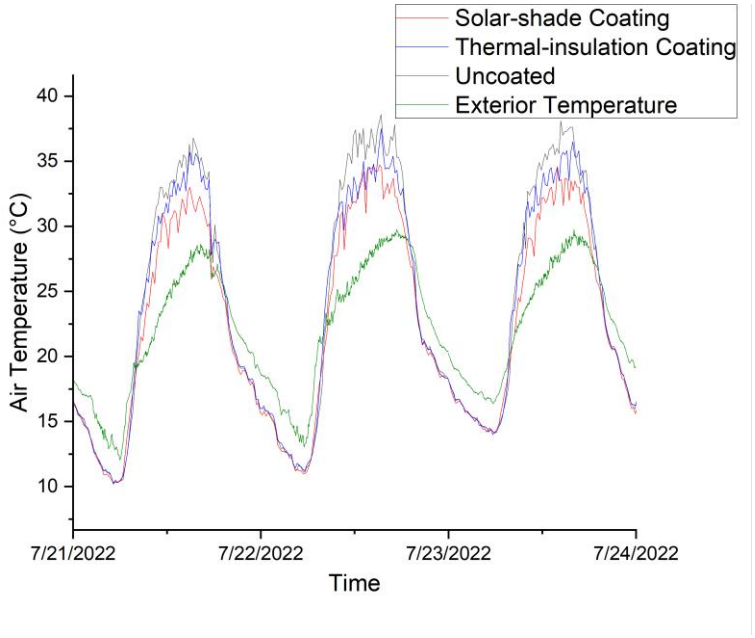


Figure 7: Example plot of the monitored temperature data from the three trial greenhouses.

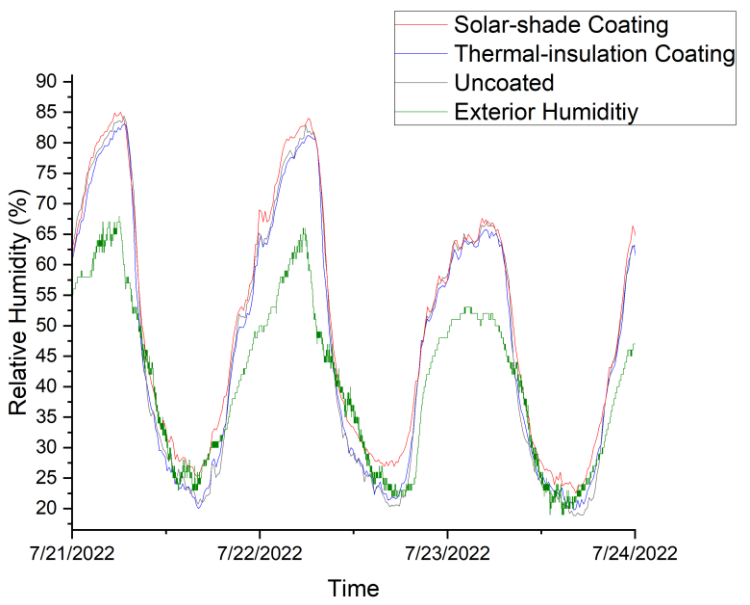


Figure 8: Example plot of the monitored humidity data from the three trial greenhouses

The temperature and humidity were tracked as described in section 2. During the recorded measurements the greenhouse doors were kept shut Figure 7 and 8 show example data from the temperature and humidity tracker. During the day the solar shade greenhouse felt considerably cooler. The temperature monitored measured approximately a 2-5 º temperature difference between the solar-shade and the reference greenhouse and a 1-3 º temperature difference between the reference and thermal insulation coated greenhouse. Comparison with exterior ###. This is directly due to the lower T_{SOL} of 51 % for the thermal insulation and 25 % for the solar shade coating (see Table 2).

The relative humidity has a corresponding trend as is temperature dependent, where with lower temperatures the relative humidity is correspondingly higher.

Measurement errors of temperature??? Did we solve the problem of that being the true temperature?? Why are the external temperature at night higher outside the greenhouses

3.3. Coating influence on the plant growth in the trial greenhouses

3.3.1 Lettuce crops

In April 2022 the greenhouses were planted with lettuces to examine the behavior of this crop in spring conditions in the three trial greenhouses. A second crop-batch was planted in July 2022 to examine the growth in summer conditions. The lettuce height, width and area were monitored periodically. In Figure 9 the graph is plotted for the periodic measurement of the lettuce area but the height and width measurement exhibit similar trend (see S1 for graphs of these). The spring crop was allowed to grow for longer. The summer crop was picked and weighed. A bar chart of the different mass categories is shown in Figure 10, also shown in the bar chart are the number of dead lettuces.

Clearly in April and May the solar shade coating stunts the lettuce growth due to the reduced PAR. These lettuces were also reported to taste bitter. The thermal insulation coating also marginally reduced the growth compared to the reference. In July and August, the largest and heaviest lettuces were grown again in the reference greenhouse. The total number of lettuces was 42 per greenhouse in July. In the reference greenhouse, however, there

was a 33 % loss of lettuce, which can, at least partially, be attributed to the high PAR levels and high temperatures in the greenhouse. The thermal insulation coated greenhouse exhibited 14 % crop loss but also a distribution of smaller lettuces than the reference. The solar shade coated greenhouse had no crop loss but a distribution of smaller lettuces with lower mass.

For lettuce, it is enough to consider the average area in three sections. The graphs sent to the attachment clearly show that in the months of April and May, in 38 days, the reference section reached an area of 1,600 square centimeters, and this means that the lettuce in this section grows by an average of 38 square centimeters per day. and this figure for winter was about 35 square centimeters and finally the summer part grew by 17 square centimeters on average. Similarly, in July, in 13 days, the average growth for reference was 37.5 square centimeters for each day, and for winter, this number was 35 square centimeters for each day, and for summer, 29 square centimeters. According to the above data, it can be said that lettuce had the best yield in April and May in the reference section and reached a stage that can be marketed in 38 days. Lettuces of the summer section are 19 days behind the reference in terms of growth.

Important note: Lettuce should reach the harvesting stage in seven weeks (Conventional - with soil).

As for July, the reference has grown well again, but some lettuces have been lost due to the high heat. Also, some lettuce was wasted in winter and this is the negative point of reference and winter sections. Therefore, according to the growth of 29 square centimeters in the summer section, it can be concluded that the summer section has reached 1421 square centimeters in 49 days and can be supplied to the market without losses. The great success is that lettuce is not a summer crop, but it can be cultivated in this season by using summer cover.

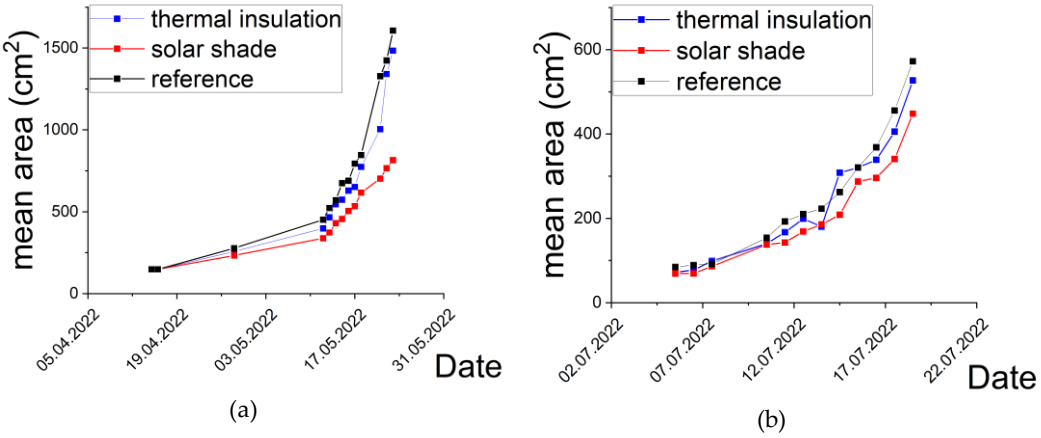


Figure 9: Comparative growth for the lettuce in the (a) spring and (b) summer planting in the three trial greenhouses.

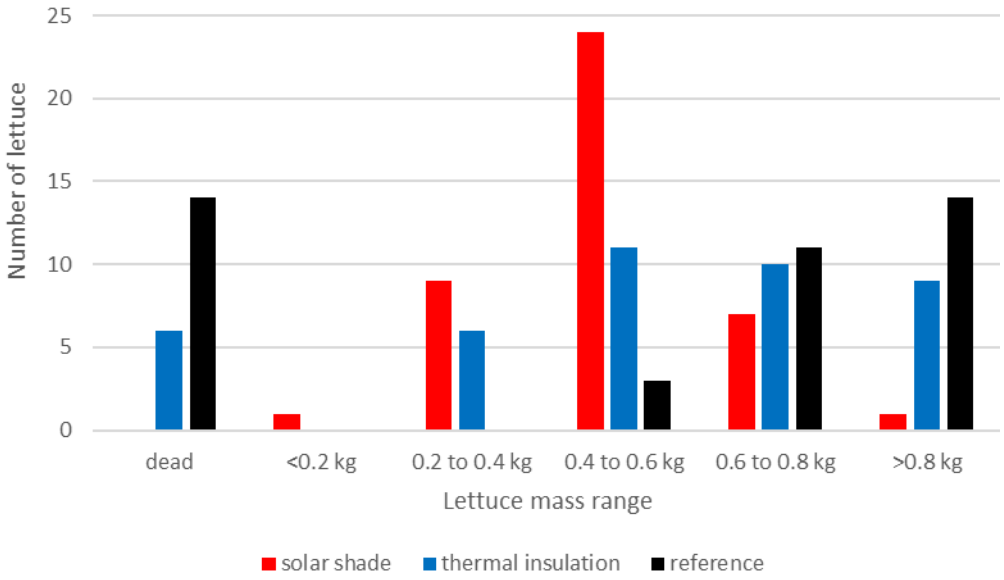


Figure 10: Number of lettuces as a function of range of lettuce mass for July/August lettuce crop for the three different greenhouses.

3.3.2 Tomatoes and Peppers Crops

In July 2022 crops of tomato and pepper were planted in the three trial greenhouses. The plant height, plant width, number of buds, number of flowers, number of fruits and fruit size were all periodically measured. Figure # shows the plant heights for the pepper (Figure 11 (a)) and tomato (Figure 11 (b)). Both for tomatoes and peppers the tendency for the plants to be increase as the greenhouse T_{PAR} values decrease, although for the tomatoes the mean plant height from the reference greenhouse exceeds that of those from the thermal insulated coated greenhouse. The solar shade has the tallest greenhouse plants.

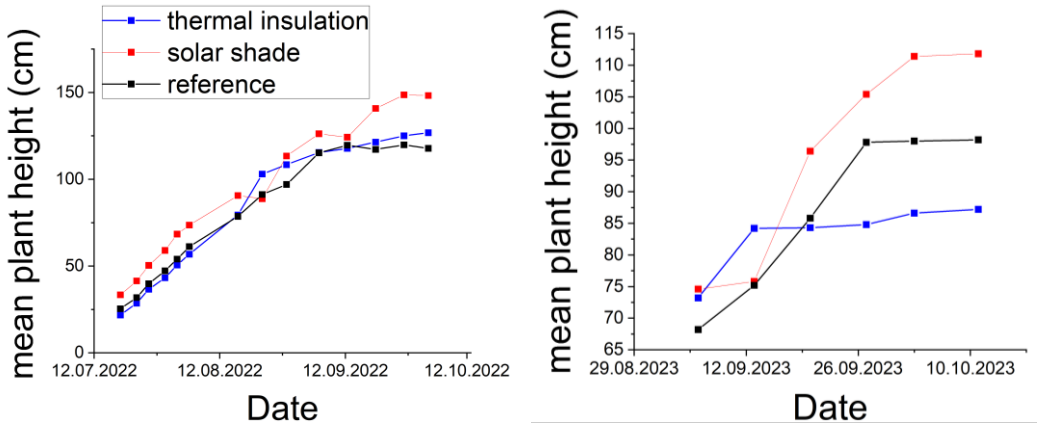


Figure 11: Mean plant height for (a) peppers (b) tomatoes planted in the three trial greenhouses.

The normalized Growth Score were calculated attain a figure of merit in the flowering and fruit-producing phases of the crop. For all the rest of the data please see (??data available?? or put it in as supplementary material??)

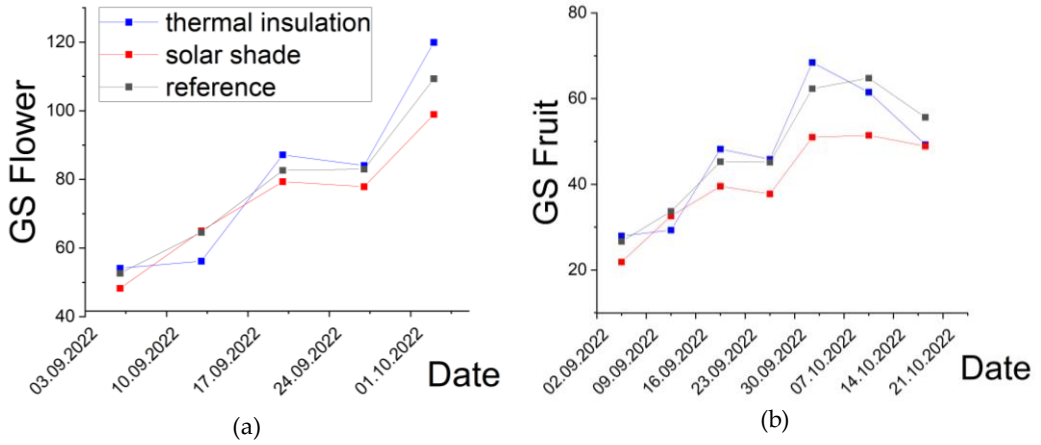
The normalised Growth Score for the flower period (GS_{Flower}) is defined as;

$$GS_{Flower} = 0.8*BFF_{nomalised} + 0.2*L_{p_mornalised} \quad (1)$$

where $BFF_{nomalised}$ = (1*number of buds+2*number of flowers+4*number of fruits) normalized and $L_{p_mornalised}$ is the plant height nomalised. The normalised Growth Score for the fruit period (GS_{Fruit}) is defined as;

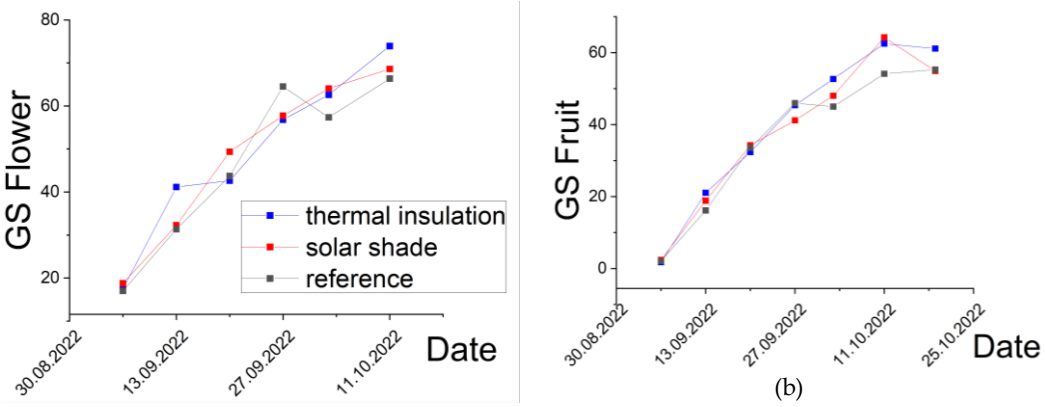
$$GS_{Fruit} = 0.5*BFF_{normalised} + 0.5*F_{S_normalised} \quad (2)$$

where $F_{S_normalised}$ is the fruit size nomalised.



(a) (b)

Figure 12: The Growth Score (GS) merit of figure for (a) flower and (b) fruit for peppers planted in August 2022 in the three trial greenhouses.



(a) (b)

Figure 13: The Growth Score (GS) merit of figure for (a) flower and (b) fruit for tomatoes planted in August 2022 in the three trial greenhouses.

The first protraction of the growth score for the pepper, in the September is that the thermal insulation coated greenhouse…

???? comment and interpretation from Antalya or ARTECS….similar??? Yes

4. Discussion

4.1 Influence and analysis of the coating spectral parameters

70 % "thermal insulation" and 40 % "solar shade" T_{PAR} coating were chosen for production and investigation, based on estimates of the required PPFD of the crops (lettuce, pepper, tomato) and the greenhouse location (Ankara, Turkey). The manufactured coated PET Melinex products achieved within 1 % the targeted T_{PAR} values (measured values

being 69 % and 39 % respectively for the thermal insulation and solar shade coated product). The T_{SOL} was measured to be 50 % and 25 % for the thermal insulation and solar shade products respectively. The products are spectrally selective, in contrast to standard shading materials, allowing a higher T_{PAR} value to T_{SOL}.

The measured PAR values in PPFD in the assembled greenhouses correspond approximately to the spectroscopy-measured values. The measured day-time temperature is reduced in the thermal insulation coated greenhouse (1-3 ºC cooler than the reference greenhouse) and even more in the solar shade coated greenhouse (2-5 ºC cooler than the reference greenhouse) directly because the T_{SOL} has also been reduced. The humidity is marginally also influenced by the spectral properties of the greenhouse cladding, inversely proportional to the temperature trend.

The thermal insulation coating has high infra-red reflectance to the inside of the greenhouse. This meant that the plants would lose less radiative heat particularly on clear nights. This would be then beneficial for early spring when cold clear nights lead to rapid cool down of plants which can be damaging, although this was not confirmed experimentally here.

The thermal insulation coated greenhouse provided a cooler environment with less PAR than the reference greenhouse. From inspection of the incident radiation data for Ankara it was assumed to be beneficial to reduced exposure to PPFD over the photosynthetic saturation point during the summer months and midday in the spring months. The overall DLI is of course reduced, which is not optimal for growth.

From the prediction (given in Figure 2) it was also determined that the solar shade product, although beneficially cutting 50 % of T_{SOL} to yield a cooler greenhouse environment, would cut too much of the T_{PAR} leading to too low DLI for all months except June to August. The influence on the June to August crops were therefore of particular interest.

For the lettuce crop both coated greenhouses with reduced PAR levels yielded in both in spring and summer crops smaller, less massive lettuces than the reference greenhouse. For example, in July, the largest lettuces grown in the reference greenhouse had an average mass of 780 g, the thermal insulation coated greenhouse lettuces had a mass of 630 g and the solar shade coated greenhouse had an average mass of 500 g. The reduced PAR DLI levels due to the coatings clearly had an adverse effect on the lettuce growth even in summer. The number of dead lettuces, however, indicated that the lower temperatures or/and the less intense PPFD allowed crop protection where in the cooler, shadier solar shade greenhouse had no crop in summer, in the thermal insulated 14 % crop loss and in the reference a third of the crop was lost.

The ideal spectrally designed greenhouse cladding would have adaptive spectral properties that are tuned not only to the location but are sensitive to the temporal (time of day, seasonal) solar radiation. Here the technology is not adaptive, but the aim was to test two specified T_{PAR} filters which are spectrally selective and thus block as much T_{SOL} for a given T_{PAR}. In summary it is observed that reducing the T_{SOL} leads to a cooling environment and crop protection for PPFD greater than the photosynthetic saturation point. As the cladding remains permanently in place (i.e., is not a curtain which can be pulled back and forth to only cut the intense midday radiation) this first trial implies that the DLI reduction can reduce crop growth. Other elements (e.g., different pest levels or other uncontrolled differences between the greenhouse environments) may have affected results.

4.2 Durability of the coating and cladding

In the climate chamber neither the solar shade coating nor the thermal insulation coating on the PET Melinex 401 CW substrate degraded after 30 days exposure. After 14 months in the field the coating….

In the greenhouses the uncoated PET Melinex 401 CW degraded, and the internally thermal insulation coated PET. This was probably due to the intense UV exposure making

the substrate brittle and high winds which ensured the substrate ripped. Both the reference greenhouse and the thermal insulation coated greenhouse failed in this way. For the solar shade coated greenhouse the coating was on the exterior of the greenhouse thus the coating protected the PET Melinex, blocking the UV portion of the spectra. It should be noted that it was the substrate and not the coating that failed, indeed the coating can be used to UV-protect the substrate.

The coating can be undertaken on other substrate must notably on ETFE. LDPE is difficult to coat currently due to hardening temperatures and time of the current lacquer used.

5. Conclusion

The paper presents the design, conceptualization, and first-time testing methodology of sputtered dielectric-Ag-dielectric thin film layer and lacquer coated PET greenhouse cladded greenhouses. The aim was to test two specified T_{PAR} filters which are spectrally selective and thus block as much T_{SOL} for a given T_{PAR}. The effects of these spectrally selective coatings were examined on the greenhouse environment and the crop growth inside. The conclusion was during the daytime the coated greenhouses were cooler and more humid, scaling with the T_{SOL} of the greenhouse cladding. The reduced DLI, however, reduced the growth of the lettuce crop in both spring and summer crops. The cooler temperature and reduced PPFD levels below the photosynthetic saturation point, however, lead to no crop loss of the lettuces in the summer crop in the solar shade greenhouse and only 15 % crop loss compared to 33 % for the reference.

The coated PET was durable for 30 days in a climate chamber. UV from the sunlight degraded the PET. When the coating was placed on the exterior of the PET due to low UV transmittance of the coating the PET was protected. Spectrally after 14 months in the field the coating degraded by ###.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Figure S1: title; Table S1: title; Video S1: title.

Author Contributions: Conceptualization, funding acquisition and funding C. Hildebrandt and Y. Katircioglu , analysis, investigation, writing S.E. Gledhill.; data collection and analysis in the greenhouse B. Dur and B. Taeb (Plant Analysis with AI: Developing Software for Image Processing and Growth Comparison of Plants). All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

References must be numbered in order of appearance in the text (including citations in tables and legends) and listed individually at the end of the manuscript. We recommend preparing the references with a bibliography software package, such as EndNote, ReferenceManager or Zotero to avoid typing mistakes and duplicated references. Include the digital object identifier (DOI) for all references where available.

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1. Author 1, A.B.; Author 2, C.D. Title of the article. *Abbreviated Journal Name* **Year**, *Volume*, page range.
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