doi: 10.17221/93/2015-HORTSCI

Morphogenesis and productivity of *Cucumis sativus* L. hybrids under the thermic polyethylene films modified by coating of metals by magnetron sputtering

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Abstract

Minich A.S., Minich I.B., Chursina N.L., Ivanitckiy A.E., Butsenko E.S., Rozhdestvenskiy E.A. (2016): **Morphogenesis and productivity of *Cucumis sativus* L. hybrids under the thermic polyethylene films modified by coating of metals by magnetron sputtering**. Hort. Sci. (Prague), 43: 59–66.

The results of the investigation of morphogenesis and productivity characteristics of *Cucumis sativus* parthenocarpic hybrids Marinda and Kurazh in ontogenesis in greenhouses under the thermic films are presented. The thermic films have IR- and UV-shielding properties at the expense of coating with nanoparticles of copper compounds (film TF1) and compounds of silver and copper (film TF2) on the surface of films by magnetron sputtering. It is shown that thermic films contributed to levelling of day and night temperatures. The use of the film TF1 favoured seeds germination, activation of plant growth and development, shortening of period of the fruiting beginning and increase in productivity of hybrid Marinda by 13% and hybrid Kurazh by 35%. The use of the film TF2 led to inhibition of growth processes of both hybrids and decrease in their productivity.

Keywords: *Cucumis sativus* L.; growth and development; crop; modified polyethylene films; greenhouses

At present in the world economy great attention is paid to development of agriculture the main orientation of which is to maximize utilization of agricultural crops resources with shorter period of getting a crop (Ekebafe et al. 2011). In protected cultivation particular reference is made to the important role of usage of polymeric materials to this purpose, i.e. specifically modified polyethylene films (Arboli 2000; Laverde 2002; Brown 2004; Espí et al. 2006; Minich et al. 2010; Max et al. 2012). Light and temperature are two most important environmental parameters that determine the climate of the greenhouse and depend on the type of used covering material and their properties (Semida et al. 2013). Therefore, modifications of film are intended to change their transparency, which leads to improvement of microclimate in the greenhouses and increase in plant productivity (Brown 2004; Max et al. 2012).

One of the modifications is photoselective polyethylene film with thermic properties opaque to the IR radiation (thermic film). The advantage of these films is formation of favourable microclimate in the greenhouses due to control and regulation of heat (Espí et al. 2000). During daytime with a maximum of IR radiation in the solar radiation, thermic films contribute to a decrease of temperature.

doi: 10.17221/93/2015-HORTSCI

At night, with a decrease of air temperature films reduce heat losses emitted by heated soil and plants of greenhouses during the day (Espí et al. 2006; Semida et al. 2013). The absence of sharp changes in air temperature in greenhouses in daytime and at night enables to reduce the risk of overheating of plants or their destruction by frost (in the greenhouses with solar heating). This contributes to the intensification of plants vegetative development and getting of earlier and great harvests (Marcelis, Hofmaneijer 1993; Espí et al. 2006; Del Amor et al. 2008; Ekebafe et al. 2011).

The research workers of the Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences (Tomsk, Russia) have developed two thermic polyethylene films of original composition. Films are produced by deposition of coatings of the metal layers of subnanomicron thickness (subnanometer thickness) based on copper (TF1) and silver (TF2) at the films surface by magnetron sputtering (Zakharov et al. 2012).

The objective of this work was to investigate the morphogenesis and productivity characteristics of *Cucumis sativus* hybrids F_1 Marinda and Kurazh in protected cultivation under the thermic films TF1 and TF2.

MATERIAL AND METHODS

Greenhouses facilities and plant material. The experiment was carried out during 2012–2013 at the agrobiological station of the Tomsk State Pedagogical University (56°28.493'N, 84°58.673'E and 159.8 m altitude) in three tunnel greenhouses, each measuring 3.0 × 6.0 m, height 2.7 m. In the capacity of control the greenhouse was covered with light-stabilized low density polyethylene (LDPE) film thickness of 120 μm. The experimental greenhouses were covered with films TF1 and TF2, produced by deposition of coating of metal compounds particles at the surface of the control film. The choice of the experimental greenhouses to cover with film was random. Heating inside the greenhouses was accomplished by sunlight without additional heating.

The objects of the research were plants of two *Cucumis sativus* L. parthenocarpic hybrids F_1 Marinda and Kurazh. The growing seed method was used. Stocking density was 3 plants/m^2. Watering was carried out with tap water by the method of drip irrigation.

Greenhouse climate and film spectral properties. Air and soil temperature in each greenhouse and outside air temperature were measured by data logger in automatic performance using temperature sensors DS18S20 (Maxim integrated, San Jose, USA). The soil temperature was determined as the average value of the upper layer temperatures (to 3 cm).

The transmission of IR radiation by films was estimated on the basis of IR spectra using the IR-Fourier spectrometer Nicolet 6700 (Thermo Scientific, Waltham, USA) over the range 400–3,000 cm^{-1}.

The spectral transmission of films in the range of PAR, UV-A and UV-B radiation was calculated from data obtained using spectrophotometer AvaSpec-2048FT-2-SPU (Avantes, Apeldoorn, The Netherlands) (Raida et al. 2003).

Growth analysis, measurement of ion-cation composition of fruits. The phenological stages of plants development were recorded over a vegetation period. In ontogenesis counting of leaf number, measuring of main stem length and leaf surface area were conducted without plant damage. The productivity of plants was determined by measuring the weight of all picked fruits at a given point in time and at the end of vegetation in terms of 1 kg/m^2. The picking of fruits was performed concurrently in three greenhouses as commercial maturity stage occurred.

Ion-cationic composition of cucumber fruits was determined using the system of capillary electrophoresis Kapel 105 (LLC «Lymeks», St. Petersburg, Russia). To this purpose several fruits in the stage of commercial maturity stage were taken from each plant in a random way (Komarova, Kamentsev 2006).

Statistical analysis. Statistical treatment of the experimental results was performed using the program Microsoft Excel with a confidence interval of 0.95 (significance level – 0.05, reliability level – 95%). The tables and figures show the arithmetic means with two-sided confidence interval. The Tukey´s HSD Test (OriginPro 9.0 Northampton, USA software) was used for comparisons of the measurements.

RESULTS AND DISCUSSION

Greenhouse Microclimate

The results of investigation have shown that everyday transmission of solar radiation and tempera-

doi: 10.17221/93/2015-HORTSCI

Table 1. Photophysical properties of non-thermic film (control) and thermic films TF1 and TF2 (material – LDPE, thickness – 120 μm)

Region of the spectrum (nm)	Light transmission (%)		
	control	TF1	TF2
290–330 (UV-B)	54.2 ± 4.8	0.3 ± 0.1	28.6 ± 1.0
320–400 (UV-A)	62.4 ± 3.6	12.9 ± 0.8	35.0 ± 3.5
380–710 (PAR)	76.6 ± 1.8	58.4 ± 0.6	55.2 ± 0.8
430–500 (blue)	45.1 ± 1.5	16.9 ± 1.2	36.0 ± 2.2
750–1400 (NIR, IR-A)	81.1 ± 1.6	36.5 ± 6.7	12.3 ± 4.6
1,400–3,000 (SWIR, IR-B)	80.5 ± 6.0	41.2 ± 6.1	14.6 ± 5.4

values within the same row have significant differences according to the HSD Tukey's test ($P < 0.05$)

ture were heavily dependent on the film modification (Table 1).

The non-thermic polyethylene film has a higher permeability in all studied spectral regions in comparison with thermic films. Deposition of nanoparticles of metal compounds at the surface of the films TF1 and TF2 results in a significant decrease in optical transmission not only in IR region, but also in the regions of UV radiation and PAR. TF1 film practically does not transmit UV-B radiation, and transmits 4.8 times less UV-A radiation and 1.3 times less PAR as compared with the control film. TF2 film transmits 1.8 times less UV-A radiation, 1.9 times less UV-B radiation, and 1.4 times less PAR than the non-thermic film. Relative to the control film, TF1 transmits nearly 2.0 times less IR radiation (both near infrared and medium infrared region) and TF2 transmits 5.5 times less IR-B and 6.6 times less IR-A radiation.

The light transmission of thermic films TF1 and TF2 also strongly varies among themselves, which is determined by different composition of particles of metal compounds-modifying agents of films. The film TF2 transmits to 29% of UV-B radiation and the film TF1 is practically not transparent to radiation of this spectral region. The film TF2 transmits nearly three times as much UV-A radiation and IR radiation, but less by 3% PAR as compared to TF1 film.

Thus, the film TF1 is virtually non-transparent to UV radiation with a significant reduction of transparency in the region of PAR and IR radiation in comparison with the non-thermic film. The decrease in TF2 film light transmission is also significant, but relative to film TF1 it has a different character in the region of IR radiation and UV radiation. The film TF2 has a minimum transparency to IR radiation, lower permeability for PAR (both relative to the control and TF1 film). It is less transparent to UV radiation than the control film, but it is more transparent in comparison with the film TF1.

The significant differences of transparency of solar radiation by the films, including IR radiation have resulted in changes of air temperature and temperature of upper layers of soil inside the greenhouses. The measurements of temperature showed that in the daytime in the greenhouse covered by the film TF1 air temperature and temperature of the soil were lower by 0.23°C and 1.73°C, respectively, and at night they were higher by 1.63°C and 1.93°C, respectively in comparison with the control greenhouse. Such result is explained by the ability of the thermic film TF1 to transmit 2 times less heat rays as compared to the non-thermic film, that in the daytime leads to decrease in temperature inside the greenhouse, and at night results in reduce of heat losses.

In the greenhouse, under TF2 film during the day the soil temperature was lower by 0.27°C compared to the control, and it was lower by 1.46°C, than in the greenhouse under the film TF1. This is due to the fact that the level of IR radiation does not enable to heat the soil because of the thermic film TF2 low transparency to the direct thermal rays. In the sequel, when forming of plants vegetation mass, a minor share of heat radiation transmitted through the thermic film TF2 is absorbed generally by plants leaves and dispersed in the form of heat. This determines the increase in air temperature by 0.43°C in the greenhouse under the film TF2 in comparison with the control and by 0.66°C as compared to the greenhouse under the film TF1.

At night in the greenhouse under the film TF2 air and soil temperatures were higher by 0.96°C and 0.53°C than under the control film, respectively,

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Table 2. Phenological stages of *Cucumis sativus* L. hybrids Marinda and Kurazh in the greenhouses under non-thermic polyethylene film (control) and thermic polyethylene films TF1 and TF2

Phenological phases of plants and farming practices		Time from sowing (days)					
		Kurazh			Marinda		
		control	TF1	TF2	control	TF1	TF2
Young growth	single	8	6	8	8	6	8
	mass	9	7	9	9	7	9
Disclosure of cotyledon	single	10	8	10	10	8	10
	mass	11	9	11	11	9	11
Formation of true leaves							
First	single	16	11	14	16	11	14
	mass	17	13	16	17	13	16
Second	single	18	16	18	18	16	18
	mass	20	17	20	20	17	20
Third	single	22	21	22	22	21	22
	mass	25	22	23	25	22	23
Fourth	single	24	22	24	24	23	24
	mass	27	24	27	27	25	27
Fifth	single	27	25	27	27	25	27
	mass	29	27	28	29	28	28
Tenth	single	36	32	36	38	34	37
	mass	37	33	37	39	36	39
Formation of lateral shoots	single	29	28	29	31	29	29
	mass	31	30	32	32	30	32
Formation of ovaries and flowers	single	33	29	32	33	31	32
	mass	34	30	33	34	32	33
Plants habit formation		47					
Fruits pickles	single	46	44	46	46	43	46
	mass	47–50	45	47	47–48	44	48–49
Fruits gherkins	single	50	45	47	49	46	50
	mass	51	46–47	49–50	50	47–48	51
Young fruits	single	51	47	50	51	48	51
	mass	52	48	51	52	49	52
Fruits in commercial maturity	single	52	49	52	53	49	53
	mass	53	50	53	54	50	54
First fruit harvest		53	50	53	54	50	53
Mass fruiting		57	55	57	57	55	57
Elimination of plants		134					

but they were lower by 0.66°C and 1.4°C, respectively, as compared to the greenhouse under the film TF1. The reason was low level of transparency of the thermic film TF2 in the range of IR radiation. Hereupon, in the daytime the soil surface was heated least of all, and at night the soil heat was better retained.

Plant growth and development

At the start of plants vegetation period, meteorological conditions on the outside of the greenhouses were unfavourable, accompanied by rapid air temperature difference in the daytime and at night. The use of the films TF1 and TF2 contributed to

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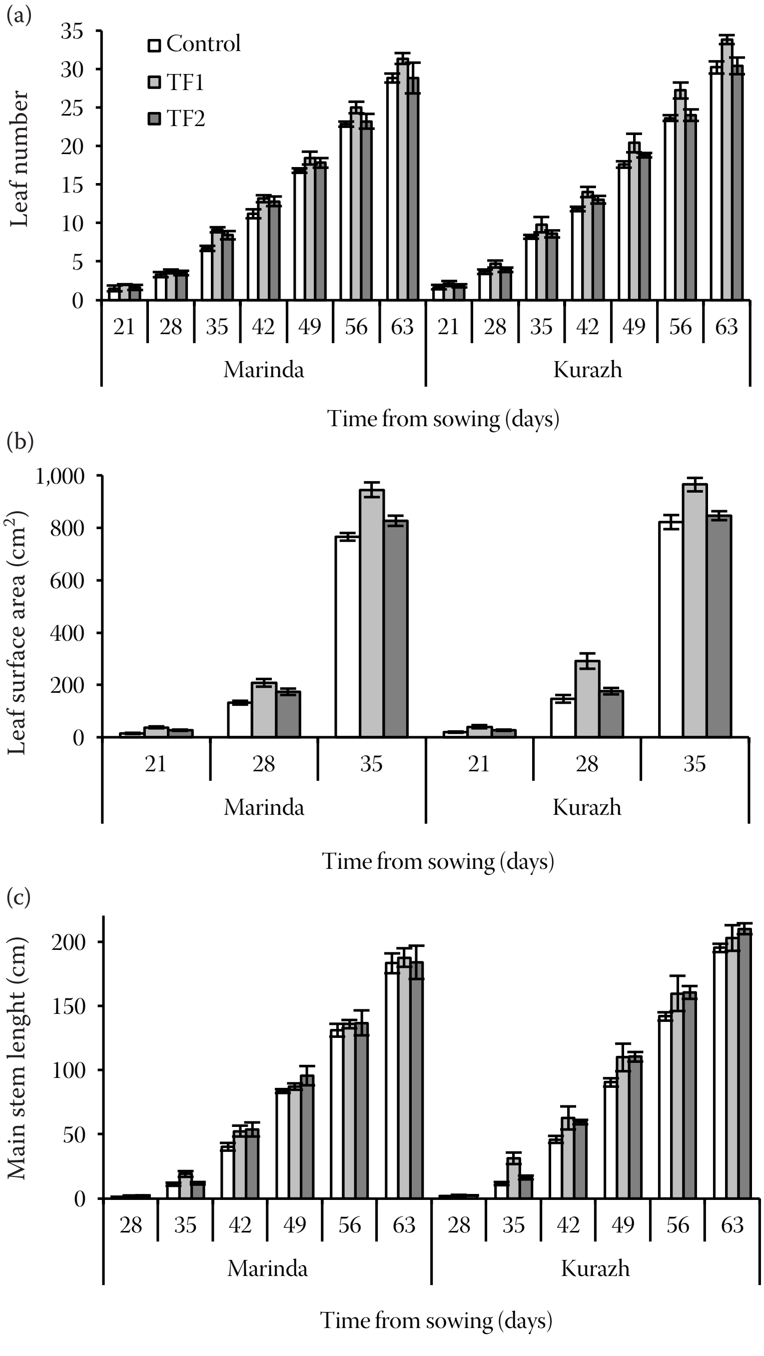

Fig. 1. The dynamics of (a) leaf number of main stem, (b) leaf surface and (c) main stem length of *Cucumis sativus* L. hybrids Marinda and Kurazh in the greenhouses under non-thermic polyethylene film (control) and thermic polyethylene films TF1 and TF2

the formation of the microclimate inside the greenhouse, which differed from the control greenhouse, that resulted in changes of growth and development of investigated *Cucumis sativus* hybrids.

The film TF1 contributed to form more favourable microclimate in the greenhouse, compared to the control at the expense of lower heat losses, that enabled to reduce wide fluctuations in day and night temperatures. Especially it had a favourable effect in the initial vegetation period when night temperatures were negative (to 1.8°C below zero). More favourable conditions in the greenhouse under the film TF1 contributed to the seedling emergence of both hybrids 2 days earlier, and further to faster plants growth and development, than in the control greenhouse (Table 2).

It was noted that both hybrids under the film TF1 had active development of the main stem, accompanied by intense formation of layers and development of assimilating surface (both due to formation of more leaf number and increase in leaf size) compared to the control plants (Fig. 1). In most cases, for both hybrids in comparison of TF1/control significant differences were observed ($P < 0.05$). For both

doi: 10.17221/93/2015-HORTSCI

Table 3. Productivity of *Cucumis sativus* L. hybrids Marinda and Courage in the greenhouses under non-thermic polyethylene film (control) and thermic polyethylene films TF1 and TF2

Hybrid cucumber	Greenhouses	Productivity (kg/m^2) (% from control)					No. of fruits pcs/m^2	Average fruit weight (g)
		50 days	71 days	92 days	112 days	133 days		
Marinda	control	0.00^a	6.65^a	16.01^a	23.80^a	25.49^a	366.00^a	69.65^a
	TF1	0.28^b	7.66^b	18.53^b	26.53^b	28.97^b	364.09^a	79.56^b
		–	(115.28)	(115.76)	(111.46)	(113.62)	(96.22)	(114.23)
	TF2	0.00^a	5.14^c	11.67^c	16.74^c	18.81^c	237.00^b	79.37^b
		–	(77.28)	(72.68)	(70.31)	(73.79)	(62.64)	(113.96)
Courage	control	0.00^A	6.64^A	14.46^A	20.54^A	22.41^A	282.00^A	79.46^A
	TF1	0.48^B	9.93^B	20.06^B	27.93^B	30.40^B	372.90^B	81.52^A
		–	(149.55)	(138.75)	(135.94)	(135.69)	(132.23)	(102.59)
	TF2	0.06^A	6.11^A	13.85^A	18.84^C	20.68^A	240.69^C	85.93^B
		–	(92.00)	(95.78)	(91.69)	(92.31)	(85.35)	(108.14)

values within the same column marked with different letters (lowercase for hybrid Marinda, capital for the hybrid Courage), have significant differences according to the HSD Tukey's test (P <0.05)

hybrids in comparison TF2/control and TF2/TF1, significant differences were not always observed.

Such results may be connected with the ability of the film TF1 both to retain heat (Espí et al. 2000) and significantly reduce the intensity of UV-A radiation and almost block transmittance of UV-B radiation into the greenhouse (Krizek et al. 1997). It has been shown that the increase in level of UV-B and UV-A radiation in the spectral range has a negative photobiological effect on plant growth and development (Teramura, Sullivan 1991; Krizek et al. 1997; Sicora et al. 2006; Tsormpatsidis et al. 2010), including *Cucumis sativus*, which has an extraordinary sensitivity to levels of UV-A and UV-B radiation (Krizek et al. 1997).

It was observed that hybrids under the film TF2 had identical alternation date of phenological stages over plants vegetation period compared to the control (Table 2). However, the intensity of growth and vegetative mass development of plants significantly differed. In the beginning of plants vegetation period both hybrids had more intensive leaf surface development due to the decrease in unfavourable fluctuations in temperature out of the greenhouses by the film TF2 because of the ability of this film to block maximum of IR radiation (Fig. 1b). The increase in the leaf surface area of plants under film TF2 in comparison with the control was connected with only blade size changes, but not leaf number (Fig. 1a). Further, the differences in development of cucumber hybrids were probably connected with differences in spectral composition (quality) of radiation under the control and TF2 films (Caldwell et al. 1994), in the first place in the region of PAR.

Table 4. The concentration of some anions and cations in the fruit of *Cucumis sativus* L. hybrids Marinda and Kurazh in the greenhouses under non-thermic polyethylene film (control) and thermic polyethylene films TF1 and TF2

Hybrid cucumber	Greenhouses	Ion concentration in the fruit (mg/kg)				
		potassium	magnesium	calcium	nitrate	phosphate
Marinda	control	784.8 ± 13.2^a	27.7 ± 0.3^a	116.5 ± 1.7^a	47.9 ± 0.8^a	1,132.0 ± 84.2^a
	TF1	740.2 ± 7.2^b	26.0 ± 0.2^b	125.2 ± 2.5^b	37.2 ± 0.2^b	839.7 ± 54.1^b
	TF2	802.8 ± 15.1^a	27.8 ± 0.3^a	101.8 ± 1.9^c	36.4 ± 0.2^c	2,222.0 ± 102.7^c
Courage	control	765.3 ± 12.3^A	27.4 ± 0.3^A	124.4 ± 2.0^A	27.9 ± 0.3^A	1,273.0 ± 51.2^A
	TF1	770.2 ± 9.6^A	28.7 ± 0.4^B	144.7 ± 3.1^B	80.0 ± 1.2^B	1,168.0 ± 45.1^A
	TF2	762.8 ± 11.4^A	27.6 ± 0.2^A	119.5 ± 1.8^C	traces^C	2,547.0 ± 109.8^B

values within the same column marked with different letters (lowercase for hybrid Marinda, capital for the hybrid Courage), have significant differences according to the HSD Tukey's test (P < 0.05)

doi: 10.17221/93/2015-HORTSCI

Plant productivity

The intensive growth and development of plants vegetative mass in the greenhouse under the thermic film TF1 contributed to promotion of reproductive organ formation (Table 2), that hereafter led to an increase in plants productivity compared to the control (Table 3).

The first fruits of both cucumber hybrids were picked in the greenhouse under the thermic film TF1 on 50th day of plants vegetation. In the control greenhouse yield of cucumber was started 3 days later. By the time of culture elimination the increase of hybrid Marinda yield under the film TF1 relative to the control was 13.6%, the increase of the hybrid Kurazh yield was 35.7%.

The increase in productivity of hybrid Marinda relative to the control under the film TF1 was due to fruit weight gain; that of hybrid Kurazh was due to an increase in the number of fruits.

The use of the film TF2 to cover greenhouses led to a decrease in the yield of cucumber hybrid Marind' by 26.2%, and hybrid Kurazh by 7.7% compared to the non-thermic film. This indicates that the difference in the yield of experimental and control plants is determined not only by microclimate formed by the films, but also by cucumber hybrid.

Biochemical studies of fruits

The results of investigation have shown that the sugar content and the dynamics of their accumulation in fruits of experimental and control plants of both hybrids were not significantly different over the fruiting. It can be supposed that the greenhouse microclimate formed by the thermic films due to the change of thermal and light conditions does not sufficiently influence the biochemical processes of sugar synthesis and accumulation in the fruits.

The content of most studied cations and anions in the fruits of both hybrids experimental and control plants was not significantly changed. An exception was the level of cations of magnesium, potassium, calcium, nitrates, and phosphates accumulation which was conjugated with the microclimate in the greenhouses, hybrid specifics and plant yield (Table 4).

The increase in yield of both hybrids grown under the film TF1 relative to control was accompanied by accumulation of calcium cations and decrease in phosphate in the fruits. On the contrary, the decrease in cucumber yield under the film TF2 was associated with reduction of calcium ions accumulation and an increase in phosphate anions level in the fruits.

Nitrate accumulation in the fruit depends both on the greenhouse microclimate and cucumber hybrid. Hybrid Marinda accumulated less nitrate ions under both thermic films in comparison with the control. Fruits of hybrid Kurazh picked in the greenhouse under the film TF1 had nitrate level 2.9 times as much relative to the control, and only traces of this anion were found in the fruits under the film TF2.

The reduction of potassium cations level was noted in hybrid Marinda fruits grown in the greenhouse TF1, but was not determined in the fruits from the greenhouse TF2. Significant changes in the content of potassium cation in hybrid Kurazh fruits were not revealed. The accumulation of magnesium cations in the fruits of both hybrids in the control greenhouses and greenhouse TF2 was practically identical, but differed from that in fruits of greenhouse TF1. The hybrid Kurazh fruits had the increased level of magnesium ions relative to the control, and the hybrid Marinda fruits, on the contrary, had the decreased level. Such result indicates that accumulation of potassium and magnesium ions in fruits is caused only by cucumber hybrid.

CONCLUSION

The use of the thermic polyethylene film TF1 modified by deposition of nanoparticles of metal based on copper compounds at the film surface as greenhouse coverings is effective in cultivation of *Cucumis sativus* hybrids Kurazh and Marinda. In the climatic conditions of midland (including Western Siberia) the use of the thermic film TF1 contributes to formation of favourable microclimate in the greenhouse to multiplication of natural soil microflora and enhancement of plant photosynthesis. This makes it possible to promote cucumber growth and development, increase the yield by 13–35%. It is necessary to take into consideration the dependence of physiological responses of cucumber hybrid, which is necessary for obtaining the maximum yield.

The application of the thermic polyethylene film TF2, modified by deposition of nanoparticles of metal based on copper and silver compounds as

doi: 10.17221/93/2015-HORTSCI

greenhouse coverings reduces the yield of hybrids Marinda and Kurazh. This is accompanied by inhibition of photosynthesis and growth processes and connected with photophysical peculiar properties of the film TF2 – almost opaque to IR radiation and changes in the ratio of PAR and UV towards the increasing of UV component.

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Received for publication April 28, 2015
Accepted after correction November 19, 2015

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