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RESEARCH ARTICLE

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Influence of spunbond degradable floating row covers on microclimate modification and yield of field cucumber

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Abstract

In recent years, there has been an increase in interest in innovative plastic materials for use in horticulture. The aim of this study was to examine the effects of (bio)degradable floating covers (polylactide nonwoven – PLA, and oxo-degradable polypropylene nonwoven with 0.1% iron stearate – PP photo, both 20 g/m^2) compared to the conventional PP nonwoven (control, 20 g/m^2) on microclimate modification and yield of field-grown cucumber. The greatest PAR transmittance was recorded for the control nonwoven (83%), while the degradable materials transmitted 8% less radiation. Maximum soil surface temperatures were the highest under the PLA nonwoven, but minimum temperatures – under the oxo-degradable fleece. The mean temperature under the oxo-degradable material was comparable to the control, while PLA increased the soil temperature by 1.8 °C, on average. The yield from cucumber plants covered with degradable materials was similar to that from the plants cultivated under the conventional oil-based nonwoven fleece. There were no significant changes in dry weight and soluble sugar content in cucumber fruits in 2013; however, the degradable nonwovens decreased these parameters in 2012. The lifespan of the oxo-degradable nonwoven was limited only to one growing season, thus the durability of the polymer must be increased. Polylactide nonwoven can be a sustainable ecological alternative to conventional non-degradable PP covers.

Additional keywords: *Cucumis sativus* L.; degradable polymers; direct covers; iron stearate photoactivator; polylactide.

Abbreviations used: DAT (days after transplanting); PAR (photosynthetically active radiation); PLA (polylactide nonwoven); PP (polypropylene nonwoven); PP-photo (oxo-degradable polypropylene nonwoven with 0.1% iron stearate).

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Introduction

Plastic direct covers have been applied to an area of about 60 thousand hectares of commercial horticultural land in European countries at the beginning of the 21st century (Scarascia-Mugnozza *et al.*, 2011). Non-degradable polypropylene spunbonded nonwovens are primarily intended for this purpose. Lightweight nonwoven fleeces, weighing 17-23 g/m^2, are used for the protected cultivation of field vegetables: leafy crops, brassicas and cucurbits in the spring season in moderate climate conditions (Siwek & Libik, 2012), while heavier nonwovens, weighing 50-100 g/m^2, are used in winter to cover alliaceous vegetables (Siwek *et al.*, 2013b). Numerous studies have described the results of applying direct covers, mainly non-degradable nonwoven PP (polypropylene) and PE (polyethylene) films, to protect vegetable crops from cold and ground frosts, and to achieve a greater marketable yield (Olle & Bender, 2010). Floating oil-based row covers have been reported to significantly alter air and soil temperatures, allowing temperatures to be higher underneath than on the outside, thereby affecting plant growth through changes in leaf characteristics, biomass accumulation and relative growth rate (Soltani *et al.*, 1995; Gimenez *et al.*, 2002). The microclimate modifications induced by direct covering have been studied, inter alia, in the cultivation of muskmelon (Ibarra *et al.*, 2001), summer squash (Gordon *et al.*, 2008) and cucumber (Zawiska & Siwek, 2014). The beneficial effect of direct covers, mainly standard nonwoven covers, on the yield of economically important vegetable species, *e.g.* cucumbers (Ibarra-Jiménez *et al.*, 2004; Zawiska & Siwek, 2014) and other cucurbits (Ibarra *et al.*, 2001; Kołota & Adamczewska-Sowińska, 2011; Dantas *et al.*, 2013) has been demonstrated many times. Several other vegetable crops exhibit a positive increase in early and total yield with the application of floating row covers, which was described by Olle & Bender (2010) in their review.

There have only been a few studies concerning possible application of floating direct covers made from oxo- or biodegradable polymers. Oxo-degradable materials are enriched with inorganic metal salts, like iron carboxylates (for example iron stearate), used as prodegradants, and they are degraded into small fragments in the process initiated by oxygen and accelerated by solar radiation and/or temperature (Kasirajan & Ngouajio, 2012). Degradation of these products under laboratory conditions has been proven (Briassoulis & Degli Innocenti, 2017), while the biodegradability of such materials in the soil, even if photodegraded to very small fragments, is still disputed (Kyrikou & Briassoulis, 2007; Singh & Sharma, 2008). Only very few articles have reported a considerable percentage of biodegradation of oxo-degradable plastics (Jakubowicz *et al*, 2011). Polylactide (PLA) is a sustainable alternative to petrochemical-derived polymers, since the lactides can be produced on a mass scale by microbial fermentation of agricultural by-products (John *et al.*, 2006), such as corn, wheat, barley, cassava, potato, rice, and sugar cane, rich in carbohydrates (Briassoulis, 2004). PLA-based polymers are completely biodegradable (Gutowska *et al.*, 2014), with properties comparable to those of some fossil oil-based plastics used in horticulture.

Biodegradable nonwoven fabric made with the melt-blown technology for covering overwintering leeks had a positive effect on the plants by maintaining a higher temperature and providing a windbreak (Siwek *et al.*, 2013a). The authors used Bionolle nonwoven made of polybutylene succinate, which is biodegradable, a thermoplastic aliphatic polyester obtained by the reaction of 1,4-butandiol with aliphatic di-carboxylic acids such as succinic and adypic acid (Lichocik *et al.*, 2012); So called IBWCH (Polish abbreviation of Institute of Biopolymers and Chemical Fibres, Łódź, Poland) cover was made from aliphatic-aromatic copolyesters containing a 57-60% tri-component aliphatic portion (copolymers of butylene glycol and adypic, succinic, glutaric acids and terephtalic acid) (Twarowska-Schmidt *et al.*, 2016). During winter, the mean soil temperature at 10 cm under the biodegradable cover (Bionolle, basis weight 59 and 100 g/m^2) was about 1 °C higher than at the same depth in uncovered soil. In an experiment with overwintering onion, differences in soil temperature among biodegradable nonwovens (Bionolle 100 g/m^2; IBWCH 75 g/m^2) and the standard PP nonwoven (50-60 g/m^2) were not significant (Siwek *et al.*, 2013b), as well as in the cultivation of spring butterhead lettuce, where soil temperature was comparable among the tested covers (PP 20 g/m^2, Bionolle 100 g/m^2 and IBWCH 75 g/m^2) and higher than in the non-covered soil (Siwek *et al.*, 2012). Based on those data, it can be concluded that the tested degradable covers showed similar effects on temperature and may promote faster and more balanced growth of plants. A key question is whether such degradable covers positively affect the yield of crops. As it turned out, the degradable covers in the above-cited studies did not always increase the yield. The most repeatable and positive impact on yield was obtained in the case of leeks produced under Bionolle 59 and 100 g/m^2 (Siwek *et al.*, 2013a), and in field cucumber (Zawiska & Siwek, 2014) covered with IBWCH 75 g/m^2 and PLA 54 g/m^2.

The major problem associated with the use of non-biodegradable covers is management and disposal of large amounts of plastic waste, as the removal of these plastic residues from the field is costly and time-consuming (Gutowska *et al.*, 2014; Briassoulis *et al.*, 2015). A common practice employed by farmers is to incorporate them into the soil or even burn them in the field, which creates a serious risk of environmental pollution (Kasirajan & Ngouajio, 2012). For this reason, new polymer materials that are designed to degrade have been developed over past years (Martín-Closas *et al.*, 2017). The aim of the present research was to assess the suitability of spun-bonded PLA nonwoven and oxo-degradable PP nonwoven supplemented with iron stearate prodegradant for use in horticultural production. Due to the different properties of these materials, we hypothetically assume their different effects on microclimatic conditions and the yield of cucumber, which is a plant sensitive to environmental changes often occurring in the field. Comparison of degradable covers with a commercial PP nonwoven will provide additional information about the usability of innovative materials in vegetable crop production.

Material and methods

Site description, experimental design, and plant production

The experiment was carried out at the Vegetable Experimental Station of the University of Agriculture in Krakow, Poland (50º04′N, 19º51′E). The soil type was a Fluvic Cambisol, with respect to the classification of the World Reference Base for Soil Resources. The climate of the experimental station, located in southern Poland, is humid continental (Dfb) according to Köppen's classification (Kottek *et al.*, 2006).

Two degradable nonwovens made by the Institute of Biopolymers and Chemical Fibres (Łódź, Poland) were used: PP photo – polypropylene oxo-degradable nonwoven (20 g/m^2) with an addition of 0.1% iron stearate activator, and biodegradable PLA (polylactide nonwoven, 20 g/m^2). These materials were chosen because they vary in chemical nature and represent resources of synthetic and organic origin. Plants were also covered with standard non-degradable polypropylene nonwoven (20 g/m^2) to serve as the control. The experimental design was a randomized complete block design; each treatment was replicated 4 times and consisted of 60 plants. In 2013, due to the fast degradation of PP photo, only the PLA and PP 20 g/m^2 nonwovens were re-used.

The experiment involved the parthenocarpic cucumber Barvina F_1 (Nunhems Poland), transplanted to the field on 21 May 2012 and 16 May 2013 at a spacing of 200 × 25 cm. The covering period lasted 25 and 30 days from transplanting in the following years. Cultivation procedures (weeding, fertilization, drip irrigation and plant protection) were performed according to the standard recommendations for the species.

Characteristics of the covering materials

Oxo-degradable nonwoven was formed from polypropylene Moplen HP462 (Basell Orlen Polyolefins, Płock, Poland). PLA nonwoven was manufactured from polylactide 6251D (Nature Works LLC, Minnetonka, USA) dedicated to the spunbonded technology. Both nonwovens were formed on a laboratory line designed and built by the Polmatex-Cenaro Central Research and Development Centre of Textile Machines in Łódź (Poland). A description of the spunbonded technology and detailed characteristics of the nonwoven materials used in the present experiment had been previously published by Sulak *et al.* (2012) and Puchalski *et al.* (2013).

The determination of the spectral properties of the nonwovens was carried out using a LI-1800-12S integrating sphere (LI-COR, Lincoln, USA) designed for collecting optical radiation that has been reflected or transmitted through a sample material (Schettini & Vox, 2012). Three samples per each nonwoven were used. Measurements were made in the wavelength ranges of 400-700 nm (PAR – photosynthetically active radiation) and 700-1100 nm (NIR – near-infrared), with wavelength sampling intervals of 2 nm. The sphere was used with a LI-1800 portable spectroradiometer and LI-1800-10 Quartz Fiber Optic Probe. The source of radiation was a spectral halogen lamp of 3200 K. Spectral absorbance (A) was calculated from the formula: A = 100 – (R + T), where R is reflectance, and T is transmittance.

Microclimatic conditions

External air temperatures were recorded at hourly intervals by an S-THA-M017 sensor connected to a HOBO Weather Station (Onset Comp. Corp., USA), and the data were saved into the internal memory of the station. Then they were downloaded via HOBOware Pro 3.7.11 software to a computer and daily averages were calculated. A PAR sensor S-LIA-M003 has a measurement range of 0 to 2500 µmol/m^2·s over a wavelength range of 400-700 nm. The PAR sensor worked in the measurement averaging mode (logging interval: 1 hour, but the sampling interval was set to 10 minutes, thus each data point within an hour was the average of 6 measurements). PAR data were presented as averages for days; values below 3 µmol/m^2·s were omitted. The HOBO Weather Station was located in the middle of the experimental field.

The average air temperature in 2012 was slightly higher (19.1 °C) than that in 2013 (18.2 °C) over the period of the experiment (Fig. 1A, 1B). The corresponding values of the external air temperature, averaged for the plant covering period, were 16.3 and 15.0 °C. The highest and the lowest mean air temperatures in 2012 were equal to 26.2 and 12.0 °C, respectively (beginning of July and at the beginning of June). In the following year, the lowest values of air temperature were recorded at the end of May (9.8 °C), while the highest were at the end of the experiment (26.9 °C).

The averaged PAR in the period of the field experiment in 2012 was higher (650.9 µmol/m^2·s) than in 2013 (629.6 µmol/m^2·s), but these differences were small (Fig. 1C, 1D). During plant covering, the averaged PAR values, outside the covers, equalled to 602.3 and 537.1 µmol/m^2·s, respectively for 2012 and 2013. These data indicate lower availability of photosynthetic active radiation to the plants in the early stages of their growth.

The soil surface temperature was recorded in 2012 using HOBO U23-003 autonomous data loggers (Onset Comp. Corp., USA). The U23-003 is a waterproof logger with an internal temperature sensor (accuracy ± 0.21°C from 0° to 50°C). Probes were placed in the outer layer of the soil (2-3 cm) in the centre of

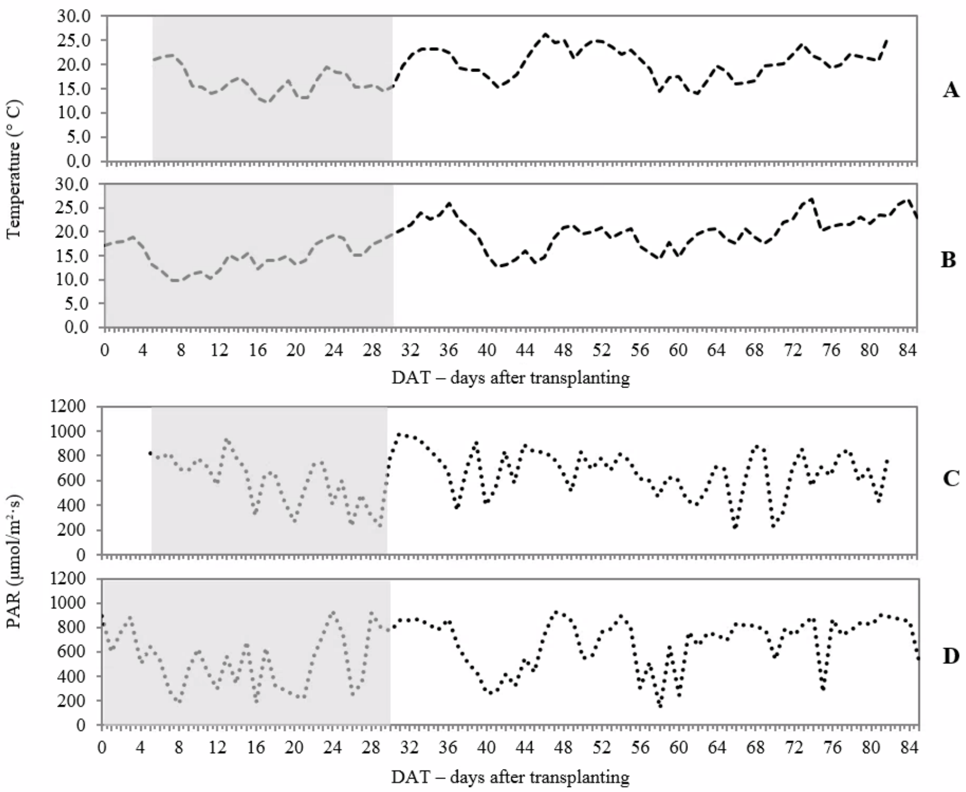

Figure 1. Daily average air temperature in the year 2012 (A) and 2013 (B) and daily average PAR (photosynthetically active radiation) in the year 2012 (C) and 2013 (D) at the experimental site. Shaded areas represent covering periods. All data represent values measured outside the covers. Transplanting: 21 May 2012 and 16 May 2013; final harvests: 10 August 2012 and 9 August 2013.

the plots covered with the particular nonwovens. The temperature was recorded hourly (624 measurements in total) in the logger internal memory and downloaded via the HOBOware Pro 3.7.11 software. The data were divided into several intervals for thermal distribution analysis: up to 15 °C; $15 \leq x<25$; $25 \leq x<35$; $35 \leq x<45$; and above 45 °C. Patterns of temperature changes under the covers during the experiment were presented as daily averages of 24 values for mean, maximum and minimum temperature. Average soil surface temperatures for the whole plant covering period were also calculated and presented.

Yield and fruit quality analysis

Harvests of cucumber fruits were conducted in the period from 18 June to 10 August 2012, and from 25 June to 9 August 2013. The marketable yield included healthy fruits, without disease symptoms and no mechanical or pest damage (PN-85/R-75359). The fruits were divided into three grades: pickling grade (8-10 cm in length), brining grade (10-15 cm) and salad grade (>15 cm). Slightly deformed fruits were also considered as marketable. The quality structure of marketable yield was calculated on the basis of the number of fruits harvested. The dynamics of cucumber yields were expressed as a percentage of all fruits belonging to the pickling, brining and salad grades in consecutive harvests in comparison to the final yield of these fruits. Cumulative percentage of the first 6 harvests (1/3 of all harvests) was presented. Cumulative yield plotted against time included all marketable cucumber fruits together with slightly deformed ones, which were also suitable for the market.

Chemical composition of the fruits

The dry weight and soluble sugar content of fresh cucumber fruits from the 3-5 harvests were evaluated in the laboratory. Dry weight was determined by drying a sample at 92-95 °C until a constant weight was obtained, and measuring using a Sartorius A120S balance (Sartorius AG, Göttingen, Germany). Soluble sugars were determined by the anthrone method (Yemm & Willis, 1954). For this analysis, plant material was mixed with 80% ethanol. After the addition of the anthrone reagent, the samples were placed in a water bath for 30 minutes (100 °C), cooled down to 20-22 °C, and the absorbance was measured at 625 nm using a Helios Beta spectrophotometer (Thermo Fisher Scientific Inc., Waltham, USA).

Statistical analysis

The results were statistically evaluated by one-way analysis of variance (ANOVA) with the use of the STATISTICA Version 12 package (StatSoft Inc., Tulsa, USA). Post hoc comparisons of yield and fruit chemical composition were conducted using Duncan's multiple range test (2012) or *t*-test (2013) to determine homogeneous groups at $p<0.05$. The presented data are means of 4 replications ± SD (standard deviation). Differences in soil surface temperature between experimental treatments were tested using the Kruskal-Wallis median test and Mann-Whitney U tests for pairwise comparisons at a significance level of 0.05.

Results and discussion

Spectral properties of the nonwovens used in the experiment

The degradable nonwovens used as direct covers were characterized by high reflectance (Table 1), especially PLA (24.2-25.2%). The reflectance of the standard PP nonwoven, used as the control, was more than twice as low as that of the degradable materials. The highest absorbance was noted for the standard PP nonwoven, while the PP oxo-degradable and PLA nonwovens absorbed around 11 times (in the range 400-700 nm) or 16 times (in the range 700-1100 nm) less radiation. The most important parameter for the covered plants – transmittance – reached higher values for the standard PP nonwoven (within both wavelength ranges), with transmission being around 8% lower for the oxo-degradable and PLA nonwovens.

Transmittance of the standard polypropylene nonwoven, tested in similar climatic conditions, can be more than 90% of external PAR radiation (Siwek, 2002). Moreno *et al.* (2005) observed a 13% reduction in the irradiance through a nonwoven polypropylene cover (17 g/m^2) with respect to the non-covered control. As reported by Gimenez *et al.* (2002), photosynthetic photon flux density (PPFD) under a spun-bonded row cover (17 g/m^2) can vary from 85 to 65%, depending on dust accumulation on the cover and water vapour condensation in the inner surface of the fabric. In recent years, prototypes of biodegradable nonwoven fabrics made by the melt-blown technique have been tested for their spectral properties. A nonwoven made from PLA (54 g/m^2), used in the experiment with cucumber plants as a floating row cover, showed PAR transmission at a level of 65.8% (Zawiska & Siwek, 2014), while PAR transmittance for a melt-blown polybutylene succinate (PBS) nonwoven (Bionolle 100 g/m^2) used in butterhead lettuce cultivation was equal to 67.6% (Siwek *et al.*, 2012). As a mechanical barrier, row covers reduce the amount of solar radiation reaching the plants. The permeability to solar radiation, as indicated above, depends to a large degree on the structure of the polymer materials and environmental conditions. In the present experiment, there was a small (8%) reduction in the amount of PAR that the plants covered with the degradable nonwovens received, in comparison to the standard PP fleece. This reduction in PAR seems to be too small to lead to severe disturbances in the photosynthetic process of cucumber plants cultivated in the season of relatively high irradiance; however, some impact on the process can be expected. Several investigations have pointed out the more vigorous growth of plants under row covers (Olle & Bender, 2010) in comparison to a non-covered control. This could be the result of greater leaf area, increased air and soil temperatures, and improved light distribution under row covers (Moreno *et al.*, 2005). We may conclude that some reduction in PAR transmittance through the nonwovens (both the non-degradable and degradable floating covers used in the experiment, with slight differences among them) could have been compensated for by higher temperatures in the immediate environment of the plants in comparison to the open field.

Table 1. Spectral properties of the nonwovens used for covering plants – reflectance, absorbance and transmittance (% ± SD – standard deviation).

Nonwoven type[1]	Reflectance		Absorbance		Transmittance	
	400-700 nm	700-1100 nm	400-700 nm	700-1100 nm	400-700 nm	700-1100 nm
PP photo	24.3 ± 1.54	24.9 ± 1.54	0.5 ± 0.31	0.4 ± 0.31	75.2 ± 6.22	74.7 ± 6.22
PLA	24.2 ± 1.54	25.2 ± 1.54	0.3 ± 0.03	0.3 ± 0.03	75.5 ± 6.23	74.5 ± 6.23
Control	11.9 ± 1.54	11.4 ± 1.54	4.7 ± 0.31	5.8 ± 0.31	83.4 ± 6.25	82.8 ± 6.25

[1]PP photo: PP nonwoven with an iron stearate photodegradation activator, 20 g/m^2; PLA: polylactide nonwoven, 20 g/m^2; Control: PP nonwoven, 20 g/m^2.

Soil surface temperature under covers

Soil temperature, reflected by the daily maximum and daily mean temperature, was higher in the first 10 days of covering in comparison to the later period, when it was lower and less varied (Fig. 2). The minimum soil temperature was characterized by lower fluctuations in comparison to the maximum and mean temperatures, especially in May. The mean soil surface temperature, equal to 30.7 °C, occurred at the end of May under PLA, while the lowest value for this temperature was recorded at the beginning of June under the control nonwoven (15.9 °C). An extremely high soil temperature was recorded under PLA on 28 May (57.8 °C), while the minimum temperature was lowest on 27 May under all of the tested materials, especially the control nonwoven (7.7 °C). Daily fluctuations in soil temperature were smallest for the oxo-degradable nonwoven (up to 18.6 °C), while for PLA the daily differences were larger and reached up to 23.9 °C.

Comparing the treatments with the conventional PP nonwoven, the mean soil surface temperature under

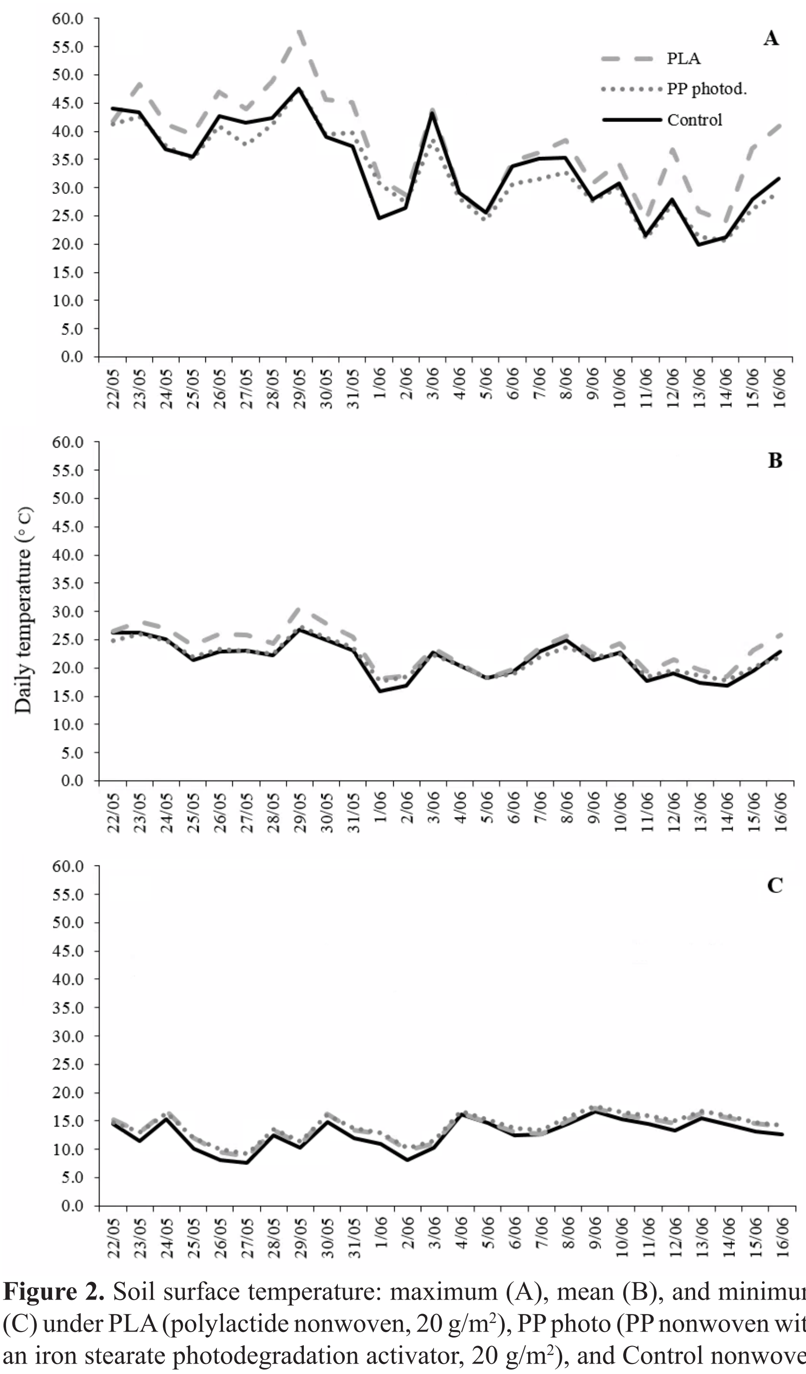

Figure 2. Soil surface temperature: maximum (A), mean (B), and minimum (C) under PLA (polylactide nonwoven, 20 g/m^2), PP photo (PP nonwoven with an iron stearate photodegradation activator, 20 g/m^2), and Control nonwoven (PP, 20 g/m^2) recorded from 22 May to 16 June 2012.

the PP oxo-degradable material was comparable (the difference reached only 0.2 °C), but the PLA nonwoven increased the soil temperature by 1.8 °C on average (Table 2). The maximum temperature, averaged over the plant covering period, was higher under PLA in comparison to the control nonwoven (by 4.2 °C), while the oxo-degradable PP nonwoven ensured a temperature lower by 0.8 °C in comparison to the control. The lowest minimum average soil surface temperature was noted for the control nonwoven, while the degradable materials used for covering plants increased slightly this temperature by 1-1.3 °C; this increase was greater for the oxo-degradable nonwoven.

The distribution of soil surface temperature under the tested nonwovens is presented in Figure 3. Temperature data below 15 °C reached the highest number for the conventional PP nonwoven, while for the oxo-degradable and PLA materials the percentage of such temperatures was lower by 6.9 and 5.9%, respectively. Most frequently, soil temperature oscillated between 15 and 25 °C, especially in the case of the oxo-degradable nonwoven (9.5% more such temperature records than in the control). Under the PLA material, more temperatures above 35°C were noted (in total 14.6%), and the differences in comparison to the oxo-degradable and standard nonwovens reached 7.2 and 6.1%, respectively.

Table 2. Average soil surface temperature under PP photo (PP nonwoven with an iron stearate photodegradation activator, 20 g/m^2), PLA (polylactide nonwoven, 20 g/m^2), and Control nonwoven (PP, 20 g/m^2). Means for the period 22 May-16 June 2012.

Nonwoven type	Daily temperature (° C)		
	Maximum	Mean	Minimum
PP photo	32.7a	21.8a	14.1a
PLA	37.7b	23.4b	13.8a
Control	33.5a	21.6a	12.8a

Mean values within a column followed by different letters are significantly different at p<0.05 according to the Kruskal-Wallis and Mann-Whitney U tests, n = 26

The application of direct covers can promote rapid plant growth mainly by improving thermal conditions for both root and shoot development (Moreno *et al.*, 2005). Several investigations have been carried out on the effect of nonwoven floating covers on air and

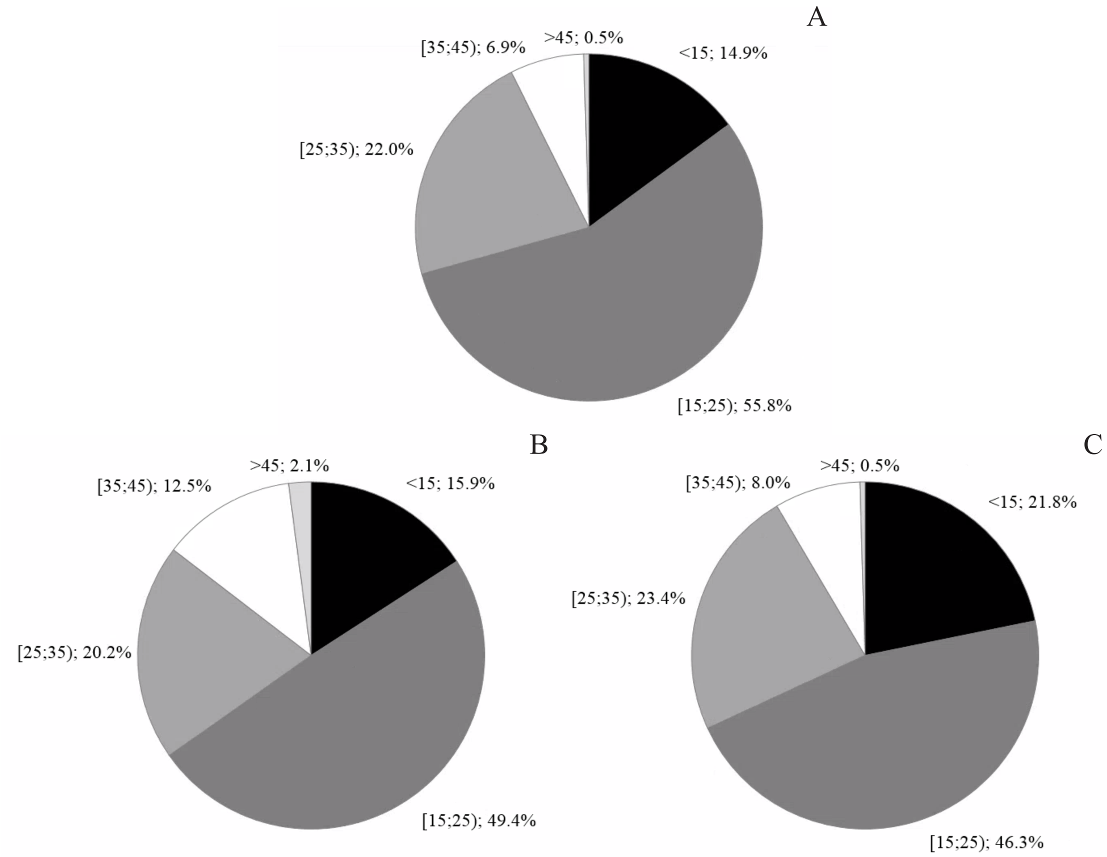

Figure 3. Frequency histograms for soil surface temperature under: PP photo 20 g/m^2 (A), PLA 20 g/m^2 (B) and Control nonwoven (C) – PP, 20 g/m^2. Measurements were made from 22 May to 16 June 2012 at 1-hour intervals, n = 624. The numbers represent left-closed, right-open temperature intervals and the percentage of recorded values of temperature within each interval.

soil temperatures (Olle & Bender, 2010), indicating an increase in temperature due to covering with different nonwoven materials. However, most of those studies focused on the impact of nonwoven row covers in comparison to the open field. Our main goal was to assess the effects of degradable nonwovens on soil temperature as compared to the standard nonwoven fleece commonly used in horticultural production. According to the results, we determined that the polylactide nonwoven raised the mean and maximum soil surface temperatures the most. Interestingly, both degradable nonwovens ensured better protective properties against heat loss at lower external temperatures, but especially so the photodegradable PP cover. These observations were confirmed by the temperature distribution analysis. Nonwovens are fibrous materials that are manufactured in different weights and structures, thus heat convection is different (Qashou *et al.*, 2009) and depends mainly on the thickness, basis weight, air permeability, fibre diameter, tensile properties, and the chemical composition (including additives) of the nonwoven materials. Hence, it is important to test such degradable nonwovens in terms of their thermal properties before their introduction into large-scale production. The very high values of daily maximum temperatures recorded under the tested nonwovens, in particular under the PLA material, also require some comments. Although the soil surface temperature can reach more than 45 °C under row covers (Hanada, 1991), detailed analysis of daily temperature changes on particular days of experiments has shown that such high temperature peaks occurred mainly between 12 pm and 3 pm, while the remaining recorded temperature values were lower. In summary, we must underline the beneficial properties of the tested degradable nonwovens in securing against heat loss.

Cucumber yield parameters

The use of degradable nonwovens (PP photo and PLA) did not decrease the yield of cucumber compared to plants covered with the control PP 20 g/m^2 (Table 3). This should be considered a good result of the experiment, which indicated a similar impact of the innovative materials on cucumber yield as that of the standard nonwoven used in horticultural production. In 2012, the plants covered with the polypropylene nonwoven with an iron stearate photodegradation activator (PP photo) and the polylactide nonwoven (PLA) gave a statistically similar number of fruits and comparable productivity per square metre (in each quality grade and in terms of cumulative marketable yield), although the data suggest slightly better, but not confirmed statistically, yielding of the cucumber plants in the control. However, the oxo-degradable nonwoven showed unsatisfactory durability, *i.e.* cracking, on the covered plants in the first month of the experiment. For this reason, in 2013 only the polylactide nonwoven was designated for further testing. In that year, there were no statistically significant differences in marketable yield (expressed as number of fruits and kg/m^2), between the control PP nonwoven and the PLA nonwoven.

The quality structure of the marketable yield of cucumber is presented in Figure 4. In 2012, the percentage of fruits belonging to the pickling and brining grades was similar for the plants covered with the degradable nonwovens and the control nonwoven. In the case of PLA, we observed slightly fewer pickling and brining fruits (by around 3.7%), and also slightly more deformed fruits (by 3.3%). In the next year, more salad and deformed fruits were obtained from the control plants (by 2.0 and 1.7%, respectively), while the effect of the PLA covering was an increase in the percentage of pickling and brining fruits, with the difference amounting to 3.7% in comparison to the control, which was quite opposite to the results obtained in the previous year. The impact of the degradable nonwovens on the quality structure of the cucumber yield was generally negligible, without a clear direction of changes.

Table 3. Yield (± SD, n = 4) of cucumber depending on the type of nonwovens used for covering plants in 2012-2013.

Year	Nonwoven type[1]	Pickling and brining		Salad		Marketable yield	
		fruits/m^2	kg/m^2	fruits/m^2	kg/m^2	fruits/m^2	kg/m^2
2012	PP photo	37.50 ± 3.99a	2.48 ± 0.27a	8.83 ± 2.00a	1.26 ± 0.29a	48.23 ± 5.91a	3.88 ± 0.55a
	PLA	38.20 ± 4.88a	2.46 ± 0.36a	9.17 ± 0.97a	1.32 ± 0.15a	51.43 ± 5.66a	4.05 ± 0.50a
	Control	42.97 ± 3.73a	2.69 ± 0.31a	9.60 ± 0.79a	1.39 ± 0.06a	55.10 ± 3.62a	4.29 ± 0.34a
2013	PLA	96.68 ± 12.78a	4.59 ± 0.57a	16.64 ± 2.40a	2.59 ± 0.42a	118.29 ± 15.77a	7.48 ± 0.88a
	Control	85.61 ± 3.03a	3.97 ± 0.25a	17.61 ± 2.21a	2.68 ± 0.32a	109.64 ± 2.07a	6.94 ± 0.31a

[1]PP photo: polypropylene nonwoven with an iron stearate photodegradation activator (20 g/m^2); PLA: polylactide nonwoven (20 g/m^2); Control: PP nonwoven, 20 g/m^2. Mean values within a column, separately for each year, followed by different letters are significantly different at p<0.05 according to the Duncan test (2012) or t-test (2013).

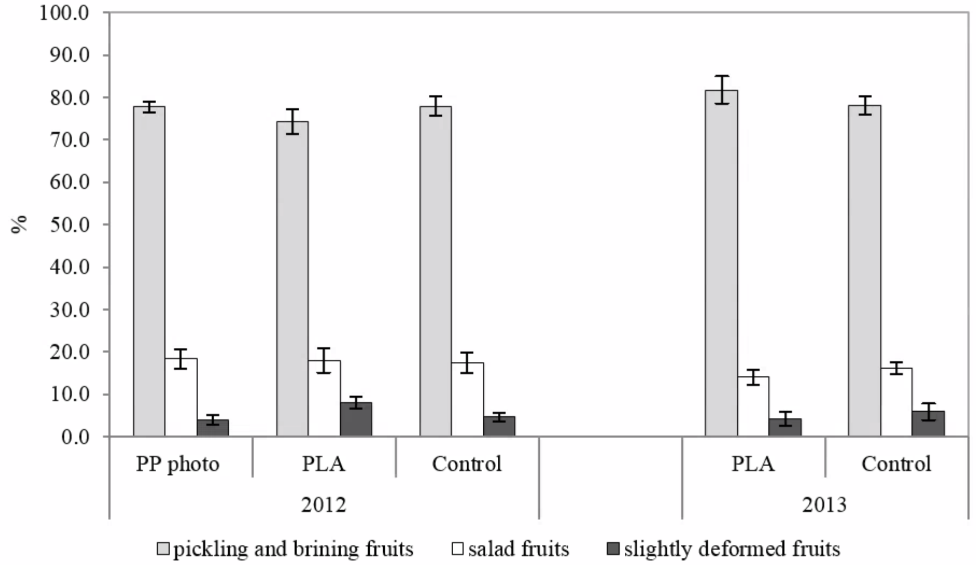

Figure 4. Classification of cucumber fruits harvested from the plots covered with PP photo (polypropylene nonwoven with an iron stearate photodegradation activator, 20 g/m^2); PLA (polylactide nonwoven, 20 g/m^2); and Control nonwoven (PP, 20 g/m^2). Error bars represent ± SD.

Based on the data presented in Figure 5, we concluded that the dynamics of cucumber yield were not markedly affected by the degradable nonwovens up to the middle of the plant vegetation period in the field; however, some differentiation was observed during this period. Greater differences generally occurred later, after 50-60 days from transplanting. In 2012, higher yields were obtained from the plants covered with PLA at 43, 57 and 67 DAT (days after transplanting), with the differences in comparison to the control plants reaching around 1.5-2%. At 67 DAT, plants from the plots covered with the oxo-degradable nonwoven also gave a higher yield, with 1.7% more fruits than the control. The use of the oxo-degradable PP nonwoven also caused a higher level of yielding a week later. In the next year, the yield dynamics trend was comparable between the control plants and the plants covered with PLA. However, the PLA-covered plants gave slightly higher yields at 54, 64, 71, 74 and 84 DAT in comparison to the control; maximum differences were observed 64 and 71 DAT, reaching 2.9% and 3.9%, respectively. Comparison of the cumulative percentage yield from the first 6 harvests did not show significant differences among the tested covers in 2012: PLA – 54.2% of all harvested fruits; PP photo – 48.4%; control PP – 53.5%; and in 2013: PLA – 29.2%; control PP – 31.5%. Cumulative yield plotted against time is shown in Figure 6. Applying the oxo-degradable cover had relatively less beneficial effect on the cumulative yield in 2012, whereas when the PLA and control PP nonwovens were applied, the cucumber yields became, and remained, higher until the end of the experiment. Yields from the plants covered with the PLA and commercial PP nonwovens in 2013 were comparable up to 70 DAT; later, the cumulative yield was higher for PLA.

A number of investigations have indicated that the application of nonwoven materials as floating row covers contributed to the advancement of harvest time by several days, to an increase in yield and improvement of vegetable crop quality, especially of the cultivars cultivated for early harvest or warm-season crops (Olle & Bender, 2010). However, in most of the research concerning Cucurbitaceae only the standard, non-degradable polypropylene materials have been used as floating covers for comparisons with cultivation in the open field (*e.g.* Cerne, 1994; Ibarra-Jiménez *et al.*, 2004; Kołota & Adamczewska-Sowińska, 2011; Dantas *et al.*, 2013), often in combination with soil mulching. Studies on biodegradable starch-based films and photodegradable polymers used for crop mulching (Kasirajan & Ngouajio, 2012) or low-tunnel structural systems (Briassoulis, 2006) are definitely more advanced than studies on degradable floating row covers. However, some prototypes of degradable nonwovens for use as direct covers have been tested. Zawiska & Siwek (2014) tested the effect of materials made using the melt-blown method – aliphatic-aromatic polyester IBWCH 75 g/m^2 and polylactic acid PLA (54 g/m^2) – on the yield of cucumber. They observed that the yield from plants covered with PLA was significantly higher than the yield from plants grown without covers (control) and under IBWCH 75 g/m^2. In an experiment

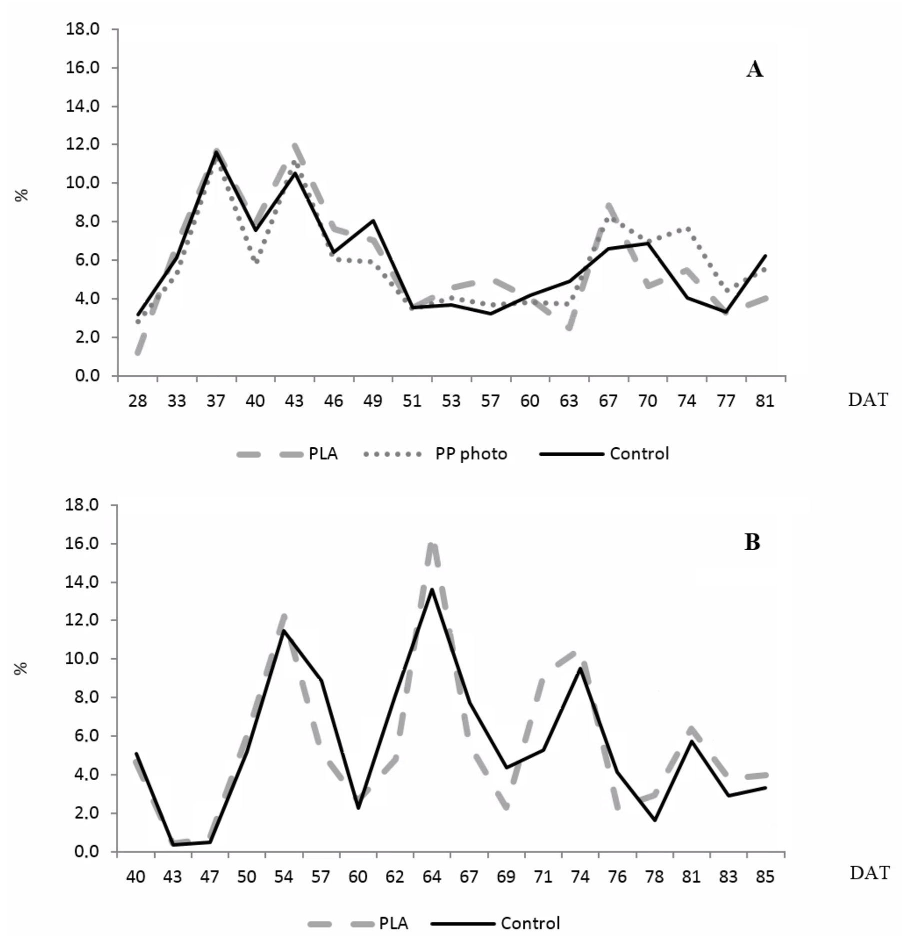

Figure 5. Influence of nonwovens on the dynamics of cucumber yield expressed as a percentage of the fruits belonging to the pickling, brining, and salad grades in consecutive harvests (DAT: days after transplanting) in comparison to the final yield. Data for the year 2012 (A) and 2013 (B).

with overwintering onion, Siwek *et al.* (2013b) observed a higher yield due to the covering with melt-blown polybutylene succinate Bionolle 59 g/m^2 in relation to the standard PP nonwoven 50 g/m^2; this, however, happened only in one year of the two-year experiment. Yields from lettuce plants covered with Bionolle 100 g/m^2 and IBWCH 75 g/m^2 were similar to those obtained from the plants grown under polypropylene nonwoven PP 20 g/m^2 (Siwek *et al.*, 2012).

Biodegradable nonwovens used as direct covers have been observed to produce some positive effects on cucumber yields. A significant achievement, however, would be to show that degradable nonwovens do not negatively affect crop yield in comparison to commercial PP covers.

Effect of nonwovens on fruit dry weight and soluble sugar content

Average dry weight and soluble sugar content were lower in the cucumbers covered with the degradable nonwovens in 2012 (Table 4). The situation was different in the second experimental year (2013) – covering with PLA had no significant effect on the chemical composition of cucumber fruits in comparison to the control plants.

Nonwoven fabrics have been demonstrated to have an influence on the concentration of several chemical compounds in the covered plants (Olle & Bender, 2010). As has been summarized elsewhere, the quality of the harvest in terms of chemical composition is lower because the levels of pigments, vitamin C, dry matter and sugar in the covered vegetable crops are lower than in the non-covered plants (*e.g.* Lopez, 1998; Moreno *et al.*, 2001; Pulgar *et al.*, 2001; Rekowska & Skupień, 2007). Those studies focused on the comparison of plants grown under the standard polypropylene nonwoven with plants grown in the open field. The effects of degradable floating row covers on the dry weight or soluble sugar content of plants, especially in comparison to the standard nonwoven fleece and not to the open field, have not

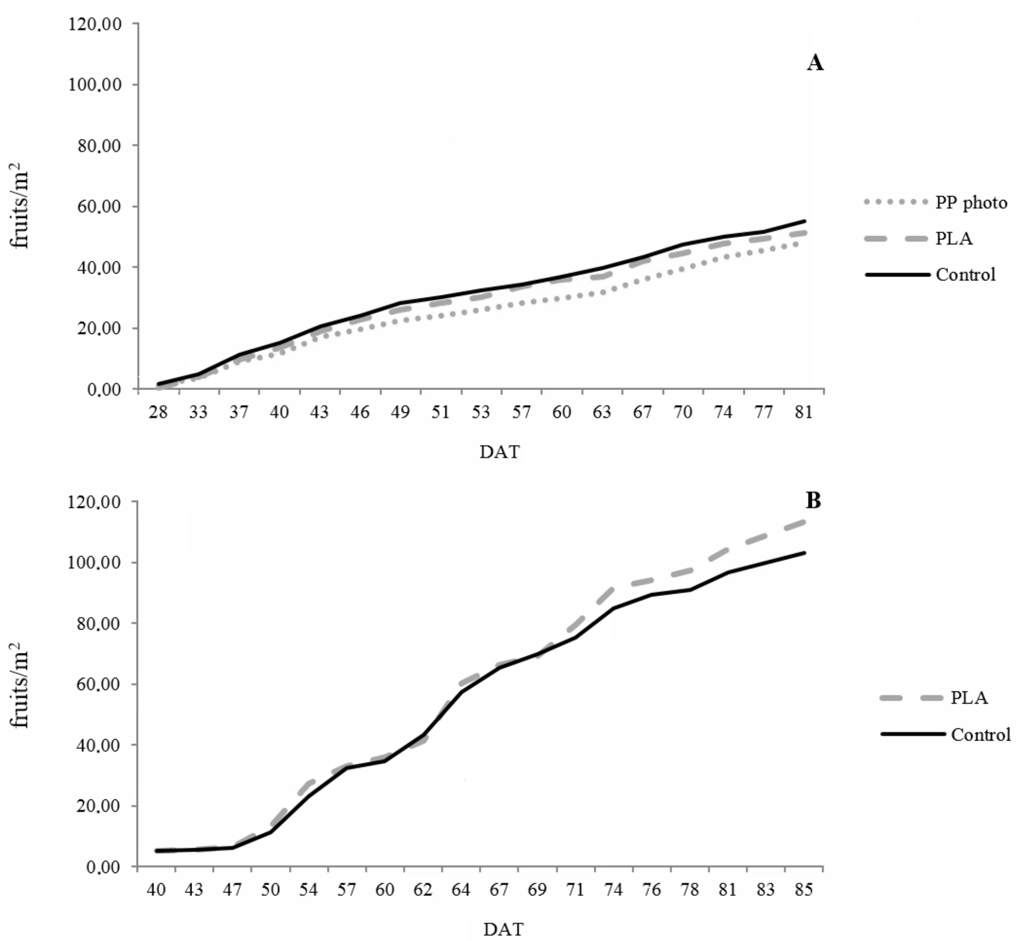

Figure 6. Influence of nonwovens (PP photo: polypropylene nonwoven with an iron stearate photodegradation activator, 20 g/m^2; PLA: polylactide nonwoven, 20 g/m^2; and Control: PP nonwoven, 20 g/m^2) on the cumulative marketable yield of cucumber. Data for the year 2012 (A) and 2013 (B).

Table 4. Dry weight (% FW ± SD, n = 4) and soluble sugar content (% FW) of mature cucumber fruits depending on the type of nonwovens used for covering plants in 2012-2013.

Year	Nonwoven type[1]	Dry weight	Soluble sugars
2012	PP photo	4.63 ± 0.12a	2.67 ± 0.03a
	PLA	4.60 ± 0.02a	2.67 ± 0.04a
	Control	5.04 ± 0.02b	2.96 ± 0.04b
2013	PLA	5.30 ± 0.60a	2.34 ± 0.06a
	Control	4.93 ± 0.86a	2.39 ± 0.01a

[1]PP photo: polypropylene nonwoven with an iron stearate photodegradation activator (20 g/m^2); PLA: polylactide nonwoven (20 g/m^2); Control: PP nonwoven, 20 g/m^2. Mean values within a column, separately for each year, followed by different letters are significantly different at p<0.05 according to the Duncan test (2012) or t-test (2013).

been widely investigated. Zawiska & Siwek (2014) observed varied effects of covering cucumbers with biodegradable nonwovens on the dry weight and soluble sugar content in comparison to non-covered plants, with no differences between the tested polymer materials. Siwek *et al.* (2012, 2013b) obtained no clear relationship with the changes in the chemical composition of overwintering onion and butterhead lettuce covered with different degradable materials. In the present experiment, we did not observe any statistically significant changes in the dry weight and soluble sugar content of cucumber in 2013; however, in 2012, both degradable nonwovens decreased the values of the two parameters relative to those for the standard nonwoven fleece. We suppose that different temperature regimes under degradable nonwovens and slightly lower PAR transmission in comparison to the standard nonwoven fleece affected photosynthesis and the respiration rates of cucumber plants, which, together with different weather conditions in 2012, contributed to reducing the dry weight and sugar content of the fruits.

The most important property of degradable polymers introduced into horticulture is in fact their degradability. Such materials can be a solution to the problem of the disposal and management of plastic waste. They can be used to enhance the sustainability of agricultural activities. The production technology of such degradable materials is constantly being improved, but we already have commercial degradable nonwovens for plant mulching. The effectiveness of the nonwoven covers tested in the present experiment on cucumber yield parameters was rather comparable with that of the conventional PP material, despite slightly greater limitations in PAR transmittance and higher soil temperatures that the plants were subjected to. A negative observation was the lower quality of cucumber fruits (a decrease in dry weight) associated with the use of degradable material for covering plants. The tested oxo-degradable nonwoven is not recommended for vegetable crop production due to its short lifespan and debatable biodegradability, while polylactide nonwovens may be used as floating row covers and represent a sustainable ecological alternative to conventional, non-degradable polymers.

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