Piotr Bucki[1,*], Piotr Siwek[1], Iwona Domagała-Świątkiewicz[2], Michał Puchalski[3]

Effect of Agri-Environmental Conditions on the Degradation of Spunbonded Polypropylene Nonwoven with a Photoactivator in Mulched Organically Managed Zucchini

[1] University of Agriculture in Krakow, Faculty of Biotechnology and Horticulture, Department of Vegetable and Medicinal Plants
Al. 29 Listopada 54, 31-425 Kraków, Poland
* E-mail: piotr.bucki91@gmail.com

[2] University of Agriculture in Krakow, Faculty of Biotechnology and Horticulture, Institute of Plant Biology and Biotechnology, Unit of Plant Nutrition
Al. 29 Listopada 54, 31-425 Kraków, Poland

[3] Lodz University of Technology, Faculty of Material Technologies and Textile Design, Department of Material and Commodity Sciences and Textile Metrology, Centre of Advanced Technologies of Human-Fiendly Textiles "Pro Humano Tex"
ul. Żeromskiego 116, 90-924 Łódź, Poland

DOI: 10.5604/01.3001.0011.5739

Abstract
An experiment with non-degradable and degradable soil mulching materials in zucchini cultivation was carried out in 2016 and 2017 in the organic field of the Vegetable Experimental Station, Agricultural University of Kraków. Two kinds of polypropylene (PP) nonwoven of 50 g m^{-2} were used: PP standard and PP with 0.1% photoactivator. The control treatment were plots without mulching. The marketable yield obtained in 2016 was 21% and 15% higher on the plots mulched with PP nonwoven and PP nonwoven with a photoactivator, respectively, in comparison with the non-covered plots. Mulching the soil with PP nonwoven increased the water resistance index of the soil structure in comparison with the control and photodegradable PP nonwoven mulch. The progress of degradation over a two-month period showed a 40% reduction in the mass of the PP nonwoven with a photoactivator, and at the end of vegetation the mass of the PP nonwoven used was 52% lower than that of a new one. Tensile parameters of the PP nonwovens and their supramolecular structure were measured.

Key words: *photodegradation, polypropylene nonwoven, zucchini, soil mulching, organic farming.*

Introduction

In Polish horticulture, PP nonwovens have been known for 25 years, mainly in the form of mulches and direct covers. Mulching is the most popular cultivation method in vegetable growing of the *Cucurbitaceae* and *Solanaceae* families [1]. The area of crops for which the use of soil and plant covers is beneficial keeps growing, and the introduction of the technology of degradable materials is also an important form of environmental protection [2-4]. Mulching treatment helps to retain water in the soil by reducing evaporation, improving the physical and chemical properties of the soil, and reducing weed infestation. Along with the modification of environmental conditions around the plants, it is possible to obtain higher yields of better quality vegetables. Mulching is particularly effective in the growing of thermophilic species requiring high humidity and constant soil temperature in countries with temperate and cold climates. The beneficial effect of using mulches on fruit yield and quality was confirmed in studies conducted on melon, tomato, pattypan squash and cucumber [5-7]. The highest increase in temperature was obtained in soil covered with black-coloured materials [8, 9]. Covering the soil reduces the leaching of nutrients into deeper layers of the soil, improves its structure, and also isolates plants from pathogens. In addition to organic materials, the basic synthetic material used for this purpose is black polyethylene film of low density. Equally widely used is PP nonwoven with a surface mass of 50 g m^{-2}, which transmits water and gaseous substances [2, 10].

The growing demand for thermoplastics from the polyolefin group for use in agriculture carries with it the problem of their long-lasting retention in the soil. In addition, the process of synthesising them involves the use of non-renewable mineral resources. Recent decades have witnessed a considerable increase in interest in degradable materials for agriculture. Among them are polymers of vegetable and bacterial origin (e.g. cellulose, starch, vegetable oils), including polyesters (e.g. polylactide (PLA) and polyhydroxyalkanoates (PHA)) [11, 12]. Studies indicate that materials made from natural fibres and biodegradable polymers have physical properties that make them suitable for use as mulches [13]. It is also possible to enrich the commonly used polyolefins with substances that enable their photo- and biodegradation. The photodegradation mechanism involves the absorption of UV light, which leads to the generation of free radicals, followed by the process of oxidation and decomposition of the material [14]. The role of degradants is fulfilled by compounds (mainly metal stearates) containing certain elements, e.g. cobalt, manganese, calcium, titanium, or iron, which, when introduced into the matrix, accelerate the breakdown of the polymer [15-18]. According to García-Montelongo et al. [19], the rate of material decomposition is related to the concentration of the degradant, which is subject to faster interaction with polypropylene fibres if present in larger amounts. Among the significant factors affecting the process of photodegradation are climatic and environmental conditions as well as polymer exposure to solar radiation [20]. The costs of producing materials with built-in components responsible for degradation are still high. However, when the additional work associated with the removal from the field and utilisation of standard mulches is taken into account, those costs are comparable [21].

The aim of the study was to determine and compare the effects of mulching with a standard PP nonwoven and PP nonwoven with a photoactivator on the environmental conditions and the yield and quality of organically grown zucchini fruit. The scope of the experiment also included an assessment of the degree of degradation of the polymers used.

Material and methods

Study site

The experiments were conducted in 2016-2017 at the experimental station of the University of Agriculture in Kraków, situated in Mydlniki near Kraków, Poland. The climate of the station, located in southern Poland (N 51°13′, E 22°38′), is humid continental (Dfb) according to Köppen's classification.

Field experiment design

A prototype PP nonwoven black mulch with an iron stearate photodegradation activator (PP photod. 0.1% 50 g m^{-2}) created using spunbonding technology at the Łódź Institute of Biopolymers and Chemical Fibres, and a standard black PP nonwoven for agricultural use with a similar mass per unit area were used for cultivating zucchini in 2016 and 2017. Spectral properties of the PP nonwovens used in the experiment show small differences and were evaluated in the range of 400-1100 nm (reflection: 5.4-6.5%, absorption: 84.7-88,6%, transmission: 6.0-8, 8%) [22]. New materials were used in each research year during the growing season from planting time (second half of May) to the end of the fruit harvest (first half of September). Seeds of the parthenocarpic 'Partenon' F_1 cultivar (HILD) were sown on 19 April in four replications of 8 plants each. Transplants were planted on 16 May 2016 and 18 May 2017 in each hole in the mulch, with row and plant spacing of 100 x 80 x 100 cm. Yielding started and ended on the following dates: 13 June-12 September 2016 and 10 June-7 September 2017. The plants were removed and the PP nonwoven with a photodegradation activator was worked into the soil using a rotary tiller. The marketable yield included, in accordance with Polish Standard PN-R-75541: UN/ECE FFY-41, healthy fruits of a regular shape, without disease symptoms, and no mechanical or pest damage. The fruits were divided into three grades: 10-14 cm, 15-21cm and >21 cm in length.

Soil analysis

Soil samples for analysis were collected from the topsoil (0-20 cm) after the end of the harvesting period. The granulometric composition was assessed according to Polish Standard PN-R-04032 [23], while the bulk density and water capacity were determined using Kopecky cylinders. The water resistance of soil aggregates was assessed using the wet sieving method. Soil aggregates were separated during wet sieving according to the Yoder procedure [24]. Air-dry aggregates in 40 g samples were used for measurements, in which four repetitions were performed. Five mesh dimensions were used: 0.25, 0.5, 1.0, 1.5 and 2.5 mm. The mass of soil in each sieve was established by drying at 105 °C and weighting. Water resistance was calculated separately for each class of soil aggregate and as a summary indicator for all the classes. The organic carbon content was established using the Tiurin method, by oxidising in potassium dichromate.

Microclimatic conditions

Soil temperature was recorded using HOBO autonomous sensors (Onset Comp. Corp., Bourne, MA, USA) located in the immediate vicinity of the plants. Temperature data were recorded at one-hour intervals over the course of the experiment and are summarised in the form of average values. In addition, measurements (at midday on 6 June 2016, during sunny weather) of photosynthetically active radiation (PAR) (spectroradiometer LI-COR 189B, USA), relative humidity and temperature of air (Hygromer A1, Rotronic Ag, Germany), soil moisture (HH2 Moisture Meter, Delta-T Devices, England), and CO_2 content in the air (Telaire 7001, Onset Comp. Corp., USA) were performed.

Plant analysis

Dry matter content, soluble sugars, and L-as-corbid acid of fresh zucchini fruits from consecutive years were determined in the laboratory. The dry matter of the fruits was determined by drying the sample at 92-95 °C until a constant weight was obtained, measured using a Sartorius A120S analytical balance (Sartorius AG, Germany). The soluble sugars were determined by the anthrone method. For this analysis, plant material was mixed with 80% ethanol. After the addition of the anthrone reagent, samples were placed for 30 min. in a water bath (100 °C), then cooled to 20-22 °C, and the absorbance was measured at 625 nm using a Helios Beta spectrophotometer (Thermo Fisher Scientific Inc., USA). The L-ascorbic acid content in 50 g plant material was mixed with 200 cm^3 acetic acid. The extract was titrated with Tillman's reagent (2,6-dichlorophenolindophenol) after the next 30 min.

Physical properties of nonwovens

Mechanical parameters of the PP nonwovens tested, such as stress at break and strain at break, were estimated using an Instron 5511 (Instron, USA) mechanical testing machine. The size of the samples tested was determined by that of the samples taken without defects from the field and was equal to 10 × 50 mm^2. The test was performed with an initial distance of 30 mm between the clamps and a velocity of 30 mm/s. The measurement of 10 samples was performed under ambient conditions. Additionally the loss of mass per unit area was determined. The measurements were made with PS.R1 precision balances (Radwag, Poland) after cleaning the samples in distilled water.

Structural WAXD analysis

The supramolecular structures of the PP nonwoven samples were investigated by wide angle X-ray diffraction (WAXD) using an X'Pert PRO diffractometer (CuKα source, λ = 0.154 nm) from PANalytical (Eindhoven, Netherlands). Diffractograms for the powdered samples were recorded over a 2θ range of 5° to 60° with a 0.05° step.

Data analysis

Statistical analyses were performed using the STATISTICA 13.0 (StatSoft Inc., STATISTICA data analysis software system, www.statsoft.com, USA). The data in the present study were subjected to one-way and two-way analyses of variance (ANOVA), and the means were separated by Tukey's HSD and Fisher's (some soil analyses) tests at $P < 0.05$.

Results and discussion

Soil testing

Particle size analysis classified the soil as fine grained, belonging to the group of silty clay soils (***Table 1***). Soil texture has a significant influence on the physical properties of soil as well as aggregation.

The bulk density of the soil in 2016-2017 was in the range 1.33-1.34 g cm^{-3} (***Table 2***). Covering the soil with mulch, regardless of its type, slightly increased the soil density measured after harvesting zucchini fruit. Higher water capacity was estimated on the cultivation site in 2016 (***Table 2***). Mulching the soil with photodegradable PP nonwoven decreased soil water capacity relative to soil mass.

In 2016, the zucchini cultivation site was characterised by a significantly higher organic matter content than in 2017 (***Ta-***

ble 2). Mulching the soil with PP nonwoven and PP nonwoven with the addition of a photoactivator had no statistical effect on the organic carbon content of the soil in 2016. In contrast, in 2017, the soil mulched with PP nonwoven had the lowest organic carbon content in relation to the control and the plot mulched with photodegradable PP nonwoven.

A significantly higher index of water resistance of the soil structure (WSI) was demonstrated in 2017. Mulching the soil with PP nonwoven increased the water resistance index of the soil structure in comparison with the control and the photodegradable PP nonwoven, especially in 2017. In 2016, the WSI index was, however, significantly higher in the noncovered soil (83.6%) in relation to the soil mulched with photodegradable PP nonwoven (80.4%).

In 2016, the highest percentage of water-stable macroaggregates in the 4.0-2.5 mm diameter range was determined in the soil mulched with photodegradable PP nonwoven and in the control (***Table 3***). Similarly significant correlations were demonstrated in 2017. In both years of the study, covering the soil surface with PP nonwoven reduced the percentage of water-stable macroaggregates in the soil. In 2017, this type of soil cover significantly increased the share of fine aggregates with a diameter <1.5 mm, especially in relation to the photodegradable PP nonwoven. The soil structure under the photodegradable nonwoven was characterized in 2017 by the highest percentage share of water-stable aggregates in the 4.0-2.5 mm size class. In the studies by Domagała-Świątkiewicz and Siwek [25, 26], mulching with nonwovens (PP and PP with an activator of photodegradation) enhanced the structure of the mulched soil in relation to bare soil under open-field conditions.

Table 1. *Soil particle size distribution by Polish Standard PN-R-04032 [23] and textural classification.*

Fraction	Particle size, mm	%	Texture
Sand	2.0-0.05	14	Silty clay
Silt	0.05-0.002	45	
Clay	<0.002	41	

Table 2. *Bulk density (g cm^{-3}), water capacity (WC %ww and %wv), soil organic carbon (%SOC), and aggregate water-stability index (%WSI) of soil from the zucchini plantation in 2016-2017.* ***Note:*** ** – bare soil; ** – mean separation by two-way analysis, Fisher's test at p = 0.05. Means followed by the same letter are not significantly different.*

Year	Kind of mulch	Bulk density	WC %ww	WC %wv	%SOC	WSI
2016	Control*	1.30 a**	37.6 a	48.8 a	1.39 c	83.6 bc
	PP	1.37 a	35.6 a	47.8 a	1.36 c	81.8 ab
	PP with act. of degr.	1.38 a	33.2 a	46.2 a	1.38 c	80.4 a
2017	Control	1.31 a	31.3 a	41.7 a	1.21 b	82.5 a-c
	PP	1.33 a	32.0 a	41.8 a	1.10 a	90.1 d
	PP with act. of degr.	1.34 a	30.4 a	41.2 a	1.20 b	84.5 c
Mean	2016	1.35 a	35.5 b	47.6 b	1.38 b	81.9 a
	2017	1.33 a	31.2 a	41.2 a	1.17 a	85.7 b
	Control	1.30 a	34.4 b	45.2 a	1.27 b	83.0 a
	PP	1.35 b	33.8 b	44.8 a	1.19 a	86.3 b
	PP with act. of degr.	1.36 b	31.8 a	43.7 a	1.26 b	82.6 a

Table 3. *Percentage of five size classes of water-stable aggregates (mm) in soils from the zucchini plantation in 2016-2017.* ***Note:*** ** – bare soil; ** – mean separation by two-way analysis, Fisher's test at p = 0.05. Means followed by the same letter are not significantly different.*

Year	Kind of mulch	Percentage of aggregates, diameter in mm				
		4.0-2.5	2.5-1.5	1.5-1.0	1.0-0.50	0.50-0.25
2016	Control*	22.1 b**	17.8 b	15.7 b	15.9 a	11.4 a
	PP	19.6 a	17.4 b	14.3 a	16.1 a	12.8 a
	PP with act. of degr.	23.3 b	15.3 a	13.6 a	15.9 a	12.4 a
2017	Control	42.5 b	20.5 a	4.4 a	10.9 b	8.7 b
	PP	36.0 a	20.8 a	11.8 b	12.4 b	8.6 b
	PP with act. of degr.	50.4 c	20.4 a	4.2 a	6.1 a	4.7 a

Table 4. *Microclimatic conditions in zucchini cultivation with mulching, 6 June 2016.*

Kind of mulch	PAR, µmol m^{-2} s^{-1}	Air humidity, %	Air temperature, °C	CO_2, ppm	Soil moisture, %
Control	3013	21	27.6	434	21.1
PP	2816	38	20.5	433	29.0
PP with act. of degr.	3004	34	22.8	435	23.4

Table 5. *Soil temperature (°C) at a depth of 10 cm in zucchini cultivation with mulching.*

Kind of mulch	Minimum		Mean		Maximum	
	2016	2017	2016	2017	2016	2017
Control	16.6	16.1	19.3	19.2	22.3	22.7
PP	16.9	16.6	18.6	19.0	20.5	21.4
PP with act. of degr.	16.8	17.6	18.5	20.2	20.2	23.0

Influence of mulching nonwovens on zucchini plants

The measurements of microclimate parameters taken in sunny and dry weather showed no differences in the intensity of irradiation of plants within the PAR range (400-700 nm) (***Table 4***). In the case of mulching the soil with plastic film or PP nonwoven, the transmission of radiation in the range of 400-1100 nm is very low, with absorption reaching 90%, and radiation not exceeding 5% [27, 28]. The relative humidity of air above the mulched soil was lower. This indicator, expressing the degree of saturation of air with water vapour, is directly dependent on air temperature, which was higher above the plots without cover. The level of CO_2 was uniform across the treatments. The insulating properties of both mulches became evident when soil moisture measurements were taken. Soil moisture was higher by 8.9% under the PP nonwoven, and by 2.3% under the PP nonwoven with a photoactivator. A similar level of reduction in evaporation as a result of mulching had been obtained by [29]. The soil temperature record indicates only a slight effect of mulching (***Table 5***). The average temperature of noncovered soil in 2016 was even higher, and in the next year slightly lower than

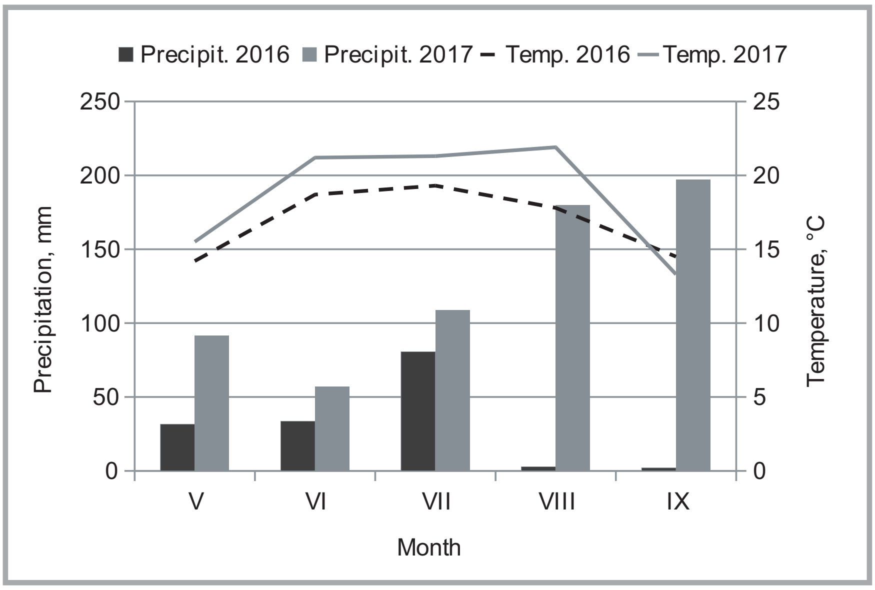

Figure 1. *Weather conditions over the course of the study (data obtained from the meteorological station at Mydlniki Station).*

Table 6. *Growth indicators of zucchini plants cultivated with mulching.* ***Note:*** ** – bare soil; ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter are not significantly different.*

Kind of mulch	Number of leaves		Number of female flowers		Number of male flowers	
	2016	2017	2016	2017	2016	2017
Control*	7.9 a**	9.7 a	3.4 a	5.0 a	5.8 a	7.3 a
PP	8.7 a	9.9 a	3.4 a	5.0 a	6.2 a	8.0 a
PP with act. of degr.	8.2 a	9.2 a	3.8 a	5.0 a	5.7 a	9.3 b

Table 7. *Yield (kg m*$^{-2}$*) of zucchini fruit cultivated with mulching.* ***Note:*** ** – bare soil; ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter are not significantly different.*

Kind of mulch	Total yield		Marketable yield	
	2016	2017	2016	2017
Control*	6.61 a**	13.78 a	6.59 a	13.76 a
PP	8.33 b	13.71 a	8.32 b	13.71 a
PP with act. of degr.	7.58 ab	14.43 a	7.57 ab	14.42 a

Table 8. *Chemical composition of zucchini fruit cultivated with mulching.* ***Note:*** ** – bare soil; ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter are not significantly different.*

Kind of mulch	Dry mass, %		Ascorbic acid, mg 100 g^{-1} fresh mass		Sugars, % fresh mass	
	2016	2017	2016	2017	2016	2017
Control*	5.28 a**	6.02 b	12.62 a	24.52 a	2.50 a	1.41 a
PP	5.33 ab	5.86 a	16.62 b	25.29 a	2.31 a	1.36 a
PP with act. of degr.	5.43 b	5.98 b	16.62 b	26.06 a	2.17 a	1.37 a

Table 9. *Comparison of the physical properties of PP nonwovens before and after their use in zucchini cultivation:* M_p *–mass per unit area, σ – maximum force at break, ε – elongation at break, MD – machine direction, TD – transverse direction.* ***Note:*** ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter are not significantly different.*

Kind of mulch	M_p, g m^{-2}		σ (N) MD		ε (%) MD		σ (N) TD		ε (%) TD	
	before	after	before	after	before	after	before	after	before	after
PP	46.5b*	64.8 a	18.95	14.11	92.9	40.2	13.92	9.74	86.3	41.0
PP with act. of deg.	55.4 a	29.1 b	12.12	1.75	22.6	5.6	10.74	1.39	36.1	13.3

that of the mulched soil. Similar trends in soil temperature measurements had been observed in the cultivation of cucumbers [3, 27] and potatoes [30]. The smaller influence of nonwovens on soil temperature compared with film results from its structure and permeability to air and water.

Growth indicators during the flowering period show a uniform initial growth of plants across the treatments (***Table 6***). In 2017, however, the number of male flowers in the plants on the PP nonwoven with a photodegradation activator was significantly higher. Differences in the growth and development of plants due to the influence of mulching became apparent during fruiting and affected yielding, especially in 2016 (***Table 7***). In that year, the marketable and total yields of zucchini fruit were significantly higher on the mulches than in the control, with the difference being 26.0% for PP nonwoven and 14.7% for PP nonwoven with a photoactivator. In the second year, the yield was uniform and much higher across all the treatments. In a study by Kołota and Adamczewska-Sowińska [31], the effects of mulching with black PE foil and a PP nonwoven on the yield of zucchini were found to be very small; however, in the case of pattypan squash the yield was 12-16% higher [7].

The yield of plants in the individual years was influenced by varied weather conditions (***Figure 1***). For zucchini plants, they were more favourable in 2017, which is why the yield was significantly higher. In particular, in the summer months of July and August, the average air temperature was higher by 2.0 °C and 4.1 °C and with a total precipitation about 180 mm, respectively. Towards the end of the harvesting period, in September 2017, the rainfall was even higher, but it no longer had a significant impact on the yield.

In terms of chemical composition, the zucchini fruits differed more in the first year of the study (***Table 8***). Those produced on the mulched plots contained more dry matter and ascorbic acid. In the second year, it was the control fruits and those harvested from the plants growing on the PP nonwoven with a photoactivator that contained more dry matter. The level of sugars in 2017 was similar across the three treatments, but lower than in the previous year. A considerably higher level of vitamin C was found in the second year of the study. The above-cited studies had demonstrated no significant effect of mulching on the chemical composition of zucchini or pattypan squash fruits. A higher level of nutrients had been obtained by Kosterna et al. [5] in melons grown on black mulches.

Assessment of nonwoven degradation

After the experiment evaluating the impact of mulching on zucchini plants, an assessment of the degradation of the soil covers used was conducted. Nonwovens collected from the plots were pre-cleaned and then subjected to tests to assess the changes in their physical properties as well as in their supramolecular structure resulting from their use as mulches. ***Table 9*** presents the results of mass per unit area measurements and those of the maximum force at break and elongation at break in the machine direction (MD) and transverse direction (TD). According to the results presented, PP nonwoven with a photoactivator showed a loss of mass, which at the end of the growing season was 47.5%. By comparison, PP nonwoven had increased its mass, which was an unexpected result, despite careful sample preparation and drying before weighing. When in use, the PP nonwoven collects soil particles, and its structure is difficult to purify; thus the mass per unit area determined is the cumulative result of the mass of the PP nonwoven together with the contaminants. According to the results shown, the largest decrease in the value of the force at break and of the deformation at break was recorded for the PP nonwoven with a photoactivator. After the end of the experiment, that nonwoven material disintegrated under the action of only a slight force. In the case of the PP nonwoven, the decrease in the value of the force at break was less marked compared with the considerable decrease in the elongation at break; the material had become more rigid and brittle. The statistical analysis determined that the changes in physical properties resulting from the use of the materials were significant.

An analysis of supramolecular changes in the materials tested was carried out by the WAXD method. ***Figure 2*** presents a comparison of the diffraction profiles of the PP nonwovens before and after using them as soil mulching materials. The WAXD profiles obtained result from the overlapping of two broader amorphous halos and seven crystalline peaks characteristic of the α-form of isotactic polypropylene (110) at 14.09°, (040) at 16.84°, (130) at 18.44°, (111) at 21.22°, (041) at 21.8°, (060) at 25.2°, and (220) at 28.7°) [32]. Additionally, in the case of the PP nonwoven sample, two broader mesomorphic peaks (at 14.8° and 21.2°) are observed. Samples of the nonwovens after their application in the field contained soil particles, which was confirmed by the diffraction peaks in the 2-theta range of 25-55°.

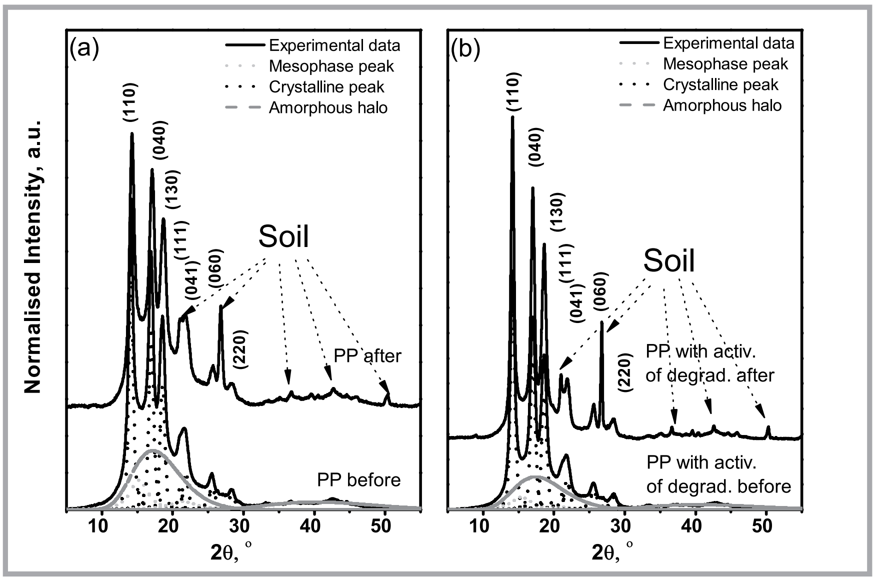

Figure 2. *Comparison of X-ray diffraction profiles of PP: (a) and PP with an activator of degradation (b) nonwovens before and after they were used as mulching materials.*

A more detailed analysis of the supramolecular structures of the test samples was obtained using WAXSFIT software [33]. ***Table 10*** presents the degree of crystallinity calculated (X_c), the amount of mesomorphic phase (X_m), and the crystallite size ($L_{(hkl)}$) measured according to the Scherrer equation. The results presented show that the degree of crystallinity increased with a decrease in mesophase content. This change, combined with an insignificant decrease in crystallite size, may account for the decrease in the strength of the two materials. The supramolecular structure became more ordered, with a lower proportion of mesophase and amorphous phase, which resulted in the materials becoming more brittle.

Conslusions

1. The PP nonwovens affected the microclimate conditions only slightly. The weather conditions had a greater effect on crop yield. In the warmer and wet season of 2017, higher yields were and we obtained on all the plots, regardless of mulching. The use of mulching did not significantly affect the quality or chemical composition of zucchini fruit.
2. Mulching the soil with PP nonwoven increased the water resistance index of the soil structure in comparison with the control and photodegradable PP mulch. However, the photodegradable PP nonwoven significantly increased the macoroaggregate content in the soil.
3. Modification of polypropylene with iron stearate causes a pronounced

Table 10. *Crystallinity degree and structural parameters of soil mulching PP nonwovens.*

Kind of mulching nonwoven	(hkl)	$L_{(hkl)}$	X_c	X_m
PP before	(110)	13.1	44.2	12.3
	(040)	12.6		
	(130)	11.3		
PP after	(110)	11.5	50.6	11.4
	(040)	11.5		
	(130)	10.4		
PP with act. of degr. before	(110)	12.1	53.9	8.2
	(040)	11.7		
	(130)	10.5		
PP with act. of degr. after	(110)	11.3	55.8	6.9
	(040)	11.4		
	(130)	10.5		

degradation of the materials for mulching. It loses mass per unit area and its mechanical properties deteriorate. Unmodified PP nonwoven does not undergo such significant changes.

4. It is not necessary to remove photodegradable PP nonwoven from the field at the end of the growing season (cost reduction), and very probably there are few negative effects of mixing them into the soil structure. Further research is expected to be conducted on the usefulness of new polymeric materials with degradation features and on the impact of their residues on the natural environment.
5. At the supramolecular level, the PP nonwoven with a photoactivator shows an increase in the degree of crystallinity and a decrease in mesophase content. The extent of these changes explains the decrease in the strength of such a material. A highly crystalline structure with small crystalline regions is brittle.

Acknowledgements

The research was financed by the European Regional Development Fund in the framework of BIOGRATEX (Biodegradable fibrous products), project POIG 01.03.01-00-07/08-09, funds assigned for 14-148-1-2117 statuary activity of the Lodz University of Technology, Department of Material and Commodity Sciences and Textile Metrology, Poland, and the subsidy for young researchers provided by the Ministry of Science and Higher Education of the Republic of Poland.

References

1. Siwek P. Warzywa pod folią i włókniną, Hortpress Sp. z o.o, Warszawa, Poland, 2010.
2. Siwek P, Libik A. Plastics covers in Polish horticulture. *Plasticulture* 2012; 9, 131: 65-73.
3. Siwek P, Domagała-Świątkiewicz I, Kalisz A. The influence of degradable polymer mulches on soil properties and cucumber yield. *Agrochimica* 2015; 59, 2: 108-123. DOI: 10.17660/eJHS.2017/82.2.5.
4. Martín-Closas L, Costa J., Pelacho AM. Agronomic effects of biodegradable films on crop and field environment. In: Soil degradable bioplastics for a sustainable modern agriculture. Malinconico M. (ed.), Springer-Verlag, GmbH, Germany, 2017: 67-104.
5. Kosterna E, Zaniewicz-Bajkowska A, Rosa R, Franczuk J, Borysiak-Marciniak I, Chromińska K. Effect of black synthetic mulches on the fruit quality and selected component of nutritive value of melon. *Acta Sci. Pol. Hortorum Cultus* 2010; 9, 3: 27-36.
6. Zawiska I, Siwek P. The effects of PLA biodegradable and polypropylene nonwoven crop mulches on selected components of tomato grown in the field. *Folia Hort.* 2014; 26, 2: 163-167. DOI: https://doi.org/10.1515/fhort-2015-0008.
7. Kołota E, Balbierz A. Yield potential and fruit quality of scallop squash (*Cucurbita pepo* L. var. *patissonina* Greb. f. radiata Nois.) cultivars grown for processing. *Acta Agrobot.* 2015; 68, 3: 261-266. DOI 10.5586/aa.2015.030.
8. Moreno MM, Moreno A. Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. *Sci. Hortic.* 2008; 116: 256-263.
9. Haapala T, Palonen P, Tamminen A, Ahokas J. Effects of different paper mulches on soil temperature and yield of cucumber (*Cucumis sativus* L.) in the temperate regime. *Agr. Food Sci.* 2015; 24: 52-58.
10. López JC, Pérez Parra J, Morales MA. Plastics in agriculture, Almeria, Spain, 2009: 55-60.
11. Siwek P, Libik A, Twarowska-Schmidt K, Ciechańska D, Gryza I. Zastosowanie biopolimerów w rolnictwie. *Polimery* 2010; 55, 11-12: 10-15.
12. Penczek S, Pretula J, Lewiński P. Polimery z odnawialnych surowców, polimery biodegradowalne. *Polimery* 2013; 58, 11-12: 835-846. DOI: dx.doi.org/10.14314/polimery.2013.835.
13. Tan Z, Yi Y, Wang H, Zhou W, Yang Y, Wang C. Physical and degradable properties of mulching films prepared from natural fibers and biodegradable polymers. *Appl. Sci.* 2016; 6: 147. DOI: doi: 10.3390/app6050147.
14. Ammala A, Bateman S, Dean K, et al. An overview of degradable and biodegradable polyolefins. *Prog. Polym. Sci.* 2011; 36: 1015-1049. DOI: https://doi.org/10.1016/j.progpolymsci.2010.12.002.
15. Roy PK, Surekha P, Raman R, Rajagopal C. Investigating the role of metal oxidation state on the degradation behaviour of LDPE. *Polym. Degrad. Stabil*. 2009; 94: 1033-1039. DOI: https://doi.org/10.1016/j.polymdegradstab.2009.04.025.
16. Pablos JL, Abrusci C, Marín I, et al. Photodegradation of polyethylenes: Comparative effect of Fe and Ca-stearates as pro-oxidant additives. *Polym. Degrad. Stabil.* 2010; 95: 2057-2064. DOI: 10.1016/j.polymdegradstab.2010.07.003
17. Gutiérrez-Villarreal MH, Zavala-Betancourt SA. A comparative study of the photodegradation of two series of cyclic olefin copolymers. *Int. J. Polym. Sci.* 2017. DOI: doi.org/10.1155/2017/1870814.
18. Zenteno A, Lieberwirth I, Catalina F, et al. Study of the effect of the incorporation of TiO_2 nanotubes on the mechanical and photodegradation properties of polyethylenes. *Compos Part B* 2017; 112: 66-73. DOI: https://doi.org/10.1016/j.compositesb.2016.12.007.
19. García-Montelongo XL, Martínez-de la Cruz A, Vázquez-Rodríguez S, Torres-Martínez LM. Photo-oxidative degradation of TiO_2/polypropylene films. *Mater. Res. Bull.* 2014; 51: 56-62. DOI: https://doi.org/10.1016/j.materresbull.2013.11.040.
20. López-Tolentino G, Cárdenas-Flores A, Ibarra-Jiménez L, Guerrero-Santos R. Field performance of a foto-biodegradable film for soil mulching in zucchini crop. *R.I.I.I.T.* 2016; 3, 19: 11-19.
21. Waterer D. Evaluation of biodegradable mulches for production of warm-season vegetable crops. *Can. J. Plant Sci.* 2010; 90: 737-743. DOI: https://doi.org/10.4141/CJPS10031.
22. Siwek P, Libik A, Kalisz A, Domagała-Świątkiewicz I. Zastosowanie prototypów wyrobów z PLA, PP z fotoaktywatorem i PBS w rolnictwie. W: Biodegradowalne wyroby włókniste. Krucińska I. (ed.), Wydawnictwo Politechniki Łódzkiej, Łódź, Polska, 2014: 392-416.
23. PN-R-04032. Soil and mineral materials. Sampling and determination of particle size distribution. 1998.
24. Yoder RE. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. *J. Am. Soc. Agron.* 1936; 28: 337-351.
25. Domagała-Świątkiewicz I, Siwek P. The effect of direct covering with biodegradable nonwoven film on the physical and chemical properties of soil. *Pol. J. Environ. Stud*. 2013; 22, 3: 667-674.
26. Domagała-Świątkiewicz I, Siwek P. Effect of plastic mulches and high tunnel raspberry production systems on soil physicochemical quality indicators. *Int. Agrophys.* 2018; 32: 39-47. DOI: https://doi.org/10.1515/intag-2016-0088
27. Siwek P. Modyfikacja warunków środowiska w uprawie ogórka i selera naciowego poprzez ściółkowanie gleby i bezpośrednie osłanianie roślin, Zesz. Nauk. AR w Krakowie, Ser. Rozprawy 2002; 279.
28. Kijchavengkul T, Auras R, Rubino M, Ngouajio M, Fernandez RT. Assessment of aliphatic–aromatic copolyester biodegradable mulch films. Part I: Field study, *Chemosphere* 2008; 71: 942-953. DOI: 10.1016/j.chemosphere.2007.10.074.
29. Snyder K, Grant A, Murray C, Wolff B. The effects of plastic mulch systems on soil temperature and moisture in central Ontario. *Horttechnology* 2015; 25, 2: 162-170.
30. Dvořák P, Hamouz K, Kuchtová P, Tomásek J, Erhartová D. *Black polypropylene non-woven textile as mulch in organic agriculture.* Bořivoj Šarapatka (ed.) Bioacademy. Proc. Organic farming – a response to economic and environmental challenges, Olomouc, Czech Republic, 2009.
31. Kołota E, Adamczewska-Sowińska K. Application of synthetic mulches and flat covers with perforated foil and agrotextile in zucchini. *Acta Sci. Pol. Hortorum Cultus* 2011; 10, 4: 179-189.
32. Marcinčin A, Hricová M, Körmendyová E, Ujhelyiová A, Broda J, Janicki J. Polypropylene/(polyethylene terephthalate/polybuthylene terephthalate) blend fibres: phasestructure and mechanical properties. *FIBRES & TEXTILES in Eastern Europe* 2006; 14, 5(59): 92-97.
33. Rabiej M. Application of immune and genetic algorithms to the identification of a polymer based on its X-ray diffraction curve. *J. Appl. Cryst.* 2013; 46: 1136-1144. DOI: https://doi.org/10.1107/S0021889813015987.

Received 30.10.2017 Reviewed 31.01.2018