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Wpływ wybranych czynników agrotechnicznych na warunki środowiska, plonowanie i jakość cukinii w uprawie ekologicznej

Autoreferat rozprawy doktorskiej

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doświadczeń oraz całego okresu pracy badawczo-rozwojowej

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1. STRESZCZENIE

Celem badań stanowiących podstawę rozprawy doktorskiej była ocena wpływu metod uprawy gleby, roślin okrywowych, ściółek organicznych i syntetycznych oraz osłon bezpośrednich na warunki środowiska, plonowanie i jakość owoców cukinii w uprawie ekologicznej. Zaakcentowano także kształtowanie się właściwości fizyko-chemicznych i mikrobiologicznych gleby. Wyniki badań zostały zamieszczone w trzech oryginalnych publikacjach naukowych. W skład rozprawy doktorskiej wchodzi też monografia zawierająca przegląd światowej literatury na temat efektów stosowania różnego rodzaju ściółek w uprawie warzyw dyniowatych.

Prace badawcze wykonane w latach 2016-2018 wykazały, że najbardziej zwiększającym plonowanie sposobem przygotowania gleby na stanowisku po roślinach okrywowych (mieszanka koniczyny białej i rajgrasu włoskiego) była pasowa uprawa glebogryzarką bezpośrednio przed sadzeniem cukinii. Spośród zabiegów agrotechnicznych związanych z osłanianiem gleby i roślin szczególnie efektywnym pod względem plonowania było bezpośrednie przykrywanie roślin włókniną i siatką. Ściółkowanie wpłynęło pozytywnie w latach chłodnych i z mniejszą ilością opadów. Nie odnotowano znaczących różnic w składzie chemicznym owoców cukinii pochodzących z badanych obiektów.

Słowa kluczowe: *Cucurbita pepo* L. convar. *giromontina* Greb., uprawa gleby, ściółkowanie, osłony bezpośrednie, rolnictwo ekologiczne, plonowanie, jakość owoców

2. SUMMARY

The aim of the research constituting the doctoral dissertation was to evaluate the impact of soil cultivation practices, cover crops, organic and synthetic mulches and direct covers on environmental conditions, yielding and quality of zucchini fruits in organic cultivation. The shaping of physicochemical and microbiological properties of soil was also emphasized. The research results were published in three original scientific publications. The doctoral dissertation also includes a monograph containing a review of world literature dedicated to the effects of using various types of mulch in the cultivation of cucurbit crops.

The research works carried out in 2016-2018 showed that streep rototilling directly before planting zucchini was a soil cultivation method which, to the greatest extent, increases yielding in the field where cover crops (white clover and Italian ryegrass mixture) were grown. Among the agrotechnical treatments related to soil and plants covering, using nonvovens and nets to plants covering was the most effective in terms of yielding. Mulching had a positive effect in cool years with less rainfall. There were no significant differences in chemical composition of zucchini fruits from the tested objects.

Słowa kluczowe: *Cucurbita pepo* L. convar. *giromontina* Greb., soil cultivation, mulching, direct covers, organic farming, yielding, quality of fruits

3. PUBLIKACJE STANOWIĄCE ROZPRAWĘ DOKTORSKĄ

Rozprawa doktorska obejmuje jedną pracę przeglądową wraz z trzema artykułami badawczymi powiązanymi ze sobą tematycznie.

Publikacja nr 1

Bucki P., **Siwek P**. **2019**. Organic and non-organic mulches – impact on environmental conditions, yield, and quality of Cucurbitaceae. Folia Horticulturae, 31(1): 129-145.

Punktacja MNiSW$_{2019}$: 20

IF$_{2019}$: 1,836

Publikacja nr 2

Bucki P., **Siwek P**., **Domagała-Świątkiewicz** I., **Puchalski M**. **2018**. Effect of agri-environmental conditions on the degradation of spunbonded polypropylene nonwoven with a photoactivator in mulched organically managed zucchini. FIBRES & TEXTILES in Eastern Europe, 26, 2(128): 55-60.

Punktacja MNiSW$_{2018}$: 30

IF$_{2018}$: 0,677

Publikacja nr 3

Bucki P., **Siwek P**., **Mora Ojeda AL**. **2021**. Characterisation of two direct covers made of PP and HDPE in the organic production of zucchini. FIBRES & TEXTILES in Eastern Europe, 29, 3(147): 14-20.

Punktacja MNiSW$_{2021}$: 40

IF$_{2021}$: 0,775

Publikacja nr 4

Bucki P., **Regdos K**., **Siwek P**., **Domagała-Świątkiewicz I**., **Kaszycki P**. **2021**. Impact of soil management practices on yield quality, weed infestation and soil microbiota abundance in organic zucchini production. Scientia Horticulturae, 281 (109989).

Punktacja MNiSW$_{2021}$: 140

IF$_{2020}$: 3,463

Sumaryczna punktacja MNISW: 230

Sumaryczny IF: 6,751

4. WPROWADZENIE

Cukinia (*Cucurbita pepo* convar. *giromontina* Greb.) jest warzywem należącym do grupy odmian botanicznych dyni zwyczajnej podobnie jak m.in. kabaczek, z którym jest niesłusznie utożsamiana. Została udomowiona już w czasach starożytnych, a pierwsze wzmianki dotyczące jej uprawy datuje się na około 8000 lat p.n.e. (Rubatzky i Yamaguchi 1997). Owoce cukinii cechują się niską kalorycznością i pomimo dużej zawartości wody mają wyższą wartość odżywczą i prozdrowotną w porównaniu do ogórka (Gajc-Wolska i Skąpski 1994). Jak podaje Biesiada i in. (2007) owoce mniej wyrośnięte zawierają więcej witaminy C, fosforu i potasu oraz mniej azotanów w porównaniu do bardziej dojrzałych. Roślina nie kumuluje w owocach metali ciężkich i innych toksycznych substancji. Jest szczególnie popularna w krajach Europy Zachodniej. W Polsce do niedawna była uważana za roślinę przeznaczoną jedynie do uprawy amatorskiej na niewielką skalę. Ostatnie lata wskazują jednak na wzrost popularności tego warzywa wśród konsumentów, co znajduje odzwierciedlenie w zajmowanej przez niego powierzchni uprawnej. Według danych GUS w 2011 roku razem z kabaczkiem i dynią olbrzymią cukinia należała do 20 najczęściej uprawianych w naszym kraju roślin warzywnych (Borowiak 2013). Obecnie na rynku znajduje się szereg odmian krajowych i zagranicznych cukinii do uprawy towarowej w polu i pod osłonami. Najbardziej cenione przez polskich konsumentów są odmiany o owocach zielonych cylindrycznego kształtu.

Pochodzi z południowo-wschodniej części Ameryki Północnej, co determinuje jej wymagania względem środowiska. Mimo, że jest rośliną ciepłolubną to jednak ma mniejsze wymagania termiczne niż ogórek i może być z powodzeniem uprawiana na terenie całego kraju. W odróżnieniu od pozostałych gatunków z rodziny Dyniowatych (*Cucurbitaceae*) większość odmian tej rośliny ma pokrój krzaczasty. Na pędzie głównym wyrastają zarówno kwiaty męskie jak i żeńskie. Charakteryzuje się szybkim przyrostem owoców i długim okresem zbiorczym. Jej owoce mogą osiągać nawet do 1 metra długości jednak najczęściej spożywa się te o długości ok. 15-25 cm lub nawet krótsze. Częsty zbiór owoców stymuluje roślinę do dalszego rozwoju i wytwarzania nowych zawiązków. Duża powierzchnia liści i główna masa korzeni zlokalizowana na głębokości do ok. 30 cm to główne cechy, które stanowią o celowości modyfikowania warunków środowiskowych wokół roślin. Wysoka temperatura oraz wilgotność powietrza i gleby sprzyjają otrzymaniu wyższych plonów, jednak zbyt obfite i długotrwałe opady mogą spowodować przyspieszenie i wcześniejsze zakończenie wegetacji cukinii co zaobserwował Silva i in. (2020). W okresie plonowania niskie temperatury często są przyczyną deformacji owoców w wyniku zwolnienia tempa wzrostu, a niedobór wody powoduje słabe zawiązywanie owoców i ich zasychanie od strony wierzchołkowej (Podymniak 2006). Na skutek nawadniania w przypadku niektórych odmian plon handlowy wzrósł o ok. 85%, a nawet uległ podwojeniu (Rolbiecki 2007, Sałata i Stepaniuk 2012).

Ściółkowanie gleby jest podstawową metodą kształtowania warunków środowiska wokół roślin. Zabieg ten poprawia efektywność wykorzystania wody przez rośliny, ogranicza ewaporację, zachwaszczenie i tym samym potrzebę stosowania herbicydów (Silva i in. 2020). Jest to szczególnie istotne w uprawie gatunków o mniejszym znaczeniu gospodarczym takich jak cukinia, dla których liczba zarejestrowanych substancji czynnych herbicydów jest niewielka (Dobrzański 2016, Matyjaszczyk i Dobrzański 2017). Poprzez osłanianie gleby przeciwdziała się destruktywnemu oddziaływaniu silnych opadów deszczu, co wpływa korzystnie na warunki fizyczne (poprawa struktury agregatowej) i chemiczne (zapobieganie wypłukiwania składników pokarmowych do głębszych warstw) gleby. W uprawie warzyw dyniowatych do ściółkowania najczęściej wykorzystuje się czarne folie polietylenowe (PE) o grubości 0,012-0,05 mm i przepuszczalne dla wody i gazów włókniny polipropylenowe (PP) o masie powierzchniowej 50-60 g m^{-2} o tej samej barwie, ograniczające zachwaszczenie i absorbujące promieniowanie słoneczne (Scaracia-Mugnozza i in. 2011, Siwek i Libik 2012). W badaniach krajowych, gdzie do ściółkowania stosowano folie PE o czarnej barwie uzyskano lepsze wyniki pod względem plonowania w porównaniu do włóknin PP (Kołota i Adamczewska-Sowińska 2011, Kołota i Balbierz 2015), co mogło być spowodowane korzystniejszymi warunkami termicznymi panującymi pod folią PE. Jak podaje Lamont (1996) wzrost temperatury gleby jest zależny od wydzielania ciepła ze ściółki do powietrza w przestworach glebowych. Ściółki pochodzenia naturalnego stanowią alternatywę dla syntetycznych materiałów ponieważ nie obciążają środowiska naturalnego. Ponadto w trakcie rozkładu uwalniają do gleby znaczne ilości związków mineralnych (zwłaszcza ściółki ze świeżych roślin bobowatych lub ich mieszanek z trawami) i poprawiają strukturę gleby. Są one jednak stosunkowo uciążliwe w stosowaniu z powodu konieczności ich systematycznego uzupełniania w trakcie wegetacji. Kompromisem mogą być wprowadzane do praktyki zwłaszcza w krajach wysoko rozwiniętych (np. Japonia, Francja) materiały polimerowe ulegające degradacji w jednym okresie wegetacji (Briassoulis i in. 2010). Wpisują się one przez to w praktykę rolnictwa ekologicznego. Przyorane pozostałości takich ściółek po zbiorze plonu z czasem ulegają degradacji. Na jej przebieg wpływają głównie warunki środowiskowe (temperatura, uwilgotnienie, pH gleby), aktywność mikrobioty glebowej oraz ilość związków przyspieszających starzenie się i pogorszenie właściwości strukturalnych materiału (Lucas i in. 2008, Sulak i in. 2012). Złożoność tego procesu sprawia, że bezpieczniejsze dla środowiska są biopolimerowe ściółki pochodzenia roślinnego (np. celulozowe i skrobiowe), które rozkładają się do węgla, CO_2 i wody (Kasirajan i Ngouajio 2012). Doświadczenia przeprowadzone w warunkach klimatycznych Meksyku wykazały, że ściółki z aktywatorem fotodegradacji zaczęły degradować już w pierwszych tygodniach od rozłożenia w miejscach wystawionych na działanie promieni słonecznych (López-Tolentino i in. 2016). Krytyczny okres konkurencji z chwastami głównie o wodę i składniki pokarmowe przypada w początkowym etapie wegetacji cukinii. Jej uprawa na ściółkach degradowalnych może sprostać temu zadaniu do czasu pokrycia gleby przez rośliny.

Szeroko rozpowszechnionym zabiegiem w Polsce poprawiającym warunki mikroklimatyczne z powodu niskich kosztów i nakładów pracy jest osłanianie bezpośrednie roślin. Daje możliwość zintensyfikowania upraw, zmodyfikowania technologii produkcji, sterowania nią, a także wprowadzenia nowych gatunków. Osłanianie roślin jest szczególnie efektywne w przypadku roślin szybko rosnących, u których wymagany jest częsty zbiór, tj. ogórek i cukinia. Szacuje się, że powierzchnia upraw w tej technologii w naszym kraju wynosi 7000 ha. Do lat 90-tych stosowane były w tym celu folie o różnej perforacji jednak obecnie duży udział w strukturze upraw osłanianych mają włókniny polipropylenowe (PP) z uwagi na wysoką przepuszczalność i możliwość dłuższego pozostawienia na roślinach. Jedną z ich największych zalet jest mała masa powierzchniowa (17-23 g m^{-2}), która jest średnio 2.5 razy mniejsza niż folii perforowanej dzięki czemu nie utrudnia rozwoju roślin (Kim i in. 2004, Yousfani i in. 2012, Turaka i in. 2018, Siwek 2020). Jak podaje Marasovic i Kopitar (2019) cytując wielu autorów zastosowanie osłon powodowało przyspieszenie we wzroście wielu gatunków roślin i zwiększyło plony. Przykrywanie zasiewów rzodkiewki włókniną przyspieszyło kiełkowanie i przyczyniło się do równych wchodów. Ponadto osłanianie włókniną PP pozwoliło uzyskać m.in. wyższy plon wczesny i handlowy kalarepy, papryki, ogórka i sałaty. Osłanianie bezpośrednie włókniną spowodowało wzrost wydajności cukinii do 44% w porównaniu do obiektu kontrolnego (Kołota i Adamczewska-Sowińska 2011). Nowością na rynku są siatki polietylenowe wykonane m.in. z polietylenu wysokiej gęstości (HDPE) o różnej masie powierzchniowej i gęstości oczek. Charakteryzują się większą przepuszczalnością powietrza i wody oraz wytrzymałością mechaniczną niż włókniny. Starannie założone osłony są przyjazną środowisku metodą ochrony roślin przed szkodnikami (Siwek 2010). Najlepsze rezultaty w uprawie cukinii Kołota i Adamczewska-Sowińska (2011) osiągnęli poprzez równoczesne osłanianie roślin i gleby materiałami syntetycznymi.

Stanowisko pod uprawę cukinii powinno być żyzne, dobrze nagrzewające się o dużej zawartości próchnicy wpływającej na poprawę stosunków wodno-powietrznych oraz pojemności sorpcyjnej i wodnej gleby. Źródłem substancji organicznej w glebie w okresie spadku pogłowia bydła są nawozy zielone uprawiane na przyoranie. Najczęściej są to gatunki szybko rosnące o dużej biomasie np. motylkowate drobnonasienne. Pod tym względem bardziej korzystne są jednak mieszanki bobowato-trawiaste ponieważ ograniczona jest wówczas konkurencja wewnątrzgatunkowa względem substancji pokarmowych pobieranych z różnych warstw gleby (Sainju i in. 2005, Staniak 2008, Helgadóttir i in. 2018). Rośliny bobowate żyją w symbiozie z bakteriami brodawkowymi z rodzaju *Rhizobium*, które wzbogacają glebę w azot wiążąc go z atmosfery. Trawy z kolei intensywnie wykorzystują azot znajdujący się w glebie, a następnie w miarę rozkładu biomasy powoli go uwalniają. Ponadto gęsto się rozkrzewiają i zmniejszają zachwaszczenie oraz erozję (Kołota i Adamczewska-Sowińska 2013, Robačer i in. 2016, Sharma i in. 2018). W wyniku oddziaływania następczego roślin okrywowych cukinia reaguje wzrostem plonowania, co potwierdzono w badaniach Montemurro i in. (2013). Na wzrost i utrzymanie wysokiej aktywności biologicznej gleby ma wpływ szereg czynników, wśród których wymienia się wykorzystanie roślin okrywowych, ściółek i wprowadzenie do praktyki uproszczeń uprawowych (Sun i in. 2018, Branco i in. 2017, Nachimuthu i in. 2017). Odchodzenie od uprawy płużnej (zwłaszcza corocznej) pomimo wynikających z niej wielu korzyści staje się obecnie coraz bardziej zalecane. Powodem tego jest m.in. dbałość o glebę i redukcja kosztów produkcji. Uprawa bez pługa koncentruje się na spulchnianiu i mieszaniu wierzchniej warstwy gleby. Zadanie mieszania resztek pożniwnych oraz poprawy napowietrzenia i pozostałych właściwości fizycznych struktury gleby przypisuje się makrobiocie glebowej, głównie dżdżownicom (Ciemniak 2018). Uproszczone systemy uprawy roli wraz z zabiegami zachowującymi resztki pożniwne zwiększają zawartość organicznego węgla i całkowitego azotu w postaci materii organicznej, a także biomasy mikroorganizmów glebowych (Zuber i Villamil 2016, Jat i in. 2018). Uprawa bezorkowa sprzyja mikrobiocie glebowej i jej aktywności metabolicznej (Tomkowiak i in. 2017). Jedną z metod płytkiego spulchniania gleby jest gryzowanie. Zabieg ten niszczy, rozdrabnia i miesza pozostałości darni z glebą. Może stanowić dobrą alternatywę dla uprawy płużnej w przygotowaniu stanowiska pod uprawę warzyw po roślinach okrywowych.

W rolnictwie obecnie sukcesywnie wycofuje się wiele substancji aktywnych stosowanych do ochrony roślin. Przypuszcza się, że polityka obostrzeń w zakresie liczby dopuszczonych środków ochrony roślin będzie coraz bardziej rygorystyczna. W ramach Europejskiego Zielonego Ładu i innych inicjatyw proekologicznych zakłada się, że do 2030 r. rolnictwo ekologiczne ma obejmować 25% powierzchni gruntów rolnych, a ilość stosowanych pestycydów ma ulec zmniejszeniu o 50%. Stąd też wszelkie działania mające na celu poprawę warunków środowiska wokół uprawianych roślin nabierają coraz większego znaczenia (Bucki 2021). Na tle pozostałych warzyw z rodziny *Cucurbitaceae* cukinia odznacza się przede wszystkim wyjątkową plennością oraz tolerancją na występowanie agrofagów. Dotyczy to zwłaszcza odmian mieszańcowych z cechą partenokarpii. Wyżej wymienione czynniki predysponują cukinię do uprawy ekologicznej. Badania wskazują na zbliżoną wielkość plonu handlowego kilku odmian cukinii w uprawie ekologicznej i konwencjonalnej (Babik i in. 2011).

5. CEL PRACY

Zasadniczym celem prowadzonych doświadczeń było porównanie zróżnicowanych metod przygotowania gleby oraz elementów agrotechniki z zastosowaniem osłon dla gleby i roślin na stanowisku po roślinach okrywowych w uprawie cukinii. Do badań wytypowano kilka metod uprawy gleby, a także rodzajów ściółek i osłon bezpośrednich. Synteza wyników badań miała za zadanie wytypowanie optymalnych rozwiązań i zaleceń agrotechnicznych dla tego gatunku w uprawie o charakterze ekologicznym.

6. MATERIAŁ I METODYKA

Trzy doświadczenia polowe w systemie uprawy ekologicznej przeprowadzono w latach 2016-2018 na terenie Warzywniczej Stacji Doświadczalnej Uniwersytetu Rolniczego w Mydlnikach.

Roślinny materiał badawczy stanowiła cukinia (*Cucurbita pepo* convar. *giromontina* Greb.), odmiana partenokarpiczna ‘Partenon F1’ (HILD Samen). Odmiana ta jest przeznaczona głównie do uprawy wiosennej i dobrze plonuje również w warunkach stresowych. Wytwarza cylindryczne owoce ciemnozielone z błyszczącą skórką. Rośliny mają charakter krzaczasty i otwarty pokrój ułatwiający zbiór.

Rozsadę cukinii wysadzano na miejsce stałe w drugiej połowie maja w dwurzędowych pasach w rozstawie 100 x 80 x 100 cm i uprawiano do połowy września. Nawożenie mineralne przeprowadzono w oparciu o wyniki analizy gleby. W razie potrzeby rośliny nawadniano i odchwaszczano ręcznie. W okresie wegetacji rośliny zasilano nawozami organicznymi, a zabiegi ochronne preparatami miedziowymi przeprowadzano gdy wzrastało zagrożenie ze strony mącznika prawdziwego.

Każde z doświadczeń założono metodą pasów prostopadłych (split-block) w 4 powtórzeniach po 8 roślin. Stanowisko uprawowe rok przed przed założeniem doświadczenia obsiano mieszanką złożoną z *Trifolium repens* L. odmiany ‘RD 84’ i *Lolium multiflorum* Lam. odmiany ‘Gaza’ w proporcji 60:40%. W pierwszym doświadczeniu czynnikiem badawczym były dwa rodzaje czarnych włóknin polipropylenowych o masie powierzchniowej 50 g m^{-2}, przy czym jedna z aktywatorem fotodegradacji (stearynianem żelaza) w ilości 0,1%. W drugim doświadczeniu ocenie poddano osłony bezpośrednie: włókninę polipropylenową o masie powierzchniowej 20 g m^{-2} i dzianinową siatkę z polietylenu wysokiej gęstości o trójkątnych oczkach o wymiarach 4,9 x 1,5 x 5,1 mm o masie powierzchniowej 38 g m^{-2}. Były one utrzymywane na roślinach do rozpoczęcia zbiorów. W trzecim doświadczeniu przedmiotem badań było pięć różnych sposobów przygotowania i pielęgnacji gleby, do których należała uprawa płużna wykonana jesienią (na głębokość 25 cm), wiosną (na głębokość 15 cm) oraz pasowe uprawki glebogryzarką wykonane wiosną (na głębokość 10 cm). W ostatniej metodzie wyszczególniono obiekty ze ściółkowaniem pokosem z mieszanki bobowato-trawiastej, czarną włókniną polipropylenową o masie 50 g m^{-2} i bez osłaniania gleby.

W doświadczeniach przeprowadzono następujące pomiary, analizy i obserwacje:

1) Analiza ilościowa plonu owoców z podziałem na klasy jakości (doświadczenie 1, 2, 3) - owoce cukinii zbierano trzy razy w tygodniu, dzieląc je na dwie klasy wielkości (o długości

15-21 cm oraz >21 cm) i jakości (I i II klasa). W pierwszych terminach zbiorów uwzględniono również owoce długości 10-14 cm. Zbiory rozpoczynano w pierwszej połowie czerwca, a kończono w pierwszej połowie września. Plon handlowy był określony zgodnie z normą PN-R-75541: UN/ECE FFY-41. Obejmował on owoce zdrowe o kształcie typowym dla odmiany, bez objawów chorobowych oraz uszkodzeń mechanicznych i spowodowanych przez szkodniki. Do pierwszej klasy jakości klasyfikowano owoce wolne od uszkodzeń, zdrowe i wykazujące niewielkie wady kształtu i koloru. W klasie drugiej zaliczano cukinie spełniające wymagania minimalne, ale mogące mieć większe wady kształtu i barwy, niewielkie oparzenia słoneczne i zabliźnione pęknięcia. Owoce nie spełniające norm minimalnych zaklasyfikowano jako poza wyborem. W doświadczeniu z osłanianiem bezpośrednim roślin oceniono również plon wczesny, który stanowił 1/3 wszystkich zbiorów.

2) Ocena wartości biologicznej owoców (doświadczenie 1, 2, 3) - do analiz laboratoryjnych wybierano owoce I klasy jakości o długości 17-18 cm losowo z każdego powtórzenia. Oznaczono w owocach w warunkach laboratoryjnych:

- zawartość suchej masy metodą suszarkową wg Pijanowskiego i in. (1964),
- kwas askorbinowy metodą Tillmansa (Tillmans i in. 1932),
- barwniki (chlorofile i karotenoidy) metodą Lichtenthalera i Wellburna (1983),
- cukry ogółem metodą antronową (Yemm i Willis 1954),
- związki fenolowe metodą Folina-Ciocalteu (Singleton i in. 1999),
- potencjał antyoksydacyjny przy użyciu rodnika DPPH metodą Branda-Williamsa (1995).

3) Pomiary czynników mikroklimatu, przeprowadzone na początku wegetacji (doświadczenie 1 i 2, 3 – wybrane parametry):

- temperatura gleby na głębokości 10 cm oraz powietrza za pomocą czujników HOBO firmy Onset,
- wilgotność gleby za pomocą miernika wilgotności HH2 do sond wilgotności gleby Delta-T Devices,
- wilgotność powietrza za pomocą urządzenia Hygromer A1 rotronic,
- zawartość CO_2 w powietrzu za pomocą czujnika Telaire 7001,
- promieniowanie fotosyntetycznie czynne za pomocą spektroradiometru LI-COR 189B z czujnikiem liniowym.

4) Pomiary fitometryczne roślin (doświadczenie 1 i 2) przeprowadzone na początku czerwca w początkowej fazie kwitnienia roślin (po 3 rośliny z powtórzenia):

- liczba liści właściwych,
- liczba kwiatów męskich,

- liczba kwiatów żeńskich.

5) Ocena stanu i stopnia zachwaszczenia (doświadczenie 2 i 3) przeprowadzona metodą ramkowo-wagową przy użyciu ramki o wymiarach 25 x 25 cm w trzech losowo wybranych miejscach. Policzono liczbę sztuk poszczególnych gatunków chwastów i ich łączną świeżą masę.

6) Analiza włóknin przeznaczonych do ściółkowania (doświadczenie 1) w trakcie i po zakończeniu wegetacji. Włókniny zostały ocenione pod kątem struktury (metodą szerokokątnej dyfrakcji rentgenowskiej WAXD przy użyciu dyfraktometru X'Pert PRO), parametrów wytrzymałościowych (za pomocą maszyny Instron 5511) i stopnia degradacji za pomocą wag precyzyjnych PS.R1.

7) Ocena stanowiska glebowego (doświadczenie 1) – oznaczono wybrane właściwości fizyko-chemiczne gleby na głębokości 0-20 cm w doświadczeniu z wykorzystaniem włóknin do ściółkowania.

8) Analiza liczebności mikroorganizmów (doświadczenie 3) – do analiz mikrobiologicznych pobierano glebę z głębokości 10-20 cm przy użyciu laski Egnera cztery razy i oznaczono liczebność:

- bakterii,
- bakterii z rodzaju *Azotobacter*,
- grzybów i drożdży.

Uzyskane dane opracowano statystycznie metodą jednoczynnikowej analizy wariancji (ANOVA) za pomocą testów analizy wariancji Duncana przy poziomie istotności p=0.05, Fisher'a i Tukey'a przy poziomie istotności $p \leq 0,05$ w programie STATISTICA 13.0 (13.3) oraz dwuczynnikowej w przypadku laboratoryjnych analiz mikrobiologicznych.

7. STRESZCZENIE ZAŁĄCZONYCH PUBLIKACJI

Tematem publikacji nr 1 było dokonanie przeglądu informacji na temat wykorzystania ściółek w uprawie cukinii i innych gatunków z rodziny Dyniowatych. W monografii zaprezentowano dużą liczbę prac źródłowych o zasięgu międzynarodowym, co wskazuje na skuteczność ściółkowania w wielu aspektach, niezależnie od strefy klimatycznej. Wysokie wymagania cieplne i wodne uwarunkowane pochodzeniem i dużą dysproporcją płytko korzeniącego się systemu korzeniowego do części nadziemnych, a także szybkie tempo wzrostu to podstawowe czynniki determinujące wysoką efektywność tego zabiegu w uprawie warzyw dyniowatych. Taka technologia uprawy w regionach chłodnych i o krótkim okresie wegetacji może stanowić warunek decydujący o jej powodzeniu.

W pracy scharakteryzowano ściółki organiczne oraz polimerowe: syntetyczne i podlegające procesom degradacji. Ich wpływ na otaczające środowisko jest ściśle zależny od rodzaju użytego materiału, m.in. jego grubości, barwy, struktury i właściwości optycznych. Najszerszy przegląd danych literaturowych dotyczył tworzyw sztucznych, głównie folii ldPE (wykonanej z polietylenu niskiej gęstości) i włókniny PP o czarnym zabarwieniu i wysokiej absorpcji promieni słonecznych, których wykorzystanie stale wzrasta w nowoczesnej gospodarce rolnej. W związku z rosnącym zanieczyszczeniem środowiska syntetycznymi odpadami rolniczymi prowadzone są intensywne badania i wprowadzane do praktyki polimery biodegradowalne.

Ściółkom przypisuje się przede wszystkim rolę ochronną gleby przed bezproduktywnym parowaniem wody, erozją i wymywaniem substancji pokarmowych w głąb profilu glebowego. Odgrywają one znaczącą rolę w ograniczaniu zachwaszczenia poprzez uniemożliwienie kiełkowania lub tworzenie bariery mechanicznej dla chwastów. Największy wpływ na modyfikowanie fizycznych i chemicznych właściwości gleby mają ściółki organiczne. Podczas rozkładu wchodzą one w interakcje z glebą powodując m.in. zmiany w zawartości składników pokarmowych i węgla organicznego. W kontekście ochrony roślin ściółkowanie ma charakter wielowymiarowy. Może posłużyć do dezynfekcji gleby w procesie solaryzacji, zmniejszyć populację szkodników oraz ograniczyć rozwój chorób poprzez odizolowanie roślin i owoców od gleby. Analiza porównawcza wyników badań nie pozwoliła jednoznacznie stwierdzić pozytywnego wpływu ściółkowania na wielkość i jakość plonu, a jedynie potwierdzić dużą zależność warunków środowiska od zastosowanego rodzaju ściółek.

W publikacji nr 2 wykazano, że ściółkowanie gleby czarnymi włókninami PP wpłynęło korzystnie na rozwój roślin szczególnie w początkowym okresie wegetacji. Spośród badanych czynników środowiska bardzo widoczne było utrzymywanie się wyższej wilgotności gleby, która ponadto charakteryzowała się wyższą temperaturą minimalną i niższą maksymalną w porównaniu do gleby nieosłanianej. Potwierdza to właściwości izolacyjne i przepuszczalność włóknin dla powietrza i wody. Plonowanie cukinii było bardziej zależne od przebiegu warunków pogodowych niż od samego zabiegu ściółkowania, szczególnie w latach cieplejszych i z wyższą sumą opadów. Ściółkowanie okazało się pod tym względem korzystne jedynie w mniej sprzyjających warunkach atmosferycznych (rok 2016). Nie odnotowano wyraźnych różnic w większości badanych właściwości fizycznych gleby i jakości owoców cukinii pomiędzy badanymi obiektami. Uzyskano bardzo zbliżony plon ogólny w stosunku do handlowego w obu latach doświadczenia niezależnie od kombinacji, co świadczy o wysokiej zdrowotności plantacji.

Ważnym wynikiem było ocenienie tempa degradacji włókniny z fotodegradantem w połowie (ubytek 40% masy) i po zakończeniu sezonu (ubytek 52% masy) w porównaniu do nowej. Jej właściwości strukturalne również uległy znacznemu pogorszeniu. Dowodzi to możliwości pozostawienia na polu resztek zużytego materiału po uprawie i jego mineralizacji. Odnotowano również duże zabrudzenie cząstkami gleby standardowej włókniny PP pomimo starannego czyszczenia przed badaniem laboratoryjnym. Może to spowodować ograniczenie przepuszczalności takiej ściółki w kolejnej uprawie.

Wyniki zawarte w publikacji nr 3 potwierdzają istotny wpływ osłaniania bezpośredniego na mikroklimat i efekt przyspieszonego wzrostu w uprawie ekologicznej cukinii. Pod wpływem osłaniania wyraźnie poprawiły się warunki termiczne i wzrosła wilgotność powietrza wokół uprawianych roślin. Wyższą efektywnością pod tym względem cechowała się włóknina polipropylenowa w porównaniu do siatki ze względu na swój przepuszczalny charakter na całej powierzchni. Osłony ograniczały transmisję promieniowania PAR do roślin cukinii. Stężenie CO_2 w powietrzu było porównywalne we wszystkich obiektach, przy czym najwyższe wartości odnotowano pod włókniną. Następstwem bardziej sprzyjającego mikroklimatu było przyspieszenie rozwoju roślin i wcześniejsze owocowanie. Średnia z trzech lat badań wykazała istotny wzrost plonu wczesnego (1/3 zbiorów) o 35% i 22% dla obiektów osłanianych odpowiednio siatką i włókniną w porównaniu do roślin kontrolnych.

W korzystniejszych warunkach środowiska kształtujących się pod osłonami lepiej rozwijały się także rośliny konkurencyjne. Wśród nich dominowały chwasty ciepłolubne np. żółtlice i chwastnica jednostronna oraz szybko kiełkujące np. komosa biała. Zachwaszczenie w obiektach, gdzie stosowano osłony było średnio o 50% większe w porównaniu do obiektu kontrolnego. Analizy składu chemicznego owoców wykazały jedynie różnice w zawartości związków fenolowych na korzyść owoców pochodzących z roślin osłanianych, zwłaszcza siatką HDPE.

W publikacji nr 4 zamieszczono wyniki świadczące o korzyściach pasowej uprawy glebogryzarką w porównaniu do klasycznej uprawy płużnej na stanowisku po wieloletniej mieszance bobowato-trawiastej. Największy plon owoców cukinii uzyskano w obiektach, w których glebę poddano działaniu glebogryzarki niezależnie od materiału do ściółkowania. Wiosenna uprawa glebogryzarką zwiększyła plon owoców o 25,3% i 34,3% odpowiednio w porównaniu do orki wykonanej jesienią i wiosną. Mimo tego na głębokości 10 cm odnotowano w nich nieznacznie niższą temperaturę gleby w porównaniu do obiektów, gdzie zastosowano do uprawy pług. Spośród badanych sposobów przygotowania gleby uproszczona uprawa okazała się jednym z najbardziej ograniczających zachwaszczenie, szczególnie wraz z dodatkowym ściółkowaniem materią organiczną. Podobnie jak w poprzednich doświadczeniach ocena laboratoryjna owoców nie pozwoliła jednoznacznie wskazać najlepszego wariantu uprawy gleby. Najwyższy potencjał antyoksydacyjny oraz zawartość związków fenolowych stwierdzono w owocach w 2018 r., niezależnie od badanych obiektów.

Ważnym osiągnięciem badawczym była analiza porównawcza liczebności mikrobioty glebowej. Wykazano, że uprawa gleby glebogryzarką ze ściółkowaniem materią organiczną sprzyja bytowaniu i rozwojowi mikroorganizmów, głównie bakterii glebowych, na co wpływ mogła mieć stopniowa mineralizacja ściółki i wyższa wilgotność gleby. Na podstawie uzyskanych wyników można stwierdzić, że uprawa płużna na stanowisku po roślinach okrywowych niezależnie od terminu wykonania nie powinna być rekomendowana do przygotowania gleby pod uprawę cukinii.

8. WNIOSKI:

1. Uprawa ekologiczna warzyw dyniowatych, w tym cukinii w glebie ściółkowanej jest efektywna pod wieloma względami. W znacznym stopniu ściółki modyfikują środowisko otaczające rośliny i w wielu pracach badawczych wpływały korzystnie na plonowanie oraz jakość owoców.
2. Cukinia w odróżnieniu od większości warzyw z rodziny *Cucurbitaceae* może być uprawiana metodą pasowo-rzędową w otoczeniu roślin okrywowych z uwagi na jej krzaczasty pokrój. Systematycznie koszone rośliny okrywowe, służące do ściółkowania stanowiły bogate źródło materii organicznej stopniowo uwalniające składniki pokarmowe.
3. Czarne włókniny PP zastosowane jako ściółki zmniejszały wahania temperatury gleby i ograniczały ewaporację. Ich zastosowanie nie wpłynęło znacząco na właściwości fizyczne gleby. Odnotowano jedynie wyższy wskaźnik wodoodporności struktury gleby pod standardową włókniną PP oraz większą zawartość wodoodpornych makroagregatów pod włókniną fotodegradowalną PP.
4. Wyraźna degradacja włókniny PP modyfikowanej stearynianem żelaza była widoczna już po 2 miesiącach ekspozycji na działanie promieni słonecznych. Po zakończeniu wegetacji redukcja masy włókniny w stosunku do nowej przekroczyła 50%. Szybkie jej osłabienie mechaniczne świadczy o możliwości pozostawienia resztek ściółki na polu i wymieszania ich z glebą po zakończeniu uprawy.
5. W okresie utrzymywania osłon w postaci włókniny PP 20 g m^{-2} i siatki HDPE 38 g m^{-2} panowały korzystne warunki do wzrostu i rozwoju cukinii. Wokół roślin odnotowano średni wzrost temperatury o 2,1°C i 1,4°C oraz wilgotności powietrza odpowiednio o 13% i 7,9% w porównaniu do obiektu kontrolnego. Pod ich wpływem odnotowano również wyższą temperaturę gleby średnio o 1,5°C i ograniczenie transmisji promieniowania fotosyntetycznie czynnego (PAR).
6. Pod bezpośrednimi osłonami wzrosło zachwaszczenie głównie gatunkami ciepłolubnymi – żółtlicą drobnokwiatową i owłosioną, chwastnicą jednostronną oraz szarłatem szorstkim.
7. Cukinia w wyniku osłaniania i stworzenia specyficznego mikroklimatu wytworzyła więcej liści i wcześniej rozpoczęła owocowanie. Z poletek osłanianych otrzymano wyższy plon, zwłaszcza wczesny.

8. Pod względem plonowania uproszczona uprawa pasowa glebogryzarką na wiosnę okazała się korzystniejszą metodą przygotowania stanowiska po roślinach okrywowych do uprawy cukinii niż klasyczna uprawa płużna.
9. Uproszczona uprawa pasowa glebogryzarką w kombinacji ze ściółkowaniem gleby materią organiczną istotnie przyczyniła się do zmniejszenia poziomu ewaporacji, ograniczenia zachwaszczenia oraz zwiększenia liczebności mikroorganizmów glebowych, zwłaszcza bakterii.
10. Warunki środowiskowe w znacznym stopniu determinowały wzrost, rozwój i plonowanie cukinii. W bardziej optymalnych dla roślin latach 2017-2018 pod względem temperatury powietrza i rozkładu opadów uzyskano istotnie większy plon niż w roku 2016.
11. Wartość biologiczna owoców cukinii była w większości obiektów badawczych podobna. Wyższe zawartości związków fenolowych stwierdzono jedynie w owocach pochodzących z roślin osłanianych bezpośrednio niezależnie od wykorzystywanego materiału. Analiza wykazała również wyższą zawartość karotenoidów i większy potencjał antyoksydacyjny w obiektach, gdzie gleba była uprawiona pługiem wiosną oraz glebogryzarką, w tym z dodatkowym ściółkowaniem.

9. POZYCJE LITERATURY CYTOWANE W AUTOREFERACIE

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Organic and non-organic mulches – impact on environmental conditions, yield, and quality of Cucurbitaceae

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ABSTRACT

The publication presents the current state of knowledge regarding the importance of mulching in the cultivation of Cucurbitaceae (cucurbit, or gourd family) vegetables. The intensifying climate change – mainly decreasing rainfall – combined with large-scale production of cucurbit vegetables worldwide prompt the application of methods that reduce evaporation and weed infestation. One of the widespread methods is mulching of the soil. The most important advantages of this treatment include the efficient use of water, the reduction in soil erosion and in the leaching of nutrients to the deeper layers. In addition, mulching improves the physical and chemical properties of the soil, and positively affects the surrounding microclimate of the plant. The report includes descriptions of the characteristics of various types of organic, mineral and synthetic mulches used. The results of studies on the environmental conditions forming in mulched soil are presented. Also, the results of research into the physico-chemical properties of mulch-covered soil are collated. The effect of mulching on cucurbit vegetables was evaluated in terms of plant growth and development as well as fruit yield and its biological value. The monograph also deals with the effect of mulching on weed infestation, as well as the occurrence of harmful and beneficial organisms.

Key words: Cucurbitaceae species, growth and development, mulching, pests, soil conditions, weed infestation, yielding

Abbreviations:

C/N – carbon-to-nitrogen ratio, EUW – effective use of water index, k_{sat} – saturated hydraulic conductivity of the soil, ldPE – low-density polyethylene, PA – polyacrylate, PBAT – polybutylene adipate-co-terephthalate, PBS – polybutylene succinate, PCV – polyvinyl chloride, PHA – polyhydroxyalkanoates, PLA – polylactide, PP – polypropylene, PVA – polyvinyl alcohol, WUE – water-use efficiency index

CUCURBITS

Cucurbits belong to the Cucurbitaceae family, the order of Cucurbitales. This covers about 95-120 genera and 800-965 species (Heneidak and Khalik, 2015; Christenhusz and Byng, 2016). The vast majority of these species originate from tropical or subtropical climates of Africa, South America, and Asia. Not many of them, in their natural state, grow in temperate zones. The common feature of all cucurbit plants is their preference for climatic

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conditions that are typical of equatorial zones, where they are cultivated on a large scale, and then transported over long distances (Paris, 2016). Vegetables representing this large group of plants include: cucumber (*Cucumis sativus* L.), summer squash (*Cucurbita pepo* L.), pumpkin (*Cucurbita maxima* Duch. and *Cucurbita moschata* Duch.), watermelon (*Citrullus lanatus* (Thunb.) Matsum. et Nakai), melon (*Cucumis melo* L.), and bottle gourd (*Lagenaria siceraria* (Molina) Standl.).

Global production of cucumbers, gherkins, pumpkins, squashes, gourds, melons and watermelons totalled 240,807,832 tonnes in 2014 (FAOSTAT, 2017). Of the highest utility are the fruits, being the key part of cucurbits harvested during the technological or physiological maturity period (Ajuru and Nmom, 2017). Intensification of the production of cucurbit vegetables is possible thanks to soil and plant protection treatments, especially using nonwoven fabrics and plastic films. Despite the many advantages of using such materials, they are not neutral to the soil environment (Steinmetz et al., 2016). Compared to conventional crops, cropping systems making use of cover plants, based on the limitation of cultivation practices and mineral fertilization, can be associated with a significant drop in yield – by as much as 57% in zucchini cultivation (Nachimuthu et al., 2017).

Environmental conditions

A temperature in the range 18-30°C is considered to be the optimal temperature for growing vegetables from the cucurbit group (melon, cucumber). A longer-lasting temperature of between zero and ten degrees Celsius inhibits the growth of plants, while sub-zero temperatures irreversibly destroy them (Ojo, 2016). The temperature of the soil, which should also be high, is considered important for the normal development of cucurbits. A drop in temperature to 12°C can already cause destabilization in the water management of plants, manifesting itself in limiting the uptake and transport of nutrients, especially phosphorus and potassium, to the aboveground part. This is detrimental to the growth rates in plant height and root length (Yan et al., 2013). The Cucurbitaceae subjected to constant temperatures of 15°C during the day and 25°C during the night, for a week in the early stages of their development, exhibit lower growth rates, as well as lower chlorophyll and dry matter contents. Under these conditions, the concentration of mineral components in the green parts of the plants increases (Inthichack et al., 2014). Exposure of juvenile cucumber plants to a temperature of about 7°C leads to slower initiation of flowering in female flowers, and to a decrease in their numbers, and therefore also to a decrease in the number and weight of the fruit and yield (Sarhan and Ismael, 2014). It is important to emphasize their sensitivity to high fluctuations in temperature as well as to low soil moisture and air humidity, which may lead to the plants shedding both flowers and young buds (Siwek, 2010).

The cucurbit root system, which forms a small part of the entire plant, reaches about 1.8 m deep into the soil, and its lateral roots are located at a depth of up to 60 cm (Kumar, 2016). The shallowest root system is that of the cucumber, with the majority of its root mass remaining in the topsoil layer (25-30 cm). The latter should be permeable, fast heating, and fertile, with regulated soil-water regimes, but with long water retention and a pH of 6.0-7.2. Cucurbit vegetables show a positive response to organic fertilization, which, in addition to providing large amounts of mineral substances in a readily available form, improves the physico-chemical properties of the soil (Sady, 2006).

The highly demanding nature of cucurbits in relation to the microclimate and soil environment, as well as their high dynamics of growth and yielding, combined with their short vegetation period, justify the use of mulching in their cultivation. Very important are also the high demands of cucurbit plants for water in connection with the rapidly diminishing water resources (WWAP, 2015; Yang et al., 2015). A system using synthetic polymers, called “plasticulture”, is particularly recommended in areas with low rainfall and low soil temperatures, as confirmed by a number of studies (Siwek, 2010; Haapala et al., 2015). The covering of the soil is carried out on vast areas, especially in developed countries with low rainfall, for instance, in China, Spain, or Israel.

DESCRIPTION OF MULCHES USED IN THE CULTIVATION OF CUCURBITS

Organic mulches

The basic organic material used for mulching is straw, which is a product of agricultural crops, mostly cereals (Kosterna, 2014; Nicholson et al., 2014). Other materials include paper mulches, which are made of wrapping paper, waxed or treated otherwise, providing a cheaper alternative to straw (Haapala et al., 2014). Compost with animal excrement seems to be the best material in terms of the quantity of organic matter it contains (Cabilovski et al., 2014). Organic materials (such as straw, sawdust, bark, or peat) exhibit low bulk density of about 0.06-0.30 g cm^{-3}. During vegetation, this can increase as a result of the natural settling process. Soil-water regime also largely depends on porosity, which is between 78-96% (Chohura, 2007). Mulches developed from biomass are increasingly used to cover the soil around the plants. According to Tan et al. (2016), a biodegradable mulch 0.35 mm thick with a surface weight of 40 g m^{-2}, consisting of 16% corn starch and 84% natural fibre, allowed about 15% of radiation in the range 450-850 mm to pass, exhibited very good water permeability and thermal stability under field conditions. Its degradation rate in soil at 10-25°C and 65% humidity was the highest compared to mulches based on natural polyvinyl alcohol (PVA) and polyacrylate (PA) (Tan et al., 2016).

Another source of organic materials for mulching is wood waste. In general, a broader C/N ratio is typical of coniferous species (such as pine) than deciduous ones (such as hornbeam). Various wood mulches differ among themselves in terms of the carbon-to-nitrogen ratio (C/N), which is 242-1569 for sapwood, and 38 for bark (Bantle et al., 2014), while the optimum range is 12-16:1 (Chohura, 2007). The composting of wood waste should be a pre-mulching activity, preceding the actual mulching of the soil.

A factor that hinders widespread use of organic mulches is the feasibility of delivering them to the field, and evenly distribute them therein. In addition, many of these mulches decompose quickly, which requires systematic replenishment.

Synthetic mulches

From the mid-twentieth century, there has been an upward trend in the use of synthetic polymers as mulch in plant production (Lamont, 1993; Espi et al., 2006). At the present time, most agricultural land is covered with mulch (total mulching area is about 18,000,000 ha) (Mormile et al., 2017). In Poland, the first attempts to mulch the soil with PVC (polyvinylchloride) film were carried out in cucumber cultivation at the turn of the 1970s and 1980s (Libik, 1976). The area of mulched crops in that country exceeds 1000 ha, on which mostly cucumber is cultivated (Siwek and Libik, 2012). The physical properties of inorganic mulches depend on the type of polymer, the manufacturing process, as well as on the substances added during the production (stabilizers, activators, carriers, dyes, fillers, etc.). The latter are also often added to biodegradable polymers in order to improve their physical properties and accelerate degradation (Vieira et al., 2011). The most commonly used mulching thermoplastics include polyethylene films (especially low density ldPE with a dark tint) with a thickness of 0.012-0.05 mm or thicker (Espi et al., 2006; Scarascia-Mugnozza et al., 2011; Orzolek and Lamont, 2013) and polypropylene (PP) nonwoven fabrics with a surface weight of 50 and 60 g m^{-2}, which, unlike PE, allow the penetration of rain water and gas exchange (Siwek, 2010; Siwek and Libik, 2012). Polypropylene is a lightweight polymer, with a density of 0.90-0.91 g cm^{-3}, and it can be processed using three different methods. The "spun-bonded" method produces stronger polypropylene fabrics than the melt-blown method (Maddah, 2016).

*Biodegradable mulche*s

At present, intensive research continues on the production technology, properties and implementation of films and nonwoven fabrics made of (or with) biodegradable polylactide (PLA) (Rudnik and Briassoulis, 2011; Weng et al., 2013; Zawiska and Siwek, 2014), naturally occurring polysaccharides (Ołdak et al., 2015; Touchaleaume et al., 2016; Moreno et al., 2017), thermosetting polymers from vegetable oils (Adekunle, 2015), as well as synthetic polymers including substances responsible for photo-, oxo- or biodegradation (Sulak et al., 2012; Abrusci et al., 2013; Gomes et al., 2014; López-Tolentino et al., 2016a, 2016b). The addition of zinc, iron, cobalt, manganese and magnesium facilitates the oxidation and degradation of long chain polymers under the influence of heat, air and light (Zenner de Polanía and Peña Baracaldo, 2013). These polymers, under aerobic conditions, can be decomposed by microorganisms into carbon dioxide or methane, water, biomass, and other organic compounds. No adverse effects on the nitrification processes occurring in the soil have been observed (Ardisson et al., 2014). Compounds (mixed mulches) composed of standard polymers produced in nature do not degrade completely (Kyrikou and Briassoulis, 2007; Li et al., 2014), while the rate of their environmental degradation is relatively difficult to estimate. The reason for this is their large variety in terms of structure and dependence on environmental conditions (microbial and enzymatic activity in the soil, soil temperature, humidity, the amounts of air and mineral salts, as well as its pH value) (Lucas et al., 2008; Liu et al., 2010; Siwek et al., 2010; Lichocik et al., 2012). The composition and concentration of additives activating the shortening of polymer chains, for instance iron and calcium stearates, are also considered of high importance. Their presence leads to accelerated ageing and deterioration in physical and mechanical properties (Pablos et al., 2010; Sulak et al., 2012). In response to increasing contamination of the environment with standard petroleum polymers, technological efforts have been undertaken aimed at speeding up the degradation processes and finding new solutions (Leja and Lewandowicz, 2010; Siwek et al., 2010; Vieira et al., 2011). Cellulose, which is also the base for polymeric materials, can be obtained from agricultural waste such as wheat straw and soybean seed coat. After chemical and mechanical treatments and homogenization process, fibres with a high α-cellulose content (about 84.6-94.0%) and a low lignin content (about 9.4-2.5%) are obtained, from which nonwoven fabrics are produced (Alemdar and Sain, 2008).

Another source of polymers are transgenic plants, including tobacco, which are genetically engineered to include bacterial cells such as *Ralstonia eutropha*, for producing bacterial polyesters and polyhydroxyalkanoates (PHA). They are fully degradable and can compete with synthetic polymers used to make films and nonwovens, or to form their composites (Mooney, 2009; Penczek et al., 2013). Laboratory studies have demonstrated lower resistance of polyethylene-starch mixtures to photo- and biodegradation, which are induced faster in those with a high starch content (30%). On the other hand, long-term exposure of a copolymer with a low starch content (5%) to radiation resulted in more effective degradation (Ołdak et al., 2005). Observing the level of degradation of several mulches based on corn and potato starch, PLA and biodegradable paper, Moreno et al. (2017) indicate the importance of the degree of shading of these materials by the crop plants to the progress of this process. López-Tolentino et al. (2016a) observed very fast degradation of photo-biodegradable film based on starch with high concentrations of a photodegradation agent (0.49% iron compounds) and oxo-degradation agent (0.52% calcium compounds) under Mexican climatic conditions. The tested mulch began to degrade as early as 1 week after application in the locations where zucchini seeds had been sown. At the end of the 2-month trial, they assessed the level of film degradation at 94% in areas with solar radiation, and only 10% in the sheltered part. In another experiment, while testing the use of oxo-degradable mulches with varying pigment concentrations and titanium dioxide content (22-23%), they observed a tendency to accelerated degradation in the mulch with increasing dye concentration (López-Tolentino et al., 2016b). The cost of using degradable polymeric materials can vary considerably, depending on the built-in components. There are indications that, taking into account the cost of removal from the field and utilization after standard synthetic mulch production, the total cost of using degradable mulches can be comparable (Minuto et al., 2008; Waterer, 2010).

IMPACT OF MULCHING ON ENVIRONMENTAL CONDITIONS

Light conditions

A study by Siwek (2002) shows that black polyethylene film with a thickness of 0.05 mm does not let through radiation in the range of 400-1100 nm, whereas only about 8.6% of it passes through polypropylene nonwoven fabrics with a surface mass of 50 g m^2. The same material, albeit white in colour, transmits 66.7% of the radiation, while green and blue transmit 37.5% and 28.9% of PAR, and 48.9% and 46.8% of 700-1100 nm, respectively. The photosynthetic activity of plants is most intense at a wavelength of 650-750 nm (red light and infrared) (Espi et al., 2006). However, blue light is required for proper photosynthesis (Hogewoning et al., 2010). As reported by Piszczek and Głowacka (2008), the growth of cucumber seedlings illuminated with fluorescent lamps emitting blue light improved with the increase in quantum radiation (from 50 to 60 μmol m^{-2} s^{-1}), namely: they were taller and had thicker stems. The investigated factors did not significantly affect the number of leaves or anthocyanin content. Measurements made by Meyer et al. (2012) demonstrate a high degree of reflection of PE white films with a thickness of 0.4 and 0.6 mm. They reflected approximately 80 to 60% of PAR and NIR radiation, with the highest rate in the case of blue-colour radiation. To compare, red PE film with a thickness of 0.1 mm reflected about 30-35% of blue and near-infrared radiation. In turn, black- and olive-coloured films with a thickness of 0.1 mm reflected 4% and 24%, respectively. The highest transmittance of radiation in the NIR range occurred in the olive-coloured film (45-75%), followed by red (about 55-65%), and white (about 30-40%) films, with the lowest transmittance recorded for black film (about 1%). Brault et al. (2002) also conducted a comparison of mulching materials in terms of their spectral properties. Their laboratory analysis demonstrated that, at the beginning of the experiment, the transmission in the PAR range for coextruded white/black film, black wrapping paper covered with latex on both sides, and natural-coloured wrapping paper covered with latex on both sides was approximately 2%, 0.08% and 4.3%, respectively. Wrapping paper coated with a biodegradable polymer allowed the sunlight to pass within a given range close to that of latex-coated paper. The black latex-coated paper reflected 6%, and the latex-coated natural beige-coloured paper reflected 33% of sunrays in the PAR range, while it absorbed 90% of those in the 400-1100 nm range. The absorption level in this range for the dichroic film was 40%, and in the infrared, it was 60%. In another experiment, it was demonstrated that squash plants growing in soil covered with blue mulch received more sunlight from the reflected surface, which resulted in higher photosynthesis and vegetative growth. Despite that, the quality of the light that reaches the plants growing on red mulch is more favourable and conducive to generative growth, resulting in higher yields (Fatemi et al., 2013). Thanks to the reflected UV radiation from mulches with high reflectivity (for instance, aluminium), the passage of pests over crop plants is impeded, leading to improved phytosanitary conditions (Shruthi et al., 2017). For a better understanding of the effects and the establishment of mulches that enhance light conditions in the growing of cucurbits, further research is needed.

Thermal conditions

The increase in temperature around the cultivated plants in a mulched soil is one of the effects of this treatment. This is particularly important in countries with temperate climates, where the cultivation of cucurbits is temperature dependent (Kalbarczyk, 2009). By influencing the growth and development processes of plants, including their underground part, higher temperatures advance their coming into the fruiting season (Pramanik et al., 2015). From a physiological point of view, the reduction in the efficiency of photosystem II is due to the reduction in CO_2 assimilation caused by low soil temperature (for cucumber, below 15°C). Therefore, maintaining the optimum temperature for the roots of cucurbits, under stress conditions, prevents the delivery to those parts of high amounts of abscisic acid that inhibits photosynthesis and causes the closing of the stomatal apparatus, thus limiting transpiration (Zhang et al., 2008b).

Currently, in many countries (for instance, in China and Israel) large areas are mulched with black film, nonwoven fabrics, or other dark-coloured materials, which are highly absorbent of sunlight, causing considerable heating of the soil (Lamont, 1993; López et al., 2009). These are especially recommended for growing cucurbit vegetables and nightshade plants, thus enabling higher – though not always earlier – yields. Thanks to the use of black film for mulching, these plants can be successfully grown in temperate regions (Ladakh region, western part of the Tibetan Highlands), where the average temperature of mulched soil in summer has been observed to rise by 2-5°C during the day (Stobdan, 2015). This is confirmed by the results of the studies into using black film-coated biodegradable paper mulch conducted by Haapala et al. (2015), as well as Moreno and Moreno (2008) and López-Tolentino et al. (2016b), who recorded the highest increase in soil temperature under black PE mulch. Numerous literature reports, however, indicate that the strongest warming of the soil occurs under colourless film (Attallah, 2016; Martín-Closas et al., 2017), with selective transmission of solar radiation (Waterer, 2010).

In Mexico, the temperature of the soil mulched with 0.038 mm thick black PE film was higher than the temperature under oxo-degradable mulches of the same thickness coloured red, blue, green, and in unprotected soil on average by 2.4°C, 2.2°C, 2.3°C, and 4.2°C, respectively (López-Tolentino et al., 2016b). In the same country, the usefulness of PE film (0.03 mm thick) of different colours in cucumber cultivation was also investigated. As a result of covering the soil, the temperature at a depth of 10 cm increased significantly on all the test sites, and the highest average increase in the maximum, minimum and average temperatures for the test years amounted to: 7.8°C for brown film, 3.6°C for black embossed film, and 5.2°C for brown embossed film. In addition, it contributed to the accumulation of heat, expressed by the sum of active temperatures (Ibarra-Jiménez et al., 2008). As reported by Siwek (2002), the soil temperature at a depth of 10 cm during the initial stage of cucumber growth under black PP nonwoven and under PE film was higher by 0.5°C and by 1.9°C, respectively, than in the unprotected soil. According to Filippi et al. (2011), the maximum temperature of the soil under the influence of mulching with green-coloured biodegradable films (0.015 mm) was higher than that for black film of the same thickness, for black ldPE (50 μm), and for unprotected soil. The observed increase in temperature occurred especially in the first days after the application of the mulches. Soil temperature analysis performed by El-Shaikh and Fouda (2008) in their experiment using polyethylene (black, transparent and yellow) and organic mulch (wheat straw) in cucumber cultivation showed considerable variation. All the mulches from synthetic polymers raised the temperature of the soil during the day between 6 a.m. and 2 p.m., and then radiated the heat out until the following morning. The highest increase (by about 7°C) relative to the unprotected soil occurred under the colourless film. On the other hand, in the case of the organic mulch, an increase in soil temperature was recorded only at night (1°C), while at 2 p.m. it decreased by an average of 2°C relative to the control site. At night, as a result of thermal radiation, the temperature was the lowest at the soil surface. Similar results of soil temperature decreasing under an organic mulch composed of wood chips have been observed by van Donk et al. (2011). Their studies have shown a correlation between the decrease in soil temperature during the day with increasing depth. In the Florida area, White (2004) reported a higher soil temperature at a depth of 6 cm between 3 p.m. and 4 p.m. under black polyethylene film compared to black biodegradable, silver, white and bicolour (black-and-white) films. In Ontario, it was observed over 11 days that the soil temperature under black film was about 1.5°C higher during the day, while at night the minimum temperature was as much as 2-3°C higher than the temperature of the unprotected soil. The authors also noted a negative correlation between the soil temperature under films of different colours and the temperature of soil without mulch application, and the absolute value of temperature in the unprotected soil (Snyder et al., 2015). Homez and Arouiee (2016) investigated the effect of the type and colour of mulch on the accumulation of heat in the soil in unheated greenhouses. The highest degree of heat accumulation was noted under black PE film, slightly lower under transparent PE foil, and then under organic mulch of rice husks. The amount of heat absorbed was the lowest in unprotected soil in winter and spring. The results show that mulches of synthetic polymers are worthy of even more extensive use for thermophilic vegetables in relatively cold countries, while mulches of natural origin are more suitable in countries with hot climates, in order to reduce temperature or minimize excessive thermal fluctuations throughout the day.

Soil moisture

Maintaining a high moisture content of the soil during the cucurbit vegetation period allows advancement and prolongation of the cropping season, leading to an increase in yield (Kuslu et al., 2013). The barrier posed by both synthetic and organic mulches limits soil evaporation, the intensity of which is determined mainly by the type and thickness of the material. It is estimated that mulching makes it possible to retain about 20-41% more water in the soil (Abouziena et al., 2014; Ingman et al., 2015; Stobdan, 2015).

Under laboratory conditions, during the first 4 days of drying, the evaporation index of a soil covered with black film (0.01 mm), pine bark, wheat straw, chopped vine shoots, and natural jute fibres was, respectively: 81%, 55%, 34%, 23% and 11% lower than of the same soil without mulch (Zribi et al., 2015). High effectiveness of water loss prevention in soil has been observed especially in desert and semi-arid areas (Yang et al., 2015). Evaporation is most effectively limited by the use of organic mulches (except for wheat straw) and mineral mulches (gravel mulch), less so in the case of synthetic mulches based on hydrogels and organic polymer emulsions (Farzi et al., 2017). Some studies show that the soil moisture content increases with organic mulching only in deeper layers (80-220 cm), while at a depth of 30-80 cm, soil moisture may be lower (Li et al. 2017). A positive correlation was found between the thickness of organic mulch and the water content of the shielded soil (van Donk et al., 2011). There are indications of soil humidity being lower by about 5-10% under synthetic mulches immediately after precipitation, while during the dry period, the index is about 5% higher (Snyder et al., 2015). Also, a negative correlation was observed between the size fraction of the material used (gravel) and the degree of blocking the evaporation (Xie et al., 2006; Yuan et al., 2009).

White (2004) reported no significant effect of mulch colour (white, silver, black, blue and red, biodegradable and bi-coloured) on soil moisture. The lowest value of water field capacity was measured in uncovered soil. It amounted to 37%, compared with the average of 40-68% under the mulches. In a test conducted in the conditions of extreme dryness (Central Sudan, annual rainfall of <400 mm), mulching with colourless film contributed to a decrease in soil water loss by 6 to 11% (Abdelrahman et al., 2016). Other authors, studying the use of synthetic dyed materials for mulching, have obtained similar results (Mahadeen, 2014).

As a result of mulching, a decreased need for irrigation water has been observed in cucumber cultivation (El-Shaikh and Fouda, 2008; Spiżewski et al., 2010) as well as in melon cultivation (Alenazi et al., 2015). The index of water-use efficiency (WUE, t m^{-3}) under straw mulch as well as under black, yellow and transparent ldPE film amounted to, respectively: 6.22, 7.76, 8.34, and 8.51 kg m^{-3}, which was >160% higher than on the control site (2.32 kg m^{-3}) (El-Shaikh and Fouda, 2008). This is expressed as a quotient of the crop yield of the plant (t hm^{-2}) and the amount of water consumed during the vegetation period (total sum of evapotranspiration) (m^3 hm^{-2}) (Zhuo and Hoekstra, 2017). Opinions are divided as to the importance of the efficient use of water (EUW) and water-use efficiency (WUE), which determines the yield under drought stress. The more important determinant of plant yield under such conditions is the EUW calculated from the maximum transport of soil water, used in the transpiration process, to the stomatal apparatus of plants (Blum, 2009).

Physical and chemical properties of the soil

Mulches of organic origin typically enter into a relationship with the soil, increasing the activity of the enzymes which break down plant residues. As a result of the use of such mulches, increased presence of worms as well as their greater mass is also observed (Jodaugienė et al., 2010). Organic mulches with a high carbon to nitrogen ratio (such as sawdust) may cause temporary soil impoverishment in nitrogen due to the activity of microorganisms. The differences also concern the levels of macro- and micronutrients in the mulched soil and its acidity (Sas-Paszt et al., 2014). During vegetation, as the decomposition processes proceed, the mulch gradually enriches the soil with humus, which is the source of nutrients in an easily digestible form. Estimation of the organic matter mineralization rate is one of the principles of optimum management of mineral components in the soil for successive crops in crop rotation (Tittarelli et al., 2014). Mulching with flaked paper, on sites where municipal compost and sludge were used, increased the amount of microorganisms involved in the nitrogen and phosphorus cycle compared to synthetic mulches (Forge et al., 2003). Fang et al. (2007) reported that as a result of mulching with grass (*Imperata cylindrica* var. *major*) over 55% of the available nitrogen was released to the soil during the first 4 months of application. The layers of organic mulches applied at 2.5, 5.0 and 7.5 kg m^2 released, respectively: 69, 161 and 322 kg of nitrogen per ha during the year. Broschat (2007) reported an increased concentration of nutrients in the soil after 6 weeks of applying wood mulches, such as cypress chips (K), pine bark, and eucalyptus chips (Mg).

The exposed soil is exceptionally susceptible to the destructive effects of heavy rainfall, which causes the soil structure to break apart and intensifies the elimination of nutrients. This is evidenced by the results obtained by Siwek et al. (2015), where the lowest nitrogen level (especially in the nitrate form) was recorded on the unprotected control site. In turn, Cabilovski et al. (2014), in strawberry mulching with organic fertilization, reported higher concentrations of micronutrients under the surface of synthetic mulches compared to straw. Under the influence of the protective mulch of fodder radish, an increase in the number of soil macropores with a diameter of 50-500 μm was observed in the upper soil layer (0-10 cm) (Głąb and Kulig, 2008). At the same depth, the largest water-borne soil macroaggregates (>250 μm) and the highest saturated hydraulic conductivity (k_{sat}), defined as the degree of water conductivity (mm h^{-1}), were found in studies conducted in China (Zhang et al., 2008a). According to the authors, mulching with organic matter combined with no-tillage cultivation results in improved physical properties of the soil and increases organic carbon content. Similar results for the improvement of soil porosity were obtained by Blanco-Canqui and Lal (2007), but only in the topsoil. On the site with mulching, k_{sat} was 123 times higher, while the water content was 40-60% higher compared to the control. Joy and Varghese (2017), who investigated flaked straw, natural rubber, cardboard and wood chips as mulch, recorded reduced soil permeability. The permeability coefficient (cm s^{-1}) for all the mulches decreased with each 1 cm increase in thickness of their layer by an average of 0.5; 0.9; 1.2; 1.7 × 10^{-3} cm s^{-1} for straw, natural rubber, wood chips and cardboard, in that order. Kahlon et al. (2013), after several decades of experiments, have demonstrated positive changes, among others, in the organic carbon content, k_{sat}, the structure of soil aggregates, and other physical and chemical properties of the soil, when using organic wheat straw in zero tillage and conservation tillage. In another experiment, it was demonstrated that soil under the layer of 10 cm-thick mulch of maize residue possessed better properties (all except porosity) as compared to unprotected soil and mulch layers 5 and 15 cm thick (Kakaire et al., 2015).

Soil analysis carried out by Domagała-Świątkiewicz and Siwek (2015) after cucumber and tomato cultivation showed a decrease in the number of small soil aggregates and an increase in the number of large ones under PLA and PBS (polybutylene succinate) mulches. During the high humidity season, a reverse effect was observed. In addition, protecting the soil contributed to an increase in its bulk density and a reduction in its water capacity in a year with high precipitation. In another experiment, as a result of mulching with black ldPE film, an increased share of 0.6-1.5 mm aggregates was observed, along with better physical parameters of the soil, and a reduction in the concentration of nitrate-N form, with an increase in ammonium-N form, in comparison with non-woven PP and unprotected soil (Siwek, 2002). As evidenced by the study, soil responds to mulching in various ways depending on the type and thickness of the mulch. In most cases, this results from the biological interaction with the mulch, as well as the changes in their physical properties due to the protection against rain erosion.

WEED INFESTATION

The elimination of undesirable plants should take place in the period preceding the sowing or planting of vegetables (Brainard et al., 2013). The reduction of weed infestation using herbicides is performed on a small scale due to the limited availability of herbicides authorized for use (Matyjaszczyk and Dobrzański, 2017). Multiple mechanical weeding of the field is associated with high energy and financial cost. It also contributes to the excessive drying of the soil and disturbing its structure. Manual weeding is problematic due to the overgrowth of the shallow root system of cucurbits with the roots of weeds, so that the damage becomes unavoidable. Soil mulching, on the other hand, is an effective and safe method (Abouziena and Haggag, 2016). In the case of mulching with material that transmits solar radiation to a large extent, herbicides or other techniques are used, for instance, application of heat energy (Martín-Closas et al., 2017). Under conditions of water stress, the presence of weeds can reduce the crop yield by up to 50% (Abouziena et al., 2014). According to Schonbeck (2015), who quotes several other authors, the critical period of competition, for cucurbits, falls on the first 4-6 weeks after planting. During this time the plants grow rapidly, and they cover the soil in the spaces between the rows.

The diminishing effect of mulches on weed populations is reduced to the creation of a physical barrier and blocking of the PAR radiation. It is also important that mulches transmit heat waves in the far-infrared range, which inhibits the growth of undesirable plants at an early stage of their development. This is confirmed by the results of studies conducted by Ngouajio and Ernest (2004) on the assessment of weed infestation using PE mulches with different wave transmittance in the 400-1100 nm range. The largest numbers of weeds and their largest biomass were observed under white film, followed by grey. The remaining black, brown and green mulches effectively limited the development of weeds, the number of which did not exceed 25 plants per m^2. The effectiveness of weed protection when using a thick layer of organic mulch is so high that the simultaneous application of chemical preparations may not produce the expected result, e.g. due to the difficulty in displacement of or interaction with organic matter (Marble, 2015).

A study by Broschat (2007) found that wood mulches (bark and pine needles, finely flaked eucalyptus and cypress chips) significantly reduced the development of dicotyledonous weeds. A positive correlation was observed between the thickness of organic material and the reduction in overall weed infestation (van Donk et al., 2011; Jodaugienė et al., 2014). In addition, allelopathins (for instance, phenols, or benzoxazine) can reduce the amount of herbicides used, for example, by decreasing weed germination rate (Tabaglio et al., 2008), but they can also affect the development of crop plants (Bantle et al., 2014). As reported by Gill et al. (2011), the vegetal mass of a 3-5 cm thick mulch of *Vigna unguiculata* plants degraded the fastest compared to a mulch consisting of the biomass of *Crotalaria juncea*, *Sorghum bicolor* × *S. sudanense* and pine bark of the same layer thickness. As a result, the site mulched with the leaves of *Vigna unguiculata* plants, as well as the unmulched one, had a higher level of weed infestation with dicotyledonous species compared to the other organic mulches.

Under the specific conditions of the environment inside the high plastic tunnel, from among several types of organic mulch, newspaper sheets degraded the most, followed by flaked newspapers, and wheat straw the least. The ratio of degradation of these mulches, assessed visually at the end of vegetation, was 4.9 : 3 : 1. However, all of these mulches significantly reduced the level of weed infestation in the summer cultivation of cucumber (end of June-early September) (Sanchez et al., 2008). Biodegradable mulches made from waste products consisting of short cotton fibres, crushed immature seeds and small pieces of vegetative material are equally effective in reducing weed infestation as the standard ldPE films (Johnson et al., 2014).

Taking into account the rapid growth of cucurbits, the use of mulches is of great importance in limiting weed infestation, especially at the beginning of the growing season, when the soil is not fully covered with the crop.

PEST OCCURRENCE

For a long time now, non-chemical methods of combating pathogens and weeds have been sought in many countries. One of them is the so-called soil solarisation based on the use of colourless film mulches, such as PE, PVC, or EVA. They must be mechanically strong and as transparent to sunlight as possible in order to facilitate the maximum possible heating of the soil during the day and reduce heat loss at night. After solarisation, the availability of mineral components in the soil is increased, which reduces the cost of production associated with fertilization (Puoci et al., 2008; Pramanik et al., 2015). The key parameter for the effectiveness of the treatment is the temperature, which remains above 50°C for subsequent days. This causes many pathogens to die. An increase in the amount of beneficial microorganisms (e.g. *Bacillus* bacteria or *Trichoderma* fungi) has been observed in the soils subjected to solarisation. This may be due to their increased resistance to high temperatures, or to the relatively rapid reproduction and re-colonization of the soil. The effectiveness of this method is strongly dependent on climatic conditions, which, in consequence, justifies its practical application only in warm climate regions. One modification may be the use of solarisation together with chemical preventive measures against pests. Under conditions of elevated temperature, it is also preferable to use organic fertilizers whose decomposition proceeds faster with more rapidly growing microorganisms (Dai et al., 2016).

It has long been known that pests are also responsible for the spread of viruses. According to Ali et al. (2012), in the southern part of the United States, more than half of viral infections in cucurbits were caused by species from Aphidoidea and Aleyrodoidea superfamilies. Mulching the soil using polymers with a UV-reflecting surface (280-400 nm) is a method for limiting or delaying viral vectors, which merits a broader dissemination, as confirmed by the study (Nyoike et al., 2008; Murphy et al., 2009). For example, in the cultivation of watermelon, 71.4% fewer thrips and 24% less damage by the *Watermelon bud necrosis virus* (WBNV) were recorded on sites using silver mulch (30 μ) compared to the control (Shruthi et al., 2017). Owing to its properties, silver mulch can make it considerably more difficult for the insects to locate the plants, but on the other hand, the number of predatory insects can also be reduced (Diaz and Fereres, 2007).

Observations have shown differences in the number of aphids and their preferences or repellent effects depending on the colour of the mulch (Žanić et al., 2009a). However, it is difficult to fully determine the relationship between the type and colour of mulch used and the scale of the occurrence of live organisms. Differences in the infestation of cultivated plants with pests may be due to their variable abundance during the growing season (Žanić et al., 2009b). In addition, allelopathic substances released in the decomposition process may deter pests (Roger-Estrade et al., 2010). It is also desirable to emphasize the significant role of weeds as a feeding place for both harmful and beneficial arthropods. As a result of mulching, Blanco-Canqui and Lal (2007) observed an upward trend in the number of earthworms in proportion to the wheat straw layer thickness.

Covering the soil with the biomass of Fabaceae plants accelerated, by rapid degradation, the colonization of the site by fauna such as Hemiptera and other insects; silmilarly so on the control site (Gill et al., 2011). Mulching also protects the fruit – for example, watermelon – from direct contact with the soil, and thus prevents the development of diseases.

GROWTH, DEVELOPMENT, YIELD, AND QUALITY OF CUCURBITS GROWN ON MULCHED SOIL

The response of plants to changing structural properties of the soil and to environmental factors under mulching is generally an increase in yield, as well as positive changes in plant growth and development.

Phytometric measurements conducted by Habimana et al. (2014) on mulch-grown watermelons, at varying spacing, 60 days after sowing, clearly emphasize the beneficial effect of mulching on the length of the main shoot, the number of leaves and lateral shoots. There was a trend that, as the spacing increased, so did the values of the tested parameters. In addition, the fastest growing and highest yielding plants were those on the mulch of polyethylene film, followed by wheat straw, as compared to unprotected soil. Also on black film (PE 0.125 mm), statistically significant faster emergence and earlier coming into the flowering period as well as 76% higher fresh weight of the aboveground part were noted in pumpkin plants (Mahadeen, 2014). Earlier development of this plant species was also noted in Egypt in February, outside the typical cropping season. The overall yield was 38.8 and 51.1% higher, and the average fruit dry matter was 0.9 and 2.05% higher due to the use of black and colourless PE mulch, compared to the plants cultivated on unprotected soil (Attallach, 2016). In a pot experiment, it was also observed that mulching with red PE film with a thickness of 0.05 mm resulted in a decrease in the relative water content of watermelon leaves. On the site with the mulch, watermelon plants formed greater biomass of the subterranean and aboveground parts, and the assimilation area of the leaves was larger, which increased transpiration but decreased evaporation (Ferus et al., 2011). The increase in the transpiration level, in the absence of significant differences in the intensity of cucumber photosynthesis, was confirmed using straw as a mulch (Hnilička et al., 2012). After growing *Cucumis melo* var. *reticulatus* on biodegradable films, Filippi et al. (2011) expressed their belief about the importance of the high rate of mulch degradation for the quality of the fruit, while adherence should be avoided due to limit skin colouration during ripening of fruits. Furthermore, the plants growing on these mulches generated higher yields of better quality fruit, that is, with higher sugar concentrations. In the conditions of northeastern Poland, a beneficial effect of mulching with black film on the dry matter content of melon has been observed. Concentration of nitrates increased in places where mulch and direct cover were combined (Majkowska-Gadomska, 2010). Crop residues mulch with the addition of peat, also had a beneficial effect on the synthesis of dry matter, crude fibre, protein as well as ash content in oilseed pumpkin (Černiauskienė et al., 2015).

Studies conducted in the United States, in Wyoming, testify to the high utility of dark blue polyethylene mulch for yielding cucurbit vegetables, that is, cantaloupe melons, cucumbers and zucchinis. The commercial fruit yield of plants of these species was approximately 35, 30 and 20% higher, respectively, than of those grown on black film. The lowest yields were obtained from sites with black-and-white mulch (melon), and yellow mulch (cucumber and zucchini). In the authors' opinion, the response of plants to the colour of the film may vary depending on the location of the crop, that is, depending on climatic factors (Orzolek and Lamont, 2013). As reported by Minuto et al. (2008), the total yield of zucchini obtained from cultivation on PE and biodegradable mulches can exceed up to two times the crop yield on unprotected soil.

In an arid climate (Iran), Fatemi et al. (2013) observed a significantly increased total yield of summer squash grown on red and blue plastic films by 100% and 31.5%, respectively, in comparison with bare soil. López-Tolentino et al. (2016b) recorded that the leaves of cucumber plants growing on an oxo-degradable mulch had a larger assimilation surface, which, according to the authors, was a physiological response to the increase in soil temperature. Similar results have been reported by other authors with regard to the intensity of photosynthesis and fruit yield of this plant (Ibarra-Jiménez et al., 2008). The same authors and Torres-Olivar et al. (2016) under Mexican climatic conditions recorded increased marketable, early and total yields of cucumber grown on coloured polyethylene mulch (including oxo-degradable) by, respectively, 12.9-46.6, 32.5-136.9, 10.8-48.5 (blue), 19.4-62.1, 36.1-148.6, 17-58.8 (red), 22.3, 60.3-165.9, 20.3-43.9 (white), and 63.4, 29.3, 58.8% (green film). Also White (2004) in central Florida (USA) observed higher marketable and total yields of summer squash cultivated on soil mulched with white, white on black, silver, silver on black, blue and red PE films by 50.3 and 60; 60 and 69.6; 58.9 and 80.2; 55.4 and 70; 56 and 52.2; 26.3 and 30%, respectively, relative to bare soil. Higher yields of cucumber fruits were also harvested using non-woven fabrics: photodegradable PP (0.02% iron stearate) and PLA, both with a surface weight of 50 g m^{-2}. The fruits showed a decreased dry matter content, with a similar amount of soluble sugars compared to the fruit from the control site (Siwek et al., 2015). Kosterna et al. (2010) observed increases in dry matter, total and reducing sugars, and vitamin C in melon as a result of mulching with black polyethylene film. In the experiment where mulches of rice husks (2 cm thick layer) and of white and black ldPE films were used, higher solubility (°Brix index) and higher yields of watermelon (Saraiva et al., 2017) were obtained. The yield of cucumbers cultivated on a soil mulched with wheat straw and with black, yellow, and transparent PE films increased by 67.7, 109.2, 124.8 and 129.3%, respectively, relative to the non-mulched site (El-Shaikh and Fouda, 2008).

In temperate climates (southern Finland), the yield of cucumbers increased by 39-91% as a result of covering the soil with packaging paper lined with black biodegradable film, and it was comparable to that obtained from plants growing in a soil mulched with only the film of that same colour (Haapala et al., 2015). On the other hand, Kołota and Adamczewska-Sowińska (2011) observed a decrease in early and total yields of summer squash cultivated on soil mulched with white PE film by 20.1 and 13.3%, respectively. No significant differences in yield and amounts of individual components were reported by Saraiva et al. (2012) for *Cucumis melo* var. *inodorus* cultivated on black ldPE film (0.025 mm) as well as black and green (0.015 mm) starch-based biodegradable films; also, Johnson et al. (2014), for cantaloupes and watermelons, using a mulch of black ldPE film (0.025 mm) and compressed fibres coated with black latex or cooked linseed oil, approximately 1 cm thick. In an experiment with zucchini and cantaloupe melons, it has been demonstrated that the colour of the mulch has more impact on the yield than whether or not it is degradable (Waterer, 2010).

In China, covering the soil with gravel had a beneficial effect on the yield of watermelons, which more than doubled. Also the sugar content in the fruit was observed to increase, irrespective of the size fraction of the material used for mulching (Xie et al., 2006). Among the organic and synthetic mulches tested in the cultivation of sponge gourd, black polyethylene film has proven to be the best, as confirmed by the yield results (increase by 169.7%). Other mulches such as farmyard manure, white PE film, grass and rice straw increased yields by 92.5%, 8.1%, 26.5% and 15%, respectively, compared to bare soil (Khan et al., 2015). Differences in

Table 1. Marketable, early and total yields of cucurbit crops grown on black mulches

Type of climate	Authors	Country	Crop	Kind of mulch	Marketable (MY), early (EY) and total (TY) yield increase/ decrease as compared to uncovered control (%)
temperate	Kołota and Adamczewska-Sowińska, 2011	PL	summer squash	black PP nonwoven fabric	-5.1 EY, -13.1 TY
	Kołota and Adamczewska-Sowińska, 2011	PL	summer squash	black PE film	10.4 EY, 1.9 TY
	Kołota and Balbierz, 2015	PL	summer squash	black PE film	15.8 MY, 15.7 EY
	Kołota and Balbierz, 2015	PL	summer squash	black agrotextile	13.2 MY, 13.2 EY
	Siwek, 2002	PL	cucumber	black PE film	184.1 MY
	Siwek, 2002	PL	cucumber	black PP nonwoven fabric	138.4 MY
	Siwek et al., 2015	PL	cucumber	black PP nonwoven fabric	24 MY
	Siwek et al., 2015	PL	cucumber	black PP photo. nonwoven fabric	8 MY
	Siwek et al., 2015	PL	cucumber	black PLA	64 MY
	Spiżewski et al., 2010	PL	cucumber	black PE film	≈8.4 MY, ≈6.5 TY
warm	Attallah, 2016	EG	summer squash	black PE film	38.8 TY
	Ibarra-Jiménez et al., 2008	MX	cucumber	black PE film	147.9 EY, 36.1 TY
	Lopez-Tolentino et al., 2016b	MX	cucumber	black PE film	50 MY, 34.6 EY, 42.6 TY
	Mahadeen, 2014	JO	summer squash	black PE film	63.6 EY, 61.4 TY
	Torres-Olivar et al., 2016	MX	cucumber	black film	21.2 MY, 79.3 EY, 21.6 TY
	White, 2004	USA	summer squash	black PE	44.6 MY, 52.2 TY
	White, 2004	USA	summer squash	black bio.	27.4 MY, 31.9 TY

marketable, early and total yields of cucurbit crops grown on black mulches are shown in Table 1.

The effects of mulching on the growth and development, and on the yielding and chemical composition of cucurbits are not clear. This is especially due to the nature of the mulching materials and the underlying environmental conditions, resulting in the differences in plant responses.

Literature on the influence of mulching on the quality of yield during and after storage of cucurbits vegetables was not found.

CONCLUSIONS

The beneficial impact of soil mulching around cultivated plants is well known, and has long been practiced. It mainly amounts to the protection against erosion and evaporation, coupled with the modification of microclimatic conditions. The end result of vegetable cultivation using mulching is often an increase in yield and its biological value. A comparative analysis of the discussed research results suggests that there is a strong correlation between the variable environmental conditions produced by the mulch and the size and quality of the yield of cucurbit vegetables. Diverse climatic conditions, prevailing in various geographical regions of the world, as well as the differences in the physical and chemical properties of coloured mulches, should determine the right selection for a particular region. With the development of organic farming around the world, more data is needed on the effectiveness of using cover crops subjected to natural or mechanical disintegration before the cultivation of cucurbits. Taking into account the strong growth parameters and the long shoots, typical of most of the vegetables in this family, the possible practical use of so-called live mulches seems to be limited.

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AUTHOR CONTRIBUTIONS

P.B. – reviewed the relevant literature, wrote the manuscript and prepared it for submission; P.S. – concept of paper, contributed to such aspects of this manuscript as development of the idea and critically revised the text.

CONFLICT OF INTEREST

The Authors declare no conflict of interest.

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

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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

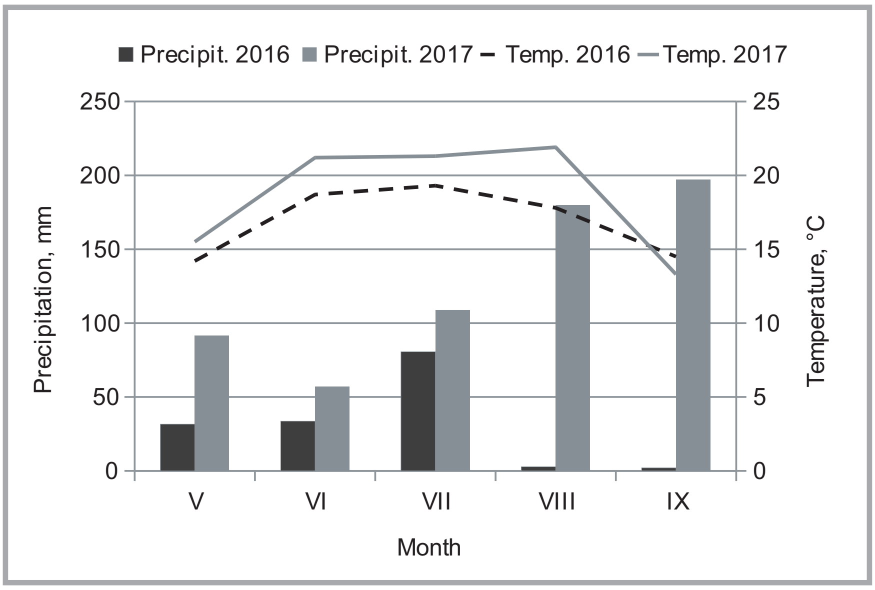

Figure 1. *Weather conditions over the course of the study (data obtained from the meteorological station at Mydlniki Station).*

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°.

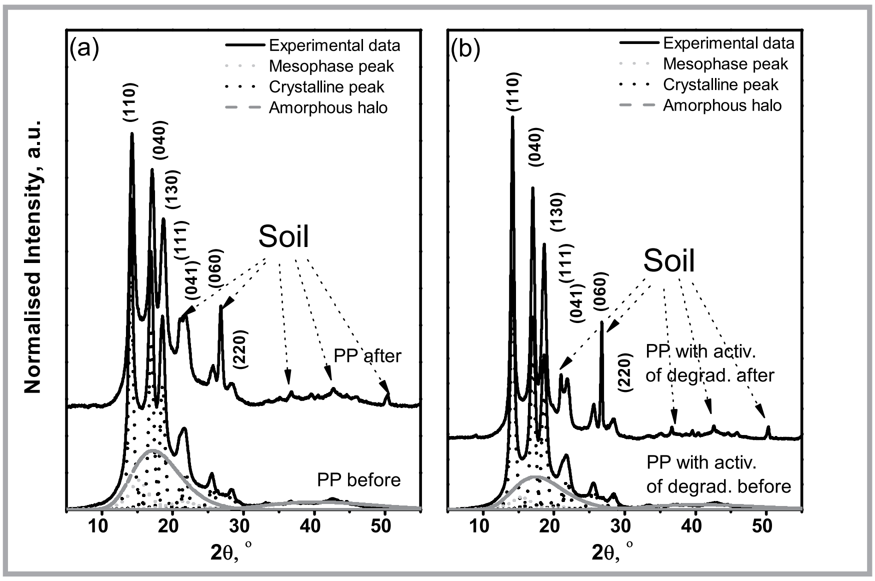

Figure 2. *Comparison of X-ray diffraction profiles of PP: (a) and PP with an activator of degradation (b) nonwovens before and after they were used as mulching materials.*

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.

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Characterisation of Two Direct Covers Made of PP and HDPE in the Organic Production of Zucchini

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Abstract
The aim of the research conducted in 2016-2018 at the University of Agriculture in Krakow was to assess the effect of the direct covering of 'Partenon' F1 zucchini plants with polypropylene nonwoven fabric (PP 20 g/m^{-2}) and polyethylene netting (HDPE 38 g/m^{-2}). While the covers were in place, measurements of environmental factors were taken. The air temperature and humidity during that period were on average by 2.1 °C and 13% and by 1.4 °C and 7.9% higher on the plots covered with the nonwoven and the net, respectively, compared to the control. Uncovered plants formed the smallest number of leaves and produced the lowest marketable yield. Weed infestation was greater on the plots with the covers by 43% and 56% for the HDPE net and the PP nonwoven, respectively, compared to the control. Laboratory analyses of the zucchini fruit did not show any significant differences in its chemical composition.

Key words: *Cucurbita pepo L. convar. giromontina Greb., direct covers, agrotextiles, yield, fruit chemical composition, weed infestation.*

Introduction

Intensive agriculture based on the use of plastics is nearly 70 years old. From the early 1950s to 2017, the world's production of plastics increased by 22.233% [1]. Along with mulching the soil around plants, cultivation under cover is one of the fastest growing branches of horticulture due to independence from external conditions and the possibility of production almost all year round. According to the available government statistical references, updated to January 2018, the global protected agriculture vegetable area that includes mulches, row covers, greenhouses, and any type of method or structure used to extend the growing season of plants is 3.414.353 ha [2]. It is estimated that the area of vegetables cultivated under direct cover in Poland in 2018 was 7.000 ha. Agriculture based on the use of plastics makes it possible to obtain higher yields of better-quality crops compared to traditional methods, and to reduce the use of pesticides and water. Despite environmental pollution, it has become, due to its versatile applications, an inseparable element of the food economy in many countries in a relatively short time and is still gaining importance in the era of limited agricultural land. An alternative to permanent supporting structures is the direct covering of plants, which is cheaper and less troublesome to implement [3, 4]. The basic properties of agrotextiles that have allowed them to be widely used are, among others, strength, porosity, and resistance to sunlight and harsh environmental conditions [5]. Direct (flat) covering stabilises the temperature around the plants, protects them from overheating, excessive transpiration, wind, hail, and heavy rain, and reduces ground-level frosts. Improvement of the microclimate also affects the duration of seedling adaptation and the capacity and rate of seed germination [6, 7]. However, the improved conditions also favour weed infestation, which can be several times greater. Weeds with higher thermal requirements may emerge and develop earlier, e.g. *Echinochloa crus-galli* L. and *Galinsoga parviflora* Cav. [8].

In Poland, accelerated cultivation of vegetables under direct covers in the spring is widespread. In the years of a rapidly changing climate, there has been a decline in interest in perforated 50 μ thick foil covers with 100-500 holes, under which the microclimate is subject to large fluctuations, and the crop plants become overdelicate and susceptible to unfavourable conditions after the covers are removed. Currently, polypropylene (PP) nonwovens are most often used for this purpose, one of the best features of which is their low weight (17-23 g m^{-2}) and high airiness. Moreover, their surface mass is on average 2.5 times lower than that of perforated foil, so that it does not hinder the development of plants [9-11]. The layers of polypropylene fibres have a low structural strength. Under the influence of UV radiation, the bonds between the fibres are broken, which leads, inter alia, to an increase in the air and water vapour permeability of nonwovens [12]. Compared to netting, nonwoven fabrics, especially heavy ones, are rapidly destroyed by long-lasting strong winds [13]. Uniform environmental conditions also prevail under nets, most often made of rigid high-density polyethylene (HDPE). They are made of threads joined together to form a regular and porous knitted and woven structure. Knitted nets are obtained by the method of warp knitting with raschel machines. Nets produced by the techniques of making openwork warp-knitted fabrics with an openwork weave and openwork-weft weave are characterised by high durability and preservation of the mesh structure. Fixing them with UV stabilisers increases their resistance to degradation by ultraviolet radiation, ensuring their durability to 5-6 years in a mild climate (e.g. Mediterranean). They are used, for example, in greenhouses and tunnels, as well as in orchards and vineyards as shade cloths and protection against pests and hail. Their colour depends on that of the pigment used. Transparent nets are characterised by the highest light transmission and are recommended for crops that do not require shading [14, 15]. Among coloured nets with a shading coefficient of 30%, the highest PPFD (400-700 nm) transmittance values have been recorded for red and blue nets [16]. After colour, the second most important factor affecting permeability is porosity. Plastic netting can be regarded as a translucent material with equivalent optical parameters (refractive and absorption indices) [17]. At present, a lot of emphasis is put on the production and use of biodegradable plastics in agriculture [11], but this does not apply to nets. The need for new and advanced technologies to develop biodegradable plastic nets, free of plasticisers, was postulated by Maraveas [18], pointing to the electrospinning technique as a method enabling their introduction into circulation.

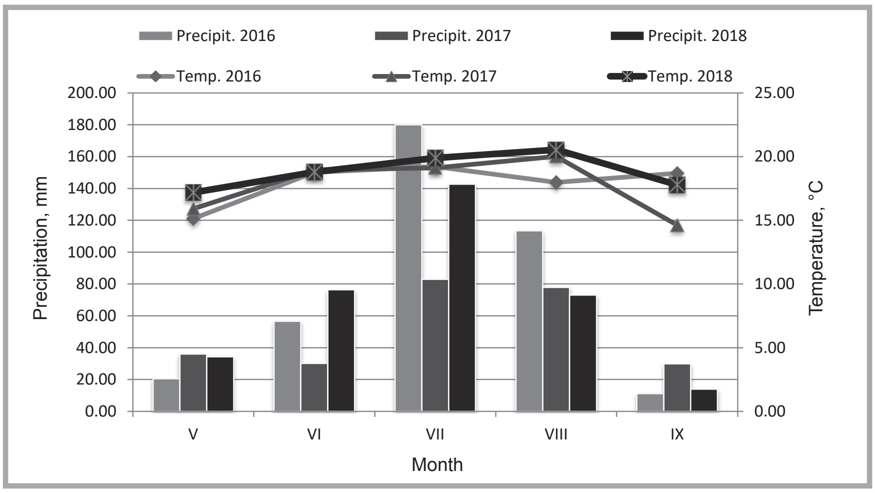

Figure 1. *Weather conditions over the course of the study.*

Zucchini plants, like those of cucumber, positively respond to the improvement in environmental conditions resulting from the influence of covers made of polymer materials. Optimisation of the microclimate accelerates their growth and development, which is favourable to obtaining a higher, especially early, yield. The aim of the research was to evaluate the physical properties of covers and the response of zucchini plants (*Cucurbita pepo* L. convar. *giromontina* Greb.) as a result of using two direct covers in the form of PP nonwoven fabric and HDPE netting.

Materials and methods

Experimental site

The experiments were carried out during the years 2016-2018 at the Experimental Station of the University of Agriculture in Krakow, south Poland (N 51°13', E 22°38'). The climate of the Experimental Station is humid continental (Dfb) according to Köppen's classification [19]. The soil type is Fluvic Cambisol (Humic).

Experimental design and treatments

The experimental material consisted of two types of direct covers: PP nonwoven (20 g m^{-2}) and a transparent knitted net with triangular holes, 4.9 × 1.5 × 5.1 mm, made of UV-stabilised HDPE (38 g m^{-2}). They were used to cover zucchini seedlings (produced in a standard way) of the cultivar 'Partenon' F1 (HILD Samen) immediately after planting in the second half of May (16 May 2016, 18 May 2017, and 15 May 2018). The experiment was set up in a split-block design with 4 replications. Each experimental plot included 32 plants planted at a distance of 100 × 80 × 100 cm. Plants not covered with the synthetic materials served as the control. The covers were removed on 6 June 2016, 10 June 2017, and 7 June 2018, before the first harvest. The fruit were harvested three times a week, every other day, and divided into 3 size classes: 10-14 cm, 15-21 cm, and > 21 cm. The fruit harvesting periods were: 13 June – 12 September 2016, 10 June – 7 September 2017, and 7 June – 12 September 2018. The fruit collected in the first 1/3 of all the harvests was regarded as an early yield. Non-marketable fruit were not included in the total yield due to their incidental occurrence. The marketable yield was determined in accordance with Polish Standard PN-R-75541: UN/ECE FFY-41 [20] – healthy fruit of a regular shape, without disease symptoms, and no mechanical or pest damage.

Fertilisers and plant protection products meeting the requirements of organic farming were used in the experiment. The frequency and amount of water supplied depended on the distribution and amount of precipitation. The plants were weeded mechanically.

Agri-environmental conditions

The weather conditions (mean air temperature and total precipitation) during zucchini vegetation are presented in ***Figure 1*** based on data from the National Environmental Satellite (NOAA) (www.ncdc.noaa.gov) for the Kraków-Balice meteorological station. Throughout the experiment, hourly soil temperature measurements were performed from the transplantation date to the removal of covers date in each year at a depth of 10 cm using HOBO U12-001 autonomous sensors (Onset Comp. Corp., Bourne, MA, USA) placed vertically in the central part of each treatment plot. Daily soil temperatures were calculated, and the data then presented as mean daily temperatures. Other parameters measured each year (6 June 2016, 10 June 2017, 7 June 2018) included photosynthetically active radiation (PAR) (spectroradiometer LI-COR 189B, USA), the relative humidity of air (Hygromer A1, Rotronic Ag, Germany), and the CO_2 content of the air (Telaire 7001, Onset Comp. Corp., USA). In addition, soil moisture measurements (HH2 Moisture Meter, Delta-T Devices, England) were performed at the same depth in four replications on 6 June 2016, 26 July 2017, and 7 June 2018, on average 3 days after rainfall.

Zucchini growth indicators and weed assessment

Assessments of zucchini plant development were performed on 7 June 2016, 12 June 2017, and 2 June 2018, and included 12 randomly selected plants from each experimental treatment. The number of true leaves and that of male and female flowers (buds) were counted for each plant.

Weed infestation was assessed once in June (8 June 2016, 22 June 2017, and 14 June 2018) using the frame-weight method with a 25 × 25 cm frame in three randomly selected locations. The number of individual weed species and the total fresh biomass were estimated directly in the field.

Plant development and laboratory fruit analysis

Chemical analyses were performed on 17-18 cm long fruit. They were ov-

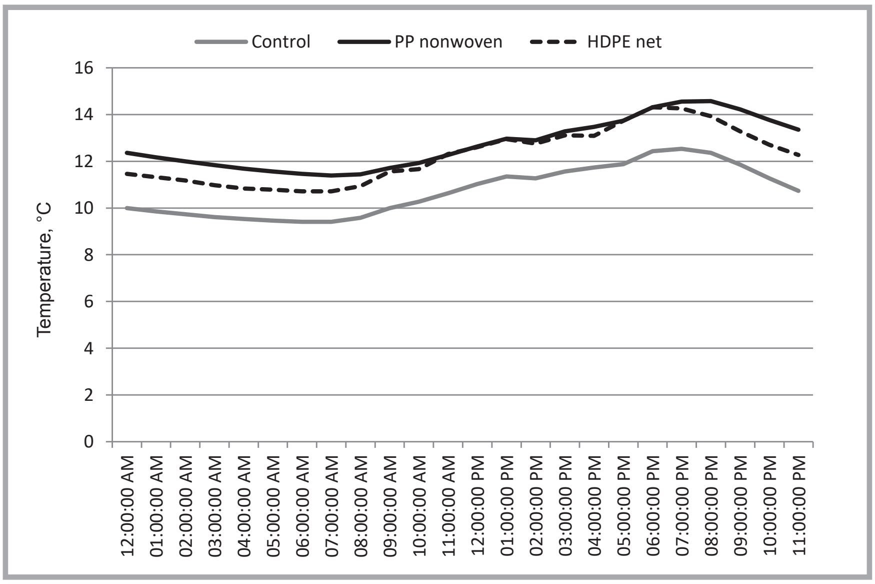

Figure 2. *Soil temperature during the coolest day of the experiment (18.05.2016).*

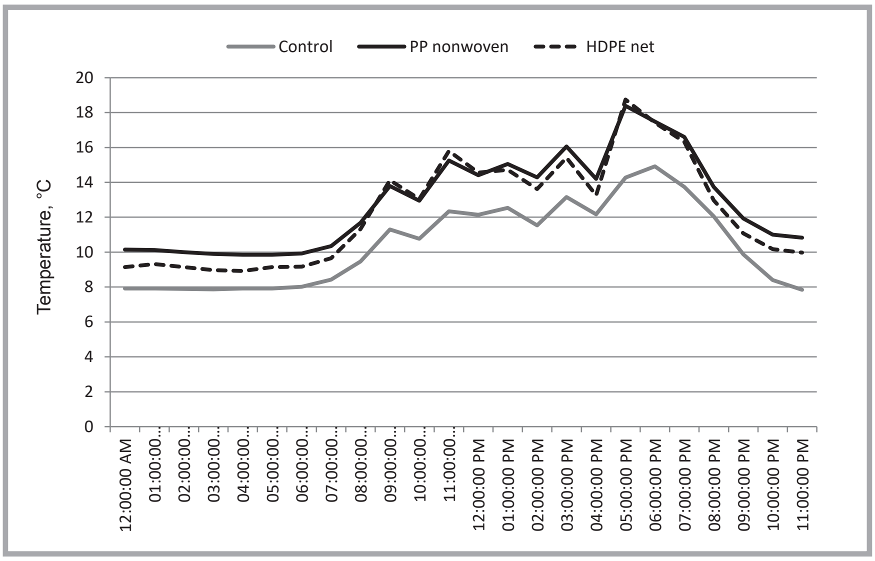

Figure 3. *Air temperature during the coolest day of the experiment (18.05.2016).*

en-dried at 65 °C, and the dry weight was measured with a laboratory balance (A120S, Sartorius AG, Goettingen, Germany). Soluble sugars were determined by the anthrone method after the extraction of plant material with 25 cm^3 of 80% ethanol. Absorbance was measured at 625 nm using a Helios Beta spectrophotometer (Thermo Fisher Scientific Inc., Waltham, USA). The total soluble sugar content was read from the calibration curve. Ascorbic acid content was determined by the Tillmans method. Plant extracts in 1% oxalic acid, after filtration and centrifugation, were titrated with Tillman's reagent (2,6-dichlorophenolindophenol). An excess of dye in an acidic environment produces a pink colour and marks the end point of the titration. The concentrations of chlorophylls (*a* and *b*) and carotenoids were determined using the peel of zucchini fruit to weigh out 0.5 g of plant material, which was ground with the addition of sand and magnesium carbonate. The pigments were extracted in 80% (v/v) aqueous acetone (25 cm^3), and after filtration the absorbance of the extracts was read at 470, 646, and 663 nm, respectively, using a Helios Beta UV-VIS spectrophotometer (Thermo Fisher Scientific Inc., USA). Phenolic compounds were extracted from plant tissues with 80% methanol solutions. Then a 2% Na_2CO_3 solution and F-C reagent were added. The reaction results in a blue compound that produces maximum absorption at 750 nm. The absorption intensity at this wavelength is proportional to the amount of phenolic compounds in the sample. Antioxidant activity (AA) was measured using 2,2-diphenyl-1-picrylhydrazyl (DPPH). Plant material was mixed with 80% methanol. The DPPH changed the violet colour to yellow, and the decrease in absorbance over time was measured with a UV-VIS Helios Beta spectrophotometer at 517 nm relative to the reference solution. Antioxidative activity was expressed as the percentage of residual DPPH not reduced by the antioxidants contained in the sample.

Statistical analysis

The results were statistically analysed by one-way ANOVA. The significance of differences was determined by the Tukey test at the significance level of p = 0.05. All statistical analyses were performed using STATISTICA 13.3.

Results and discussion

Meteorological and microclimatic conditions

More favourable meteorological conditions prevailed in 2017 and 2018 than in 2016 (***Figure 1***). In 2016, the zucchini plants, after being planted permanently, were exposed to cooler weather with less rainfall. In addition, in July and August of the same year, a total of almost 300 mm of rain was recorded, and the mean temperature in August was only 18.0 °C, which was over 2 °C lower than in the following years. The year 2017 was warm, but with the least amount of precipitation, while 2018 was exceptionally warm and humid, especially in the spring and early summer.

For the example of the coolest day, soil temperature analysis showed that, regardless of the type of material used, the soil temperature in the hottest period (between 10 AM to 6 PM) under covered objects was on average 1.6 °C higher than in the control group (***Figure 2***).

The temperature of air at the same hours were 2.69 °C and 2.53 °C higher, respectively, under PP nonwoven and a HDPE net compared to non-covered objects (***Figure 3***). At 5 PM was recorded the highest air temperature under covered plots (medium 18.6 °C). During other hours, it was warmer under PP nonwoven than a HDPE net.

The mean values for the 3 years of the study indicate that both the soil and air temperatures in the protected plots were

1.75 °C higher than in the uncovered field (***Table 1***). The most favourable conditions for the plants were under the PP nonwoven fabric, under which the soil and air temperatures were 2.2 °C and 2.1 °C higher, respectively, than in the control. Increases in the temperature of soil (0.1 °C) and air (3 °C) on covered plots had also been reported by Gordon et al. [21]. A slightly lower temperature was recorded under the HDPE net (an increase by 0.5-2.5 °C). The temperature values for the covered plots in 2017 were similar. The analysis of data obtained from sensors shows that the increase in temperature under the plastic covers was particularly pronounced during cold periods, which was confirmed in a review by Wadas [10] on potato cultivation for early harvest. Mean soil temperatures at a depth of 10 cm in early spring cultivation of butter lettuce under PP nonwoven (20 g m^2) were 0.8 °C and 3.6 °C higher in a warm year and in a cool and humid year, respectively, compared to the control, as found by Siwek et al. [22], and depended also on the thermal insulation of the material. Technical analyses showed that the physical properties of nonwovens are strongly correlated with thermal parameters. With the increase in mass, air permeability significantly decreases, and thermal diffusivity is proportional to the weight attributed to the volume fraction of fibres in the nonwoven fabric [23].

Table 1. *Mean soil and air temperatures in zucchini cultivation with floating row covers from the time of planting seedlings until the removal of the direct covers.*

Year	Type of cover	Soil temperature, °C	Air temperature, °C
2016	Control	18.1	19.2
	PP nonwoven	20.9	22.5
	HDPE net	20.1	21.7
2017	Control	–	20.9
	PP nonwoven	21.9	21.8
	HDPE net	21.6	22.0
2018	Control	22.4	23.6
	PP nonwoven	24.0	25.8
	HDPE net	23.0	24.1

Table 2. *Microclimatic conditions in zucchini cultivation under floating row covers in 2016-2018.*

Year	Type of cover	PAR, $\mu mol\ m^{-2}\ s^{-1}$	Air humidity, %	CO_2, ppm	Soil moisture, %
2016	Control	3014	21.8	434	21.2
	PP nonwoven	2675	42.3	437	20.4
	HDPE net	2738	42	436	21.9
2017	Control	589	54.3	450	16.4
	PP nonwoven	235	67.7	528	15.0
	HDPE net	268	59.3	475	17.6
2018	Control	2521	27.3	413	14.7
	PP nonwoven	1791	33.4	419	12.2
	HDPE net	1783	25.8	406	13.4

The transmission of PAR radiation (400-700 nm) varied markedly between the control plot and the covered plots (***Table 2***). The HDPE net transmitted more solar radiation than the nonwoven fabric, but the differences were not significant. The plastic covers had an average transmission of 90% on a sunny day (2016), 43% on a cloudy day (2017), and 71% in 2018. In another experiment, the same nonwoven fabric had transmitted 83% of PAR radiation [24]. The results obtained did not differ significantly from the transmission of thin nonwovens made of PP, photodegradable (0.02%) PP, and PLA with a surface weight of 20 g/m^{-2}, for which the estimated range was 74.5-83.4% [25]. In an experiment conducted in Spain, a PP nonwoven (17 g/m^{-2}) produced by the spun-bonded method transmitted from 85 to 65% of PPFD (Photosynthetic Photon Flux Density) depending on the amount of dust covering it and condensation of water vapour on the underside facing the plants [26]. In the first year of the study, in sunny and warm weather, air humidity under the covers was almost twice as high as in the control plot. In the following years, similar values were recorded under the net and in the open field, while air humidity under the nonwoven fabric was 13.4% and 6.1% higher than in the control. Other studies indicated an increase in soil temperature at a depth of 5 cm of 5.1 °C and in air humidity of 5.1% on average, as well as a reduction in the radiation reaching plants of 13% as a result of covering with PP nonwoven fabric (17 g/m^{-2}) and perforated foil (500 holes per 1 m^{-2}) [27].

The levels of CO_2 in the air around the plants in 2016 and 2018 were similar on all the plots and did not depend on the type of cover. In 2017, a higher level of this compound was recorded under both covers, with as much as 78 ppm more of it under the PP nonwoven than on the control plot. In 2016, soil moisture on each experimental plot exceeded 20%. Covering with the HDPE net was found to have a beneficial effect on soil water accumulation in 2016 and 2017 (increase of 0.7 and 1.2%). The soil in the treatment with PP nonwoven fabric was less moist by 0.8-2.5%, which may have been caused by water retention on polypropylene fibres, especially during periods with low amounts of low-intensity precipitation.

Table 3. *Growth indicators of zucchini plants cultivated under floating row covers in 2016-2018.* ***Note:*** ** – mean separation by one-way analysis, Tukey's test at $p = 0.05$. Means followed by the same letter within a column are not significantly different.*

Type of cover	Number of leaves				Number of female flowers (buds)				Number of male flowers (buds)			
	2016	2017	2018	Means for treatments	2016	2017	2018	Means for treatments	2016	2017	2018	Means for treatments
Control	7.9 a*	9.7 a	9.6 a	9.1 A	3.4 a	5.0 a	4.3 a	4.2 A	5.9 a	7.3 a	4.9 a	6.0 A
PP nonwoven	11.8 c	14.1 c	12.9 c	12.9 C	4.6 a	5.5 ab	5.3 ab	5.1 A	5.9 a	10.7 b	5.5 a	7.7 A
HDPE net	9.4 b	12.8 b	12.1 b	11.4 B	3.4 a	6.9 b	5.9 b	5.4 A	6.9 b	9.3 ab	5.8 a	7.0 A
Mean for years	9.7 A	12.2 B	11.5 B		3.8 A	5.8 B	5.2 B		6.2 A	9.1 B	5.4 A	

Table 4. *Weed infestation [g] in dependence on different soil cultivation methods in zucchini production.* ***Note:*** ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.*

Type of cover	Weed infestation, g			
	2016	2017	2018	Mean for treatments
Control	235 a*	52 a	32.7 a	107 A
PP nonwoven	250 a	184 a	67.3 a	167 A
HDPE net	275 a	118 a	67.7 a	153 A
Mean for years	253 B	118 A	56 A	

Zucchini plant growth and weed infestation under direct covers

As a result of covering zucchini plants, a clear acceleration in growth in the form of a greater number of leaves was recorded in all the years of the study (***Table 3***). The plants growing under the PP nonwoven had the most leaves (12.9), regardless of the year. Vegetables with a short growing season, covered with PP nonwovens, are characterised by a higher leaf area index (LAI) and a greater production of thinner leaves, which contributes to an improvement in the quality of leaf vegetables [26]. The use of covers had resulted in faster growth of summer squash plants; however, they had a smaller shoot diameter [21]. Anyszka and Dobrzański [28], in turn, noted a positive effect of covering with PP nonwoven fabric on the size and mass of the first true leaf of head cabbage. The zucchini plants growing under the two covers also had more male and female buds, but these differences were not confirmed statistically in the mean values for the years. The largest number of female flowers were produced by the zucchini plants under the HDPE net: 6.9 (2017). The same cover significantly contributed to the formation of more male flowers in 2016 (6.9). The highest values determining the phenological state of plants were recorded in 2017 (especially for the number of male flowers), which was caused by a later time of observation than in the other years. According to Zawiska and Siwek [29], cucumber plants under biodegradable covers produce longer roots.

In the consecutive years of the experiment, weed infestation decreased from 253 g (2016), to 118 g (2017), and to 56 g in 2018 ***(Table 4)***. Similar levels of weed biomass in the experimental plots were estimated in 2016 (235-275 g). However, there were no statistically significant differences between the treatments in any of the years. Weed infestation increased by 43% and 56% for the HDPE net and PP nonwoven, respectively, compared to the control. The weeds were dominated by thermophilic species (*Galinsoga* sp., *Echinochloa crus-galli* L., *Amaranthus retroflexus* L.) and dicotyledonous weeds emerging in early spring (*Chenopodium album* L., *Capsella bursa-pastoris* (L.) Medik. and *Thlaspi arvense* L.) (data not shown). The results obtained confirm the correctness of the statements made in this respect by other authors [8, 28].

Zucchini crop yield and quality

In 2017 and 2018, the total marketable yield was 85% and 70% higher than in

Table 5. *Effect of using direct covers on early and marketable yields of zucchini [t ha^{-1}], and on the dry matter content in fruit [%].* ***Note:*** ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.*

Type of cover	Early yield, t ha^{-1}				Total marketable yield, t ha^{-1}				Dry mass, %			
	2016	2017	2018	Mean for treatments	2016	2017	2018	Mean for treatments	2016	2017	2018	Mean for treatments
Control	30.8 a*	24.6 a	22.1 a	25.8 A	66 a	138 a	95.7 a	99.8 A	5.29 a*	6.02 c	5.67 a	5.66 A
PP nonwoven	40.2 b	26.9 ab	28.6 b	32 B	80.6 b	144 a	148 b	124.1 A	5.50 b	5.90 b	6.15 c	5.85 A
HDPE net	41.5 b	30.7 b	33.2 c	35.2 B	82 b	141 a	147 b	123.3 A	5.65 c	5.59 a	5.94 b	5.73 A
Mean for years	37.5 B	27.4 A	28.0 A		76.2 A	141 B	130 B		5.48 A	5.84 B	5.92 B	

Table 6. *Chemical composition of zucchini fruit cultivated under floating row covers.* ***Note:*** ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.*

Type of cover	Ascorbic acid, mg 100 g^{-1} FW			Mean for treatments	Total phenols, mg 100 g^{-1} FW			Mean for treatments	Sugars, % of FW			Mean for treatments
	2016	2017	2018		2016	2017	2018		2016	2017	2018	
Control	12.6 a*	24.5 a	26.8 a	21.3 A	62.9 a	67.7 a	80.1 a	70.3 A	2.50 b	2.12 a	1.73 a	2.12 A
PP nonwoven	17.5 b	24.5 a	32.3 b	25.5 A	80.6 b	67.4 a	74.3 a	74.1 AB	2.20 a	1.90 a	1.82 b	1.97 A
HDPE net	18.8 b	24.5 a	34.4 c	25.2 A	77.7 b	68.5 a	91.0 b	79.1 B	2.39 ab	1.98 a	1.81 b	2.06 A
Mean for years	16.3 A	24.5 B	31.2 C		73.7 A	67.9 A	81.8 B		2.36 C	2.0 B	1.79 A	

Table 7. *Chemical composition of zucchini fruit cultivated under floating row covers.* ***Note:*** ** – mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.*

Type of cover	Karotenoids, µg g^{-1} FW			Mean for treatments	Chlorophyls *a* and *b*, µg g^{-1} FW			Mean for treatments	Antioxidant activity, %			Mean for treatments
	2016	2017	2018		2016	2017	2018		2016	2017	2018	
Control	30.7 a*	39.0 ab	31.1 c	33.6 A	143 a	142 a	124 c	136 A	2.60 a	1.38 a	4.17 a	2.72 A
PP nonwoven	40.4 b	41.9 b	21.2 a	34.5 A	141 a	167 b	74,1 a	128 A	3.12 b	1.19 a	5.67 c	3.33 A
HDPE net	31.9 ab	36.3 a	27.4 b	31.9 A	112 a	144 a	108 b	121 A	2.53 a	1.79 a	5.10 b	3.14 A
Mean for years	34.3 B	39.1 C	26.5 A		132 B	151 B	102 A		2.75 B	1.45 A	5.0 C	

2016 (***Table 5***). The three-year average indicates an increase in the total marketable yield of approx. 24% as a result of plant covering; but this increase was not statistically confirmed. The highest fruits yield were harvested in 2018 from the plot with PP nonwoven (148 t ha^{-1}). A different correlation was noted for the early yield, which was the highest in the first year of the study (37.5 t ha^{-1} on average), compared to the others. The direct covers positively influenced the level of the early yield in all the years of the experiment. In this respect, the HDPE net proved to be a cover somewhat more effective than the PP nonwoven. Positive effects of covering with perforated foil (with 50, 100, and 500 holes per 1 m^{-2}) and PP nonwoven (17 g/m^{-2}) on yield were demonstrated in the cultivation of Chinese cabbages, kohlrabi, broad beans, and melons [27, 30-32]. Covering melon plants contributed to the obtaining of heavier and more elongated fruit [33].

On mulched plots and those covered directly with nonwoven fabric and perforated foil, the average early yield was 2.18 times higher and the total yield 16 t ha^{-1} higher in cucumber cultivation [34], while the early yield of zucchini increased by 47.9% [35].

The harvested zucchini fruit contained 5.29-6.15% dry matter (***Tables 5***). In 2016 and 2018 there was significantly more dry matter in the fruit from the covered plots than from the control. The fruit harvested in 2016 contained significantly more water and less ascorbic acid (***Table 6***). There were no differences between the treatments in terms of the concentration of the latter component in 2017. Increases in the accumulation of L-ascorbic acid were found in the successive years of the study (of 8.2 and 14.9 mg 100 g^{-1} FW on average). An inverse relationship was found for the amount of sugars, the highest level of which was in the zucchini fruit in 2016 (2.36% of FW), and the lowest in 2018 (1.79% of FW). The highest concentration of carotenoids in the fruit was recorded in 2017 (on average 39.1 µg g^{-1} FW) (***Table 7***). Their level varied between the treatments over the years. The concentrations of chlorophylls in 2016 and 2017 were comparable and higher than in 2018 (102 µg g^{-1} FW). The highest variation between the treatments was found in 2018 (74.1-124 µg g^{-1} FW). In the same year, the zucchini fruit were characterised by an antioxidant activity about three and a half times higher than in 2017 (1.45%) and nearly twice more than in 2016 (2.75%). The weather conditions in 2018 were favourable for the synthesis of phenolic compounds in zucchini fruit, which were observed to contain on average 81.8 mg 100 g^{-1} FW. Significantly greater amounts of phenols were found on the plot with HDPE netting than on the control plot. For the treatment with nonwoven fabric, intermediate values were recorded (74.1 mg 100 g^{-1} FW). Laboratory analyses of the fruit over the three years did not show any differences between the treatments in terms of the concentrations of components (except phenolic compounds). The significant differences in the chemical composition of the fruit between the treatments, although not reproducible over the years, suggest that the influence of the plant cover on the quality of the crop depends on the meteorological conditions. In another experiment with zucchini, fruit of similar length (16-22 cm) harvested from plants covered with PP nonwoven (17 g/m^{-2}) contained 22.3 mg vitamin C, 83 mg nitrates, 0.91% P, 6.4% K, and 1.20 mg 100 g^{-1} of dry matter [35]. According to Biesiada [30], flat covering of kohlrabi plants contributed to a decrease in the amounts of dry matter and sugars, but did not affect the concentration of vitamin C. By comparison, romaine lettuce covered with PP nonwovens (17 and 50 g/m^{-2}) accumulated less K and more Mg, without changes in the dry matter content, total N, Ca, or P [36]. As a result of covering melon plants with PP nonwoven and PE perforated foil, the melon fruit were characterised by a lower dry matter content than in the control, but contained more dry matter when the plants were simultaneously mulched with black PE foil. Moreover, using plant covers contributed to the accumulation of greater amounts of nitrates ($N\text{-}NO_3^-$ mg kg^{-1} FW) by 43 and 68% on the plots covered with foil and nonwoven fabric, respectively [37]. Kalisz et al. [24] showed that the use of degradable covers made of PP photo and PLA resulted in lower amounts of dry matter and soluble sugars in cucumbers, which was probably caused by rapid fruit growth. In the cultivation of the same species, biodegradable materials inhibited the accumulation of nitrates (NO_3^- mg kg^{-1} FW), while the three-year average showed that the amounts of dry matter and soluble sugars were comparable to those in the fruit from the control plot [29]. The same authors reported no differences in the concentrations of dry matter, soluble sugars, nitrates, chlorophylls and carotenoids in lettuce covered with nonwoven fabric and from the control [22].

Conclusions

1. The increase in air and soil temperatures as a result of direct covering is particularly evident in cool years. PP nonwoven fabric proved to be more effective in this respect than HDPE netting. Covering zucchini plants with these materials reduced the transmission of PAR reaching the plants.

2. The favourable microclimate conditions under flat covers contributed to faster growth of zucchini plants, mainly in the form of a greater number of leaves. The higher temperature promoted greater weed infestation.

3. Both types of cover significantly contributed to obtaining a higher early yield. The total yield from the plots covered with the nonwoven and the net increased on average by 24.3% and 23.5%, respectively.

4. Direct covering of zucchini plants at the initial stage of their development did not significantly affect the chemical composition of the fruit, except for the concentration of phenolic compounds. The content of these compounds increased as a result of covering the plants (especially the HDPE net).

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Conflict of Interest

The authors declare no conflict of interest.

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Impact of soil management practices on yield quality, weed infestation and soil microbiota abundance in organic zucchini production

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ABSTRACT

In organic farming, reduced tillage aims to maintain the natural fertility of the soil, including its microbiological diversity. Cultivation practices that change the properties of the soil environment determine conditions of plant growth and yield as well as the chemical composition of the biomass. The methods and dates of performing soil cultivation treatments in organic vegetable production were studied in southern Poland, in the years 2016–2018. The following cultivation combinations were applied: conventional autumn ploughing tillage (APT), spring ploughing tillage (SPT), spring rotary tillage (SRT), spring rotary tillage with polypropylene nonwoven (surface mass of 50 g m^{-2}) mulch (SRTPM), and spring rotary tillage with fresh biomass mulch (SRTBM). The experiment was established on a site where a mixture of white clover (*Trifolium repens* L. cv. 'RD 84') and Italian ryegrass (*Lolium multiflorum* Lam. cv. 'Gaza') was grown for green manure, which constituted a forecrop for zucchini (*Cucurbita pepo* L.) cv. 'Partenon' F1. The fresh biomass of clover and grass was used to mulch the soil on the SRTBM plots. It was shown that the spring soil cultivation with a rotary tiller before planting zucchini plants resulted in a higher marketable yield of zucchini fruit compared to the ploughing performed in the spring (an increase by 34.3%) and the ploughing performed in the autumn (an increase by 25.3%), but these differences are not statistically confirmed. The date of ploughing did not significantly affect the extent of weed infestation on the experimental plots. Zucchini fruit harvested in the last year of study (2018) were characterized by the strongest antioxidant activity and contained the highest amount of total phenols. The study demonstrated a beneficial effect of the reduced tillage and mulching with fresh biomass (SRTBM) on bacterial population (1.56×10^9 CFU g^{-1} DW) in the soil.

1. Introduction

Data from 2017 (FAO 2020) show that the total world agricultural area covers 37.1% of the total land area. In the face of climate change, sustainable agriculture is one of the most important ideas, a way to maintain the economic viability of farms and to meet human food needs. With the growing world population there is a strong necessity for development and implementation of solutions that will further minimize the progressive degradation of natural resources (Singh et al., 2005; Clark and Tilman, 2017; Carlisle et al., 2019; Moore et al., 2019). Management of the soil environment plays an important role in this respect. Problems such as wind and water erosion, decreasing organic matter content and microbial activity, deteriorating soil physical and chemical properties, increasing salinity and nitrogen leaching due to intensive agriculture can be limited to some extent by proper soil management. Limiting soil degradation and increasing its biological activity can be achieved, among others, through reduction in tillage, mulching, and the use of cover crops (Sun et al., 2018; Branco et al., 2017; Nachimuthu et al., 2017).

Despite the many benefits of plough cultivation such as effective loosening and crushing of the soil, uniform distribution of nutrients, increased porosity and root growth zone, the high rate of humus

Abbreviations: APT, autumn ploughing tillage; GLC, grass-legume mixture control; PGPR, plant growth-promoting rhizobacteria; PP, polypropylene; SPT, spring ploughing tillage; SRT, spring rotary tillage without mulch; SRTPM, spring rotary tillage with polypropylene nonwoven mulch; SRTBM, spring rotary tillage with fresh biomass mulch.

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decomposition and the negative impact on the physical properties of the soil have prompted the search for alternatives. In the era of environmental protection and cost reduction, ploughing as a conventional tillage method may be abandoned under certain conditions, as confirmed by Calcante and Oberti (2019). Eco-friendly farming systems within the framework of sustainable agriculture encourage the introduction of conservation tillage into practice (Dzienia et al., 2006). Zuber and Villamil (2016) and Jat et al. (2018) have shown that reduced tillage systems together with treatments that conserve crop residues increase the levels of organic carbon and total nitrogen in the form of organic matter, as well as stimulate the biomass of soil microorganisms. One of the methods of shallow loosening of the soil is rototilling which works well in destroying turf and preparing the site for growing vegetables. This approach also applies to land that has just been taken over for cultivation, such as permanent grassland.

The use of reduced tillage compared to conventional ploughing is less energy and time-consuming. Similar production effects can be obtained in the growing of maize, but in the growing of most cereals, ploughless cultivation reduces yields (Białczyk et al., 2008; Panasiewicz et al., 2020).

Microorganisms inhabiting the soil play an important role as indicators of its quality because of their participation in the processes occurring in agroecosystems. Microbes are involved, for example, in the decomposition of organic matter, circulation of elements in the environment, fixation of atmospheric nitrogen, transformation of mineral compounds, and in the formation and stabilization of soil aggregates (Dubova et al., 2016). Microbiota abundance and activity directly affect fertility and quality of the soil, and thereby plant growth and crop quality (Wu et al., 2011). The method of soil tillage is an important factor known to strongly influence the development of soil microorganisms. Ploughing as a conventional agrotechnical treatment that turns the soil over creates unfavorable conditions for the development of microbiota that have a preference for a specific layer of the soil profile (Sun et al., 2018).

It is possible to restore and maintain soil fertility in a sustainable manner, e.g. by using mixtures of grasses and legumes. They are not only a source of organic matter but can also reduce the use of fertilizers and pesticides. Leguminous plants live in symbiosis with nodule-forming bacteria of the genus *Rhizobium*, which enrich the soil with nitrogen by fixing it from the atmosphere. Grasses, in turn, make extensive use of the nitrogen present in the soil, and then slowly release it as the biomass decomposes. In addition, they spread and thicken, and thus reduce weed infestation (Kołota and Adamczewska-Sowińska, 2013; Sharma et al., 2018). Grass-legume mixtures are usually more effective in reducing weed infestation and soil erosion, and produce more biomass than legumes as single-species crops. The phenomenon of overproductivity of mixtures is caused by the reduction in intra-species competitiveness for nutrients taken up from different soil layers (Sainju et al., 2005; Staniak, 2008; Helgadóttir et al., 2018).

Soil mulching is an indispensable element of organic vegetable growing. The treatment helps to achieve pronounced effects, especially in thermophilic species belonging to the *Cucurbitaceae* and *Solanaceae* families. The type of mulch determines, among others, the temperature and moisture of the soil under the mulch, its structure, weed infestation, and the presence of agrophages, which ultimately translates into the quantity and quality of the obtained crop. The most commonly used mulches include low density polyethylene foil (ldPE), nonwoven PP fabric (and their degradable counterparts), and straw (Bucki and Siwek, 2019).

Mulching the soil, applying green manure and cultivation with a plough and rototiller are common for vegetable production system in Central European countries. The relatively small amount of available research dealing with the reduced soil cultivation has prompted the authors of this study to compare plough tillage with the reduced tillage performed with a rototiller after a grass-legume mixture application, using zucchini as an example. The study assessed the impact of the date and method of tillage, as well as of mulching with organic and synthetic materials, on crop yield and quality, weed infestation, and the development of soil microorganisms in organic production of zucchini.

2. Materials and methods

2.1. Field site description

The experiment was conducted during the years 2016–2018 at the Experimental Station of the University of Agriculture in Kraków, located in Mydlniki (southern Poland; N 51°13′, E 22°38′). The climate of the station is humid continental (Dfb) according to Köppen's classification (Peel et al., 2007). The soil type is a Fluvic Cambisol (Humic).

Particle size analysis (PN-R-04032, 1998) classified the soil at this site as fine-grained belonging to the silty clay soil group with particle size fractions as follows: sand 2.0–0.05 mm – 14%, silt 0.05–0.002 mm – 45%, and clay <0.002 mm – 41%). Before starting the experiment, the amounts of plant-available forms of nutrients, determined using the universal method (Ostrowska et al., 1991), were as follows (mg dm^{-3}): NO_3-N, 4.00; P, 33; Ca, 866; K, 60; Mg, 138; S, 10. Soil micronutrient concentrations, determined in 1 mol dm^{-3} HCl extracts (Ostrowska et al., 1991), were (mg kg^{-1}): B, 1.1; Cu, 6.0; Fe, 1902; Mn, 229; Zn, 51; and Ti, 7.4.

Soil fertility significantly depends on its physical and chemical attributes, which impacts the agronomic yield. In 2015, before establishment of the field experiment, the soil bulk density (BD) was 1.30 g cm^{-3}, soil water capacity 48.8% w/v, soil organic carbon 1.42%, and the water-stable aggregate index expressed as the sum of the 0.25–5.0 mm water-stable aggregate fractions was 82.0%.

Low concentrations of plant-available K in the soils was detected. The sufficient level of available K concentration determined by the universal soil test with acetate extraction (0.03 mol dm^{-3}) for most vegetables is greater than 150 mg K dm^{-3} for high textured soils (Sady, 2000). Soil phosphorus and all micronutrient concentrations were within the optimal range for vegetables.

Detailed soil analysis was performed after each growing cycle. The results of measurements of soil physical and chemical properties will be published in a separate publication.

2.2. Plant material and experimental design

Zucchini seeds (*Cucurbita pepo* L. convar. *giromontina* Greb.) cv. 'Partenon' F1 (HILD Samen) were sown in 40-cell expanded polypropylene trays filled with peat substrate on April 19 in both 2016 and 2017, and on April 17 in 2018. The seedlings were transplanted to an ecologically certified field on May 16, 18 and 15 in the successive years of the study, respectively. Plant spacing was 100 × 80 × 100 cm. The experiment was carried out in a split-block design. The five treatment combinations were carried out in four replications, making up the total of 20 plots with a plot size of 4 m × 1.8 m, with eight plants per each plot. The treatments represented five soil managements methods: autumn ploughing tillage (APT), spring ploughing tillage (SPT), spring rotary tillage (SRT), spring rotary tillage with polypropylene nonwoven mulch (SRTPM), and spring rotary tillage with fresh biomass mulch (*Trifolium r.* + *Lolium m.* mixture) (SRTBM).

2.3. Cropping system management

Before setting up the experiment, the cultivation site was sown with a 60:40% mixture of *Trifolium repens* L. cv. 'RD 84' and *Lolium multiflorum* Lam. cv. 'Gaza' (76.5 kg ha^{-1}). The biomass was destroyed during the cultivation treatments planned for individual experimental plots. The conventional autumn ploughing was performed to a depth of 25 cm in the last ten days of October. Shallower spring ploughing was performed to a depth of 15 cm, whereas rototilling (3 passes of the rototiller) was carried out to a depth of 10 cm, leaving 1 m wide strips of turf between the plant rows. Both treatments were performed one month before transplanting the seedlings. The fertilizers used in the experiment were those approved for organic farming, i.e. Bioilsa, potassium sulphate, chalk lime and Phosphocal. They were applied after ploughing and rototilling the soil in the spring, adjusting the doses to the requirements of zucchini plants, based on the soil analysis. Before transplanting the seedlings, the soil in all the plots was loosened with a rotary tiller. After planting the plants in the SRTBM plots, the soil around them was mulched with a freshly cut crop of the white clover and Italian ryegrass mixture at 3–4 kg m^{-2}. During vegetation, the plants were fertilized by top dressing with a solution of cattle manure (10%), allocating 1.5 L per plant, and the preparation Natural Crop SL (1%). Protection of zucchini as a disease and pest-tolerant plant was limited only to manual removal of single lower leaves showing powdery mildew symptoms and preventive spraying with Grevitax (0.15%). The plants were watered as needed. Weeding was carried out mechanically, regularly after the assessment of weed infestation in June. In the SRT, SRTPM and SRTBM plots, in which a mixture of clover and grass had been left in the inter-rows, these plants were mowed with a flail mower as they tended to regrow during vegetation. Zucchini was grown each year on a new site in the successive seasons of using the grass-legume mixture as a green fertilizer.

2.4. Environmental conditions

The weather conditions (mean air temperature and total precipitation) during zucchini vegetation are presented in Fig. 1 based on the data from the National Environmental Satellite (NOAA) (www.ncdc.noaa.gov) for the Kraków-Balice meteorological station.

Throughout the experiment, hourly soil temperature measurements were performed from the transplantation date to the last harvest of each year at a depth of 10 cm using the HOBO U12-001 autonomous sensors (Onset Comp. Corp., Bourne, MA, USA) placed vertically in the central part of each treatment plot. Daily soil temperatures were calculated, and the data were then presented as mean daily temperatures. In addition, soil moisture measurements (HH2 Moisture Meter, Delta-T Devices, England) were performed at the same depth in four replications on 6 June 2016, 26 July 2017, and 7 June 2018, typically, three days after intensive rain.

2.5. Zucchini yield and weed assessment

The zucchini fruits were harvested three times a week, dividing them into two size classes (15–21 cm long and >21 cm long). On the first harvest dates (two in 2016 and four in 2017 and 2018), 10–14 cm long fruits were also included. The harvests were carried out from June 13 to September 12 in 2016 (33 harvests), from June 10 to September 7 in 2017 (36 harvests), and from June 7 to September 12 in 2018 (37 harvests). The marketable yield was determined in accordance with the Polish Standard PN-R-75541: UN/ECE FFY-41 – healthy fruit of a regular shape, without disease symptoms, and no mechanical or pest damage. The yields obtained from each replicate were added up and converted to t ha^{-1}.

Weed infestation was assessed once in June (8 June 2016, 22 June 2017, and 14 June 2018) using the frame-weight method with a 25 × 25 cm frame in three randomly selected locations. The SRTPM plots were not included in the assessment of weed infestation. The number of individual weed species and the total fresh biomass were estimated directly in the field.

2.6. Fruit analyses

The zucchini fruit used for analyses were 17–18 cm long.

Dry fruit weight was determined by the drying method according to Pijanowski et al. (1964), by drying the samples at 65 °C. Soluble sugars were determined by the anthrone method (Yemm and Willis, 1954) after extraction of plant material with 25 cm^3 of 80% ethanol. Absorbance was measured at 625 nm using a Helios Beta spectrophotometer (Thermo Fisher Scientific Inc., Waltham, USA). The total soluble sugar content was read from the calibration curve.

Ascorbic acid content was determined by the Tillmans method (Tillmans et al., 1932). Plant extracts in 1% oxalic acid, after filtration and centrifugation, were titrated with Tillmans' reagent (2,6-dichlorophenolindophenol). An excess of dye in an acidic environment produces a pink color and marks the end point of the titration.

The concentrations of chlorophylls (*a* and *b*) and carotenoids were determined according to the procedure given by Lichtenthaler and Wellburn (1983). The peel of the zucchini fruit was used to weigh out 0.5 g of plant material, which was ground with the addition of sand and magnesium carbonate. The pigments were extracted in 80% (v/v) aqueous acetone (25 cm^3) and after filtration the absorbance of the extracts was read at 470, 646, and 663 nm, respectively, using a Helios Beta UV–vis spectrophotometer (Thermo Fisher Scientific Inc., USA).

The total phenolic content was determined according to the Folin-Ciocalteu method (Singleton et al., 1999). Phenolic compounds were extracted from plant tissues with 80% methanol solutions. Then a 2% Na_2CO_3 solution and the F-C reagent were added. The reaction results in a blue compound that produces maximum absorption at 750 nm. The absorption intensity at this wavelength is proportional to the amount of phenolic compounds in the sample.

Antioxidant activity (AA) was measured by the method described by Brand-Williams et al. (1995), using 2,2-diphenyl-1-picrylhydrazyl

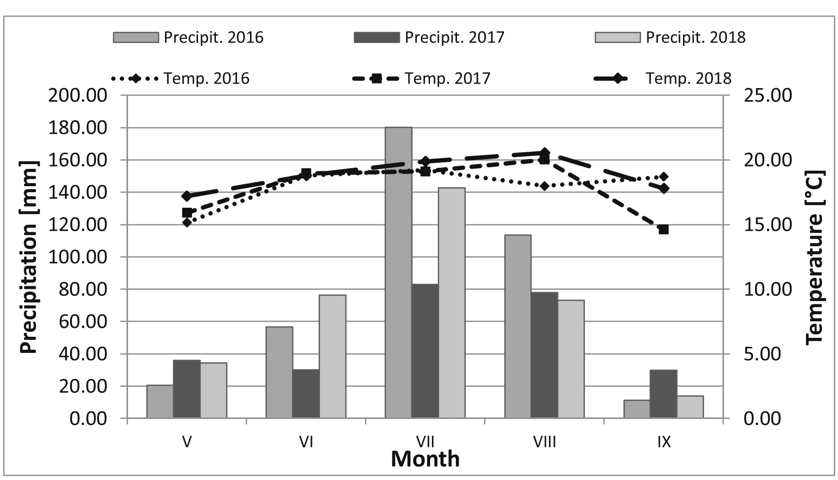

Fig. 1. Meteorological conditions during the experiment (from zucchini planting to the last harvest).

(DPPH). Plant material was mixed with 80% methanol. The DPPH changed the violet color to yellow, and the decrease in absorbance over time was measured with a UV–vis Helios Beta spectrophotometer at 517 nm, relative to the reference solution. AA was expressed as a percentage of residual DPPH not reduced by the antioxidants contained in the sample.

2.7. Microbiological analysis of soil

For microbiological analyses, soil samples were collected four times during the growing season in 2018: in April – before fertilization and mulching, in May – one week after fertilization, mulching, and planting, then in July, and finally in September. The soil material for the assessment of the frequency of individual groups of microorganisms was collected three times from each experimental variant, and from grassland as the control variant. The soil samples were taken from the arable layer at a depth of 10–20 cm using an Egner's soil sampler and stored at 4 °C until microbiological analyses were performed.

The soil samples served to establish the total number of bacteria, as well as the populations yeast and fungi and *Azotobacter* spp. in 1 g dry weight (DW) of the soil. Soil dry weight was determined by drying the samples for 24 h at 105 °C. Bacterial, yeast and fungal cell occurrence was determined in aqueous soil extracts with the Koch surface-plating method, using Petri dishes containing solidified media: 2.5% [w/v] enriched agar (optimal growth medium for bacteria; Biomaxima, Poland), 6.5% [w/v] Sabouraud medium (specific to fungi including yeast; Biomaxima, Poland), or Azotobacter selective medium (glucose 5.00 g dm^{-3}, mannitol 5.00 g dm^{-3}, $CaCl_2 \cdot 2H_2O$ 0.10 g dm^{-3}, $MgSO_4 \cdot 7H_2O$ 0.10 g dm^{-3}, $Na_2MoO_4 \cdot 2H_2O$ 5.00 mg dm^{-3}, K_2HPO_4 0.90 g dm^{-3}, KH_2PO_4 0.10 g dm^{-3}, $FeSO_4 \cdot 7H_2O$ 0.01 g dm^{-3}, $CaCO_3$ 5.00 g dm^{-3}, agar 15.0 g dm^{-3}), respectively. All the media were sterilized before use. In order to obtain homogeneous cell suspensions prior to dilutions, bacterial samples were sonicated under mild conditions for 10 min. with a laboratory ultrasound washer (Sonic-2/Polsonic, Poland). The colonies of bacteria, yeast and fungi were counted after 2-day incubation of plates at 23 ± 1 °C, except for *Azotobacter* spp. evaluated after 3-day incubation at 23 ± 1 °C. After incubation, the colony counts were converted to CFU g^{-1} of soil DW (colony forming units per gram of soil dry weight) (Kaszycki et al., 2014).

2.8. Statistical analysis

The data on the yield and biological value of zucchini fruit and weed infestation were statistically analyzed using the one-way analysis of variance (ANOVA) method, separately for each year of the study. The obtained mean values were compared employing the Tukey's test at the significance level $p = 0.05$ in the Statistica 13.3 program (StatSoft, Poland).

Each microbiological analysis was performed in duplicate, applying three independent series of dilutions and culture incubations. The obtained results of microorganism frequencies were statistically analyzed using the two-way analysis of variance (ANOVA) method. The two factors analyzed were the date of sampling and the method of tillage. The resultant mean values were compared using the Duncan's test with the significance level at $p = 0.05$ in the Statistica 13.3 program (StatSoft, Poland).

3. Results

3.1. Meteorological and microclimatic conditions

In the first and second year of the experiment, the mean air temperatures were comparable, with values of 18.0 °C and 17.7 °C, respectively, while in 2018 that value was on average 1 °C higher (18.8 °C) (Fig. 1). June proved to be the most stable month in terms of the mean air temperature, which was 18.8 °C, 19.0 °C, and 18.8 °C in 2016, 2017, and 2018, respectively.

The total precipitation was the highest in 2016 (382 mm), which was mainly influenced by the fact that as much as 180 mm was recorded in July. The year 2017 proved to be the driest year, in which the total precipitation represented only 67.3% and 75.5% of the total precipitation in 2016 and 2018, respectively. The first half of September 2017 was characterized by the highest precipitation and the lowest temperature in comparison with the other years.

The soil temperature during the zucchini growing season was higher each year in all the experimental plots (Table 1). The highest value was recorded in the SPT plots, where it exceeded 20 °C in 2018. The soil temperature in all the plots where the soil had been rototilled was lower than in the others, where the plough was used for soil preparation, by an average of 0.9 °C. Its highest value was recorded in the plots with soil turned in the spring (19.6 °C), and the lowest in the plots mulched with nonwoven polypropylene fabric (18.4 °C).

Single measurements of soil moisture indicate that it fluctuated between 13.0% and 25.2%, and was the lowest for the treatments without mulch, except for the SRTPM treatment in 2018 (Table 2). Marked water retention in the soil as a result of mulching with organic matter was recorded in 2018, when the moisture content was by at least 7% higher than in the other treatments.

3.2. Yield and dry matter content of zucchini fruit

The low yield of 10–14 cm long zucchini fruit was caused by the fact that fruit of this size were harvested only a few times at the beginning of vegetation (Table 3). In the first year of production, considerably fewer such fruit were harvested because the number of harvests was half of those in the following years. The study did not include non-marketable fruit as their quantity was negligible (data not shown). Compared to 2016, the yields in the subsequent years of the experiment were significantly higher, on average by 64.3% (in 2017) and 76.5% (in 2018) (Table 4). The lowest zucchini fruit yield was obtained from the plants grown in the plots where ploughing had been carried out beforehand in the spring of 2016 (65.9 t ha^{-1}), whereas the highest one from the plants grown in the soil cultivated with a rotary tiller and mulched with nonwoven fabric in 2018 (165.51 t ha^{-1}). There was a clear upward trend in the yield of zucchini fruit in the plots where the soil was rototilled in the spring of 2017 and 2018, as compared to 2016. In the same years, there was also a high percentage share of fruits longer than 21 cm in the marketable yield. In 2017, the yield of fruits with a length >21 cm and the total marketable yield were lower in the plots where ploughing had been performed in the autumn, compared to the other plots. As indicated by the mean values for the three years of the study, the yields obtained from the plots cultivated with a rotary tiller, regardless of the mulches used, tended to be higher (on average by 30 t ha^{-1}) than from the plots cultivated with a plough; however, it has to be noted that according to the statistical evaluation model the observed differences remained within the same groups of statistical significance (Table 4).

In 2017 and 2018, the zucchini fruit contained significantly less

Table 1
Soil temperature (°C) at a depth of 10 cm depending on different soil cultivation methods.

Treatment	Soil temperature [°C]			
	2016	2017	2018	Mean for treatments
APT[a]	19.5	19.5	19.8	19.6
SPT	19.3	19.4	20.1	19.6
SRT	18.8	19.0	19.0	18.9
SRTBM	18.6	18.7	19.0	18.8
SRTPM	18.0	18.5	18.6	18.4
Mean for years	18.9	19.0	19.3	

[a] APT – autumn ploughing tillage, SPT – spring ploughing tillage, SRT – spring rotary tillage, SRTPM – spring rotary tillage with polypropylene nonwoven mulch, and SRTBM – spring rotary tillage with fresh biomass mulch.

Table 2
Soil moisture (%) at a depth of 10 cm depending on different soil cultivation methods.

Treatment	Soil moisture [%]		
	2016	2017	2018
APT[a]	20.6	16.8	13.0
SPT	21.2	16.4	14.7
SRT	21.4	15.5	14.0
SRTBM	24.5	19.2	21.7
SRTPM	25.2	17.0	13.0

[a] see Table 1.

water than in the first year of the study (2016, Table 4). In all the years, the highest dry matter content was found in the fruit obtained from plants growing in the soil mulched with fresh biomass (5.79%) and PP nonwoven (5.75%), while the highest amount of water was observed in the fruit from the plots where the soil was rototilled without mulching (5.53% dry mass). There were no statistical differences between the treatments in terms of this trait.

3.3. Effect of soil cultivation on weed infestation

In 2016, the highest amount of weeds was found in the plots where the soil was turned over in the spring (spring ploughing, 235 g, Table 5). Significantly lower amounts of weeds were in the plots where ploughing in the autumn together with rototilling were performed. However, this relationship was not confirmed in the subsequent years of the study. Marked differences in weed infestation resulted from mulching with fresh biomass, which gave a reduction by at least 5 times in 2016 and 2018, and by 28.3–64.2% in 2017, compared to the other treatments. The mean value for the three years of the study indicates that in terms of weed reduction, rototilling proved to be more beneficial among the cultivation methods, but the differences were statistically significant only for the treatment with additional soil mulching. The assessment did not include the treatment with nonwoven polypropylene mulch (SRTPM) due to sporadic weeds occurring only at the places of planting.

3.4. Chemical composition and antioxidant activity of zucchini fruit

The chemical analyses showed an upward trend in the synthesis of ascorbic acid in the successive years of the study upon all the treatments (Table 6). There were no differences in the concentration of this compound between the treatments. The lowest amount of vitamin C was found for the APT treatment (20.7 mg·100 g^{-1}), and the highest for SRT (24.3 mg·100 g^{-1}). The lowest amounts of phenols in zucchini fruit were obtained in 2017 (55.3 mg·100 g^{-1}), while the highest in 2018 (76.8 mg·100 g^{-1}). From among all the treatments, the concentrations of phenolics were in the range 61.9–70.2 mg·100 g^{-1}. The zucchini fruit

Table 5
Weed infestation (g) depending on different soil cultivation methods in zucchini production.

Treatment	Weed infestation [g]			
	2016	2017	2018	Mean for treatments
APT[a]	160 b[**]	104 b	32 b	99 AB
SPT	235 c	52 ab	33 b	107 B
SRT	140 b	61 ab	15 ab	72 AB
SRTBM	15 a	37 a	3 a	18 A
Mean for years	137 B	63 A	21 A	

[a] See Table 1.
[**] Mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.

Table 3
Effect of soil cultivation method and mulching on the yield (t·ha^{-1}) of zucchini fruit, 2016–2018.

Treatment	Fruit length											
	10–14 cm				15–21 cm				>21 cm			
	2016	2017	2018	Mean for treatments	2016	2017	2018	Mean for treatments	2016	2017	2018	Mean for treatments
APT[a]	0.42 a[**]	0.58 a	1.33 ab	0.78 A	36.4 ab	41.1 a	43.3 ab	40.2 A	50.3 bc	62.9 a	84.5 b	65.9 A
SPT	0.18 a	0.75 ab	1.0 a	0.64 A	33.0 a	46.4 ab	38.4 a	39.3 A	32.8 a	90.5 b	56.2 a	59.8 A
SRT	0.31 a	0.75 ab	1.65 b	0.90 A	39.0 ab	56.0 c	52.4 b	49.1 B	54.2 c	94.9 b	102.9 c	84.0 A
SRTBM	0.28 a	1.01 ab	0.88 a	0.72 A	42.6 b	53.3 bc	41.5 a	45.8 AB	55.0 c	102.7 b	101.8 c	86.5 A
SRTPM	0.52 a	1.13 b	1.05 a	0.90 A	39.5 ab	47.0 ab	52.8 b	46.4 AB	39.6 ab	99.6 b	111.7 c	83.6 A
Mean for years	0.34 A	0.85 B	1.18 C		38.1 A	48.8 B	45.7 B		46.4 A	90.1 B	91.4 B	

[a] see Table 1.
[**] mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.

Table 4
Effect of soil cultivation method and mulching on dry mass (%) and total marketable yield (t·ha^{-1}) of zucchini fruits, 2016–2018.

Treatment	Total marketable yield (t ha^{-1})				Dry mass (%)			
	2016	2017	2018	Mean for treatments	2016	2017	2018	Mean for treatments
APT[a]	87.1 bc[**]	104.5 a	129.1 b	106.9 A	5.34 a[a]	5.70 b	5.65 a	5.57 A
SPT	65.9 a	137.6 b	95.7 a	99.7 A	5.29 a	6.02 c	5.67 a	5.66 A
SRT	93.4 bc	151.6 b	156.9 c	134.0 A	5.35 ab	5.57 a	5.67 a	5.53 A
SRTBM	97.8 c	156.9 b	144.1 bc	133.0 A	5.40 ab	6.12 d	5.85 b	5.79 A
SRTPM	79.6 ab	147.8 b	165.5 c	131.0 A	5.54 b	5.98 c	5.74 ab	5.75 A
Mean for years	84.8 A	139.7 B	138.3 B		5.38 A	5.88 C	5.72 B	

[a] See Table 1.
[**] Mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.

Table 6
Chemical composition of zucchini fruits depending on different soil cultivation methods.

Treatment	Ascorbic acid mg·100 g^{-1} FW			Mean for treatments	Total phenols mg·100 g^{-1} FW			Mean for treatments	Sugars g·100 g^{-1} FW			Mean for treatments
	2016	2017	2018		2016	2017	2018		2016	2017	2018	
APT[a]	12.3 a**	23.1 a	26.8 a	20.7 A	62.1 b	57.6 bc	65.9 a	61.9 A	2.39 b	2.14 a	2.22 c	2.25 B
SPT	12.6 a	24.5 ab	26.8 a	21.3 A	62.9 b	67.7 c	80.3 b	70.2 A	2.50 b	2.12 a	1.73 a	2.12 AB
SRT	18.1 c	26.3 b	28.5 b	24.3 A	53.4 a	43.4 a	90.2 b	62.3 A	1.95 a	1.96 a	1.92 b	1.94 A
SRTBM	17.5 bc	23.1 a	27.5 a	22.7 A	93.4 c	47.5 ab	64.9 a	68.6 A	1.94 a	2.14 a	1.85 ab	1.97 A
SRTPM	15.7 b	24.4 ab	27.1 a	22.4 A	53.9 a	60.3 c	82.8 b	65.7 A	2.07 a	2.14 a	1.76 a	1.99 A
Mean for years	15.3 A	24.3 B	27.4 C		65.1 B	55.3 A	76.8 C		2.17 B	2.10 B	1.90 A	

[a] See Table 1.
** Mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.

accumulated significantly more sugars in 2016 and 2017 than in 2018. Plough cultivation favored the synthesis of sugars, especially when performed in the autumn. The concentrations of carotenoids as well as of chlorophylls were comparable in the years of the study (Table 7). The highest values of these pigments were recorded in 2018 in the plots with fresh biomass mulching, where they peaked at 45.50 μg g^{-1} for carotenoids and 191.77 μg g^{-1} for chlorophylls. The fruit collected from these plots were characterized by a significantly higher concentration of carotenoids than those from the plants growing in the soil that had been ploughed in the autumn, or rototilled, or mulched with PP nonwoven. The concentration of chlorophylls in the fruits was independent of the dates and methods of soil preparation for zucchini production. In 2018, the zucchini fruits were characterized by the highest antioxidant activity (3.98%) together with the pronounced large differences between the treatments (1.60–5.72%). Significantly higher values were obtained for the treatment where the soil was rototilled (SRT) than for plough cultivation performed in the autumn. Intermediate values were recorded for the remaining treatments.

3.5. Microbiota abundance

The analyses show that the highest number of bacteria in the soil, depending on the soil cultivation system and the sampling date, was found in the SRTBM plots in August and September (7.11×10^8 CFU g^{-1} DW and 1.56×10^9 CFU g^{-1} DW, respectively, Table 8). High bacterial counts were also recorded for SRT and SRTPM in July (2.85×10^8 CFU g^{-1} DW and 5.11×10^8 CFU g^{-1} DW, respectively).

The number of bacteria of the genus *Azotobacter* was relatively high and remained at a level of 10^4 CFU g^{-1} DW in all the variants without undergoing statistically significant changes during the entire growing

Table 8
Effect of soil cultivation method and mulching on bacterial abundance in soil (CFU·g^{-1} DW) in 2018.

Treatments	Month			
	IV	V	VII	IX
APT[a]	2.86×10^5 a**	1.94×10^6 a	8.50×10^6 a	9.19×10^6 a
SPT	5.25×10^4 a	8.00×10^5 a	5.56×10^6 a	6.00×10^6 a
SRT	3.56×10^5 a	3.18×10^6 a	2.85×10^8 b	6.90×10^7 a
SRTBM	3.56×10^5 a	4.96×10^6 a	7.11×10^8 d	1.56×10^9 e
SRTPM	3.56×10^5 a	7.55×10^6 a	5.11×10^8 c	9.23×10^7 a
GLC	2.82×10^5 a	2.09×10^5 a	8.51×10^6 a	1.42×10^7 a

[a] See Table 1.
** Mean separation by two-way analysis, Duncan's test at p = 0.05. Means followed by the same letter are not significantly different.

season (Table 9). In the case of yeasts and mould fungi, significant differences in their occurrence were noticed where mulches were used, both synthetic and organic, at the end of the experiment in September. The average frequency of yeasts and moulds for SRTPM and SRTBM was 1.77×10^4 CFU g^{-1} DW and 1.71×10^4 CFU g^{-1} DW, respectively (Table 10).

4. Discussion

The mean air temperature in 2016–2018 significantly differed from the mean multi-year values for the Kraków-Balice station (1971–2010), which indicates its continuing upward trend in successive years (Skowera et al., 2014). Environmental conditions at the beginning of vegetation play a special role in the growth and development of plants and, in

Table 7
Concentrations of pigments and antioxidant activity of zucchini fruits depending on different soil cultivation methods.

Treatment	Carotenoids μg g^{-1} FW			Mean for treatments	Chlorophylls *a* and *b* μg g^{-1} FW			Mean for treatments	Antioxidant activity%			Mean for treatments
	2016	2017	2018		2016	2017	2018		2016	2017	2018	
APT[a]	20.6 a**	41.2 c	24.8 ab	28.9 A	90.2 a	156.7 b	99.5 a	115.5 A	2.60 c	1.27 a	1.60 a	1.82 A
SPT	30.7 ab	39.0 c	31.1 b	33.6 AB	143.0 b	142.5 b	123.6 b	136.4 A	2.60 c	1.38 a	4.17 c	2.72 AB
SRT	38.6 b	30.1 ab	24.7 ab	31.1 AB	140.5 b	98.6 a	95.5 a	111.5 A	1.23 a	6.15 b	4.96 d	4.11 B
SRTBM	33.7 b	34.9 bc	45.5 c	38.0 B	104.3 ab	116.6 a	191.8 c	137.5 A	1.64 b	2.35 a	3.46 b	2.48 AB
SRTPM	37.5 b	25.7 a	24.0 a	29.1 A	121.4 ab	98.0 a	97.6 a	105.7 A	1.61 ab	1.94 a	5.72 e	3.09 AB
Mean for years	32.2 A	34.2 A	30.0 A		119.9 A	122.5 A	121.6 A		1.94 A	2.61 A	3.98 B	

[a] See Table 1.
** Mean separation by one-way analysis, Tukey's test at p = 0.05. Means followed by the same letter within a column are not significantly different.

Table 9
Effect of soil cultivation method and mulching on *Azotobacter* abundance in soil (CFU·g^{-1} DW) in 2018.

Treatment	Month			
	IV	V	VII	IX
APT[a]	1.50×10^4 a[**]	1.71×10^4 a	1.79×10^4 a	1.63×10^4 a
SPT	1.43×10^4 a	1.63×10^4 a	1.68×10^4 a	1.75×10^4 a
SRT	1.61×10^4 a	1.61×10^4 a	1.67×10^4 a	1.44×10^4 a
SRTBM	1.61×10^4 a	1.69×10^4 a	1.87×10^4 a	1.68×10^4 a
SRTPM	1.61×10^4 a	1.66×10^4 a	1.92×10^4 a	1.68×10^4 a
GLC	1.51×10^4 a	1.72×10^4 a	1.87×10^4 a	1.48×10^4 a

[a] See Table 1.
[**] Mean separation by two-way analysis, Duncan's test at p = 0.05. Means followed by the same letter are not significantly different.

Table 10
Effect of soil cultivation method and mulching on the abundance of fungi and yeasts in soil (CFU·g^{-1} DW) in 2018.

Treatment	Month			
	IV	V	VII	IX
APT[a]	2.58×10^2 a[**]	6.86×10^2 a	1.53×10^3 bc	1.92×10^3 cd
SPT	4.35×10^2 a	1.75×10^3 cd	1.92×10^3 cd	1.48×10^3 bc
SRT	3.63×10^2 a	2.38×10^3 d	6.43×10^2 a	1.93×10^3 cd
SRTBM	3.63×10^2 a	8.77×10^2 ab	9.95×10^2 ab	1.71×10^4 e
SRTPM	3.63×10^2 a	2.87×10^2 a	5.63×10^2 cd	1.77×10^4 e
GLC	4.37×10^2 a	8.18×10^2 ab	2.36×10^3 d	1.84×10^3 cd

[a] See Table 1.
[**] Mean separation by two-way analysis, Duncan's test at p = 0.05. Means followed by the same letter are not significantly different.

consequence, have an impact on the crop yield obtained. During this time, the deficit of atmospheric precipitation in all the years was the cause of the drying effect of green fertilizers and resulted in the negative water balance of the soil. In August 2016, the air temperature was 2 °C lower than in the same month of the other years. Better conditions (in terms of the total precipitation and mean air temperature) prevailed in 2017 and 2018, which resulted in higher fruits yields, as zucchini is a thermophilic vegetable.

The obtained results indicate that the date of ploughing has no influence on soil temperature. However, there was a clear difference between the soil cultivation methods. The temperature of the soil in the plots where a rotary tiller was used to prepare the field for zucchini planting was markedly lower. Onwuka and Mang (2018) had shown that reducing evaporation and increasing soil moisture results in lower soil temperature. No statistical evidence was found regarding the effects of different cultivation practices on soil temperature and moisture. Moreover, the reason for the drop in soil temperature caused by mulching may be lower absorption of solar radiation through the mulch than through the cultivated, uncovered topsoil. Zawiska and Siwek (2014) reported that the 50 g m^{-2} PP nonwoven used in tomato growing absorbed 86.8% of light in the range 400–700 nm (PAR) and 700–1100 nm. The lower soil temperature under mulch may also be due to the loose covering of the soil by the mulch. Our measurements of soil moisture did not show a significant influence of the method or of the date of soil cultivation on this microclimate factor. However, the experiments of Shen et al. (2018) carried out on soybean and maize showed the lowest moisture content after mouldboard ploughing in comparison with no-tillage and ridge tillage.

The three-year study revealed a significant influence of the method and date of tillage on the yielding of zucchini plants, while the mulching treatment after rototilling the soil was of little importance. In this respect, rototilling in the spring proved to be the best form of soil preparation for zucchini grown in the field with a forecrop of a grass-legume mixture. Although zucchini is a plant highly tolerant to biotic factors, it responds with better yielding to higher temperatures (of air and soil) and soil moisture (Abd El-Mageed et al., 2016; Rolbiecki et al., 2017; Sadik and El-Aziz, 2018). The deficit of precipitation in Poland, apparently tending to widen increase year by year, is the reason why ploughing in the spring exacerbates the shortage of water for plants, which was confirmed by our study. In an earlier study, Wittwer et al. (2017) demonstrated that reduced tillage and the use of cover crops could be an effective alternative to conventional soil cultivation. In the zucchini yield structure, despite frequent harvesting, fruits with a length exceeding 21 cm had the largest percentage share. This was particularly evident in 2017 and 2018, where such fruits accounted for 58.80–70.63% of marketable yield. Therefore, it seems highly probable that the reason for the increase in zucchini yield in the second and third year was higher air temperature and a more uniform distribution of precipitation during the growing season. Mueller and Thorup-Kristensen (2001) showed that the reason for the low level of free nitrogen fixation by legumes may be unfavorable weather conditions, which are important factors at the initial stage of plant development. The beneficial effect of including cover crops in crop rotation in intensive, tunnel production of vegetables, especially in the long term, were confirmed by Domagała-Świątkiewicz et al. (2019). In the same year, after vetch and a vetch-rye mix, a lower marketable yield of zucchini was obtained, on average by 22.4% compared to the control, which may have been a result of an initial nitrogen deficit. Soil analysis showed an improvement in the physico-chemical properties of the soil, which contributed to an increase in the yield of aftercrop vegetables (romaine lettuce and celery). Salahin et al. (2013) obtained elevated yields of rice and maize after incorporating *Sesbania aculeata* plants as green fertilizer by deep tillage (20–25 cm) compared to minimum-tillage and tillage to a depth of 10–12 cm.

Soil mulching with a fresh clover-ryegrass crop and polypropylene nonwoven fabric helped to maintain higher soil moisture, with the organic mulch being more beneficial in this respect. An inverse relationship between the effectiveness of mulching with grass and with plastic in reducing soil water consumption in soybean production had earlier been demonstrated by Kader et al. (2017). Kołota and Adamczewska-Sowińska (2011), after performing deep ploughing in the autumn and rototilling in the spring, obtained a total zucchini yield of 64.89 t ha^{-1}, as compared to 56.41 t ha^{-1} from the field mulched with black polypropylene nonwoven. It should be noted, however, that the authors of that experiment grew zucchini at a larger spacing (100 × 80 × 130 cm). Moreover, the fruits were harvested every 5 days, from June 25 to September 20, which could have resulted in the observed yield differences in comparison with the results of the experiment presented here. The aim of harvesting the first fruits several times was to induce in zucchini plants intensive setting of subsequent fruits. Harvesting small zucchini fruits with the crown (7–14 cm long) throughout the growing season reduced the total yield, whereas infrequent harvesting and keeping of large fruits inhibited flowering and the setting of new fruits on the plants (Biesiada et al., 2007). The positive effects of mulching with synthetic and organic materials in the growing of zucchini was reported by Silva et al. (2019) and Di Mola et al. (2019).

The extent of weed infestation of the plots varied over the years of the study and depended on the method of soil preparation. It can therefore be assumed with a high probability that this result was caused by the different depths of soil cultivation and strong competition from clover and ryegrass before the growing of zucchini. Gruber and Claupein (2009) reached a similar conclusion in their experiment, stating that the inclusion in crop rotation of a grass-clover mixture with the highest proportion of alfalfa had a very marked influence on reducing the occurrence of *Cirsium arvense* L. Moreover, the substantial reduction in weed infestation by mulching with fresh biomass, apart from the mechanical barrier, could also be caused by the allelopathic effect of clover. The use of legumes as companion cover crops can reduce weed infestation and even increase the yield of arable crops, and is particularly recommended in organic and low-input systems (Verret et al., 2017). The dominant weeds included mainly fast-growing thermophilic species, i.e. *Chenopodium album* L., *Echinochloa crus-galli* L., *Galinsoga parviflora* Cav., *Galinsoga quadriradiata* Ruiz & Pav. and *Amaranthus retroflexus* L., and also *Capsella bursa-pastoris* (L.) Medik. and *Thlaspi arvense* L. (data not shown). Considering the rapid spreading and adaptation of weeds to specific environmental conditions, it is important from an agronomic point of view to develop comprehensive solutions to reduce weed infestation. The factors that are of great importance in this regard include: selection of the appropriate species, date of sowing and incorporation of plant mass into the soil, and mulching (Sung et al., 2010; Ciaccia et al., 2015; Alonso-Ayuso et al., 2018; Testani et al., 2019). Comparing various organic mulches in the growing of broccoli and tomato, Kosterna (2014) evidenced that mulching with rye and buckwheat straw had the greatest usefulness in reducing weed infestation.

In our experiment, the date, the method of soil preparation, and the type of mulching material had an inconsistent effect on most of the analyzed components of the zucchini fruits. The average amounts of dry matter, vitamin C, and sugars as documented for the period of the study and for all the treatments were 5.66%, 22.3 mg·100 g^{-1} FW, and 2.05%, respectively. These values mostly coincide with the results obtained by Bucki et al. (2018), which in the fruits from the plots ploughed in the spring and mulched with polypropylene nonwoven averaged at: 5.6%; 21 mg·100 g^{-1} FW, and 3.67%, respectively. Fruits of similar size (15–21 cm long) containing 5.3% dry matter, 18.27 mg·100 g^{-1} FW vitamin C, and 1.57% total sugars in fresh mass were harvested by Biesiada et al. (2007). In another experiment, 16–22 cm long fruits had been recorded as containing 19.6 and 19.9 mg·100 g^{-1} FW vitamin C, harvested, respectively, from the plots where ploughing had been performed in the autumn and from those additionally mulched with black polyethylene foil (Kołota and Adamczewska-Sowińska, 2011).Domagała-Świątkiewicz et al. (2019), after cultivating inter-crops, had recorded in zucchini fruits an average of 4.44% dry matter, 8.6 mg·100 g^{-1} FW vitamin C and 2.21% sugars, with the lower amounts of the first two components possibly caused by faster fruits growth in tunnel conditions. The most pronounced antioxidant properties and the highest amounts of phenolic compounds and ascorbic acid obtained in our study were in 2018. This may have been the result of higher rainfall in June, when the fruits were collected for analysis.

The presented results concerning soil microbiota confirm the beneficial influence of reduced tillage on the abundance of bacteria. Similar results were obtained by Martyniuk et al. (2007); Schmidt et al. (2018), and Melero et al. (2009), the latter emphasizing that the positive effect was particularly evident after a longer period of time. The research by Sun et al. (2018) showed that the method of soil cultivation had a little effect on the number of bacteria, but their spatial differentiation was clearly evident. Tomkowiak et al. (2017) report many advantages of using reduced (ploughless) soil cultivation, which stimulated an increase in the number of soil microorganisms and their metabolic activity. High bacteria frequencies in the plots subjected to rototilling resulted from the improvement in soil aeration and the improvement in air-water relations. The highest microbial abundance in the case of mulch application was associated with improved humidity (Chen et al., 2014), as well as the presence of plant residue in the surface layer of the soil, thanks to which microorganisms had easier access to nutrients. Similar results for mulching (with straw) were obtained by Fu et al. (2019); however, when synthetic mulch was used, the authors obtained lower bacterial biodiversity. While analyzing the variability in the number of *Azotobacter* bacteria on individual sampling dates for the different soil cultivation methods, no significant differences were recorded. The observed high abundance of these bacteria, maintained throughout the growing season, provides evidence of good soil quality (Martyniuk and Martyniuk, 2003). The cited authors note that too low a pH and low soil fertility are factors that inhibit the development of Azotobacter population. The presence of *Azotobacter* in the soil is desirable due to ability of these bacteria to fix atmospheric nitrogen and make it readily available to higher plants (Dev Jiawali et al., 2015).

It should be noted that many free-living soil bacteria that live in the root zone of plants are plant growth-promoting rhizobacteria (PGPR). Kalitkiewicz and Kępczyńska (2008) provide many examples of PGPR that are common in soils, while emphasizing their role in the environment. The beneficial influence of PGPR consists mainly in the supply of minerals to the plant and the production of secondary metabolites such as vitamins, phytohormones and antibiotics (Vejan et al., 2016). As a result, there is an improvement in the phytosanitary properties of the soil and better plant growth, which is particularly important in the case of organic farming, where the use of plant protection products and chemical fertilizers is limited.

Our results concerning fungi (yeasts and moulds) indicate that the method of soil cultivation had no significant influence on their abundance. Still, the use of organic (SRTBM) and synthetic (SRTPM) mulches led to an increase in the population density of this microorganism group, which was confirmed by the results of studies by Schmidt et al. (2019) and Fu et al. (2019). Note that according to Gajda et al. (2010), an increase in the number of mould fungi should be regarded as an unfavorable phenomenon due to their phytopathogenic and toxicogenic properties, which bear the risk of damaging the health of crop plantations (Reeleder, 2003). Importantly however, the higher frequency of fungi was noted for both SRTBM and SRTPM treatments only in September 2018, that is at the end of the observation period, after zucchini harvest.

Based on the collected data it is difficult to establish any correlation between the soil moisture and occurrence of soil fungi. As indicated earlier, soil moisture was measured once a year, three days after rainfalls. In 2018, when extensive microbiological monitoring of the soil environment was carried out, the elevated moisture was observed for the sole case of the SRTBM variant (see Table 1), although no statistical significance analysis was made. Therefore, it can only be suggested for the mulching with fresh biomass that the growth of fungal population became stimulated by elevated soil moisture as well as by the accumulation of organic matter in the form of plant debris.

5. Conclusions

Upon three-year experiment aiming to compare different methods of mechanical soil tillage as well as different mulch types in zucchini cultivation after multi-annual application of a grass-legume mixture it was shown that the course of meteorological conditions had a significant impact on plant yield. The higher air temperature and more favorable rainfall distribution within the years 2017–2018 facilitated the plant development and setting larger numbers of fruit. This led to faster zucchini growth and production of leaves with larger areas, which resulted in elevated competitiveness against weeds for water and nutrients at initial vegetation period. The extent of weed infestation in 2016 was found to be two- and six-fold greater than in 2017 and 2018, respectively. The lowest number of weeds was observed for treatment with the fresh biomass mulch (SRTBM). Regardless of the material used for mulching and the dates of tillage, zucchini grown on rototilled soil produced yield on average 29.3 t ha^{-1} (22.1%) higher compared to plough cultivation. The research results revealed the beneficial effect of soil mulching with organic and synthetic materials on water retention; however, on the other hand, these materials led to soil temperature decrease at a depth of 10 cm.

Based on microbiological analyses it can be inferred that rototilling, together with the application of fresh biomass mulch, increased bacterial frequency in the soil. High activity of soil microorganisms indicates good quality of soil and its proper functioning, which has a direct influence on the efficient yield of the cultivated plant. The results of fruit quality analyses have not made it possible to unambiguously pinpoint the best method of soil tillage for zucchini, which would enable production of fruit with high nutritional value. The fruit of the SPT treatment were characterized by intermediate values of the analyzed quality components. In general, it can be concluded that, in terms of the yield, reduction of weed infestation and water retention, the spring rototilling together with soil mulching has proven to be the best method for soil preparation and maintenance for zucchini organic cultivation with the application of a grass-legume mixture.

CRediT authorship contribution statement

Piotr Bucki: Conceptualization, Formal analysis, Investigation, Writing - original draft, Visualization, Project administration. **Kinga Regdos:** Investigation, Formal analysis, Writing - original draft. **Piotr Siwek:** Conceptualization, Methodology, Resources, Supervision, Writing - review & editing. **Iwona Domagała-Świątkiewicz:** Conceptualization, Formal analysis, Resources, Writing - review & editing. **Paweł Kaszycki:** Methodology, Resources, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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