INSTYTUT UPRAWY NAWOŻENIA I GLEBOZNAWSTWA

PAŃSTWOWY INSTYTUT BADAWCZY

Rozprawa doktorska

mgr Małgorzata Katarzyna Nakielska

Wpływ biopreparatów na zdrowotność, wybrane cechy morfologiczne i plonowanie truskawki (*Fragaria x ananassa* Duchesne) uprawianej w systemie ekologicznym

Rozprawa doktorska wykonana

w Zakładzie Agroekologii i Ekonomiki

Instytutu Uprawy Nawożenia i Gleboznawstwa – Państwowego Instytutu Badawczego

w Puławach

Promotor: prof. dr hab. Beata Feledyn-Szewczyk

Promotor pomocniczy: dr inż. Adam Kleofas Berbeć

Puławy 2025

Serdecznie dziękuję promotorom:
prof. dr hab. Beacie Feledyn-Szewczyk i dr inż. Adamowi Berbeciowi
za pomoc, opiekę merytoryczną, cenne wskazówki, a także cierpliwość i poświęcony czas.

Dziękuję aktualnym i byłym pracownikom Zakładu Agroekologii i Ekonomiki
za pomoc w realizacji badań.

Dziękuję również rodzinie i bliskim za wyrozumiałość i wsparcie.

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2. Nakielska M., Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112

3. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in an Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571

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1. Wykaz publikacji wchodzących w skład rozprawy doktorskiej

Lp.	Bibliografia	Udział % pierwszego autora	Impact Factor (IF)	Punktacja MNiSW
1	**Nakielska M.**, Feledyn-Szewczyk B., Berbeć A.K., Frąc M. 2024. Microbial biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation. Sustainability 16, 7559, 1-23. https:// doi.org/ 10.3390/su16177559	70%	3,3	100 pkt
2	**Nakielska M.**, Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112	55%	3,1	20 pkt
3	**Nakielska M.**, Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in an Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571	80%	3,3	100 pkt
Razem			**IF 9,7**	**220 pkt**

Sumaryczny IF – 9,7

Sumaryczna punktacja MNiSW – 220 pkt

Niniejsza rozprawa doktorska została przygotowana w formie spójnego tematycznie zbioru artykułów opublikowanych w czasopismach naukowych, zgodnie z ustawą Prawo o szkolnictwie wyższym i nauce (Dz. U. z 2024 r. poz. 1571) oraz Regulaminem czynności w sprawie nadania stopnia naukowego doktora (uchwała Rady Naukowej IUNG-PIB z dnia 13 czerwca 2020 r. z późn. zm., tekst jednolity z dnia 30 czerwca 2023 r.) oraz Regulaminem przygotowywania rozpraw doktorskich w formie zbioru artykułów naukowych (Uchwała Rady Naukowej IUNG-PIB z dnia 27 listopada 2019 r. z późn. zm., tekst jednolity z dnia 27 listopada 2023 r.).

W skład rozprawy doktorskiej wchodzą trzy artykuły naukowe, w których jestem pierwszym autorem z wkładem od 55% do 80%. Sumaryczny Impact Factor publikacji stanowiących zbiór artykułów wynosi 9,7 (na dzień 12.06.2025 r.), a liczba punktów według aktualnego wykazu Ministerstwa Nauki i Szkolnictwa Wyższego – 220 pkt.

Artykuły wchodzące w skład rozprawy doktorskiej zostały załączone na końcu niniejszej rozprawy jako rozdział 13.

2. Oświadczenia doktoranta i współautorów dotyczące wkładu w przygotowanie publikacji

Załącznik 1

Oświadczenie doktoranta jako współautora publikacji

mgr Małgorzata Katarzyna Nakielska
Zakład Agroekologii i Ekonomiki
Instytut Uprawy Nawożenia i Gleboznawstwa – Państwowy Instytut Badawczy

Oświadczam, że jestem współautorem publikacji:

1. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Frąc M. 2024. Microbial Biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation. Sustainability 16, 7559, 1-23. https://doi.org/10.3390/su16177559

   Mój udział w przygotowaniu tej publikacji wynosił 70 % i polegał na: prowadzeniu badań polowych, opracowaniu danych, przeprowadzeniu analiz i wykonaniu wizualizacji, udziale w napisaniu oryginalnego szkicu.

2. Nakielska M., Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112

   Mój udział w przygotowaniu tej publikacji wynosił 55 % i polegał na: udziale w analizie i opracowaniu danych, udziale w wykonaniu wizualizacji wyników, udziale w napisaniu oryginalnego szkicu, przeglądzie i redakcji publikacji.

3. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571

   Mój udział w przygotowaniu tej publikacji wynosił 80 % i polegał na: pozyskaniu i dostarczeniu materiałów do badań oraz próbek laboratoryjnych, opracowaniu danych, wykonaniu wizualizacji, napisaniu oryginalnego szkicu publikacji oraz przeglądzie i redakcji publikacji.

**należy opisowo przedstawić swój udział w danej publikacji*

data 24.06.2025r. Małgorzata Nakielska

(*podpis doktoranta*)

Załącznik 2

Oświadczenie współautora publikacji doktoranta

prof. dr hab. Beata Feledyn - Szewczyk
Zakład Agroekologii i Ekonomiki
Instytut Uprawy Nawożenia i Gleboznawstwa – Państwowy Instytut Badawczy

W związku z ubieganiem się mgr Małgorzaty Nakielskiej o stopień doktora nauk rolniczych oświadczam, że jestem współautorem publikacji:

1. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Frąc M. 2024. Microbial Biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation. Sustainability 16, 7559, 1-23. https://doi.org/10.3390/su16177559

   Mój udział w przygotowaniu tej publikacji wynosił 10 % i polegał na opracowaniu koncepcji i metodyki, udziale w pisaniu oryginalnego szkicu publikacji oraz przeglądzie i redagowaniu, nadzorze i udziale w prowadzeniu badań polowych.

2. Nakielska M., Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112

   Mój udział w przygotowaniu tej publikacji wynosił 5 % i polegał na współudziale w opracowaniu koncepcji i metodyki, zarządzaniu projektem, udziale w przygotowaniu oryginalnego draftu publikacji.

3. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571

   Mój udział w przygotowaniu tej publikacji wynosił 5 % i polegał na współudziale w opracowaniu koncepcji, współudziale w opracowaniu danych i przeprowadzeniu analiz, zarządzaniu projektem oraz przeglądzie i redagowaniu manuskryptu.

**należy opisowo przedstawić udział osoby składającej oświadczenie w danej publikacji*

data 24.06.2025

Feledyn-Szewczyk
(podpis osoby składającej oświadczenie)

Załącznik 2

Oświadczenie współautora publikacji doktoranta

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Zakład Agroekologii i Ekonomiki
Instytut Uprawy Nawożenia i Gleboznawstwa – Państwowy Instytut Badawczy

W związku z ubieganiem się mgr Małgorzaty Nakielskiej o stopień doktora nauk rolniczych oświadczam, że jestem współautorem publikacji:

1. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Frąc M. 2024. Microbial Biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation. Sustainability 16, 7559, 1-23. https://doi.org/10.3390/su16177559

   Mój udział w przygotowaniu tej publikacji wynosił 15 % i polegał na współudziale w opracowaniu koncepcji, metodyki, dostarczeniu materiałów do badań, prowadzeniu badań oraz przeglądzie i redagowaniu manuskryptu.

2. Nakielska M., Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112

   Mój udział w przygotowaniu tej publikacji wynosił 20 % i polegał na współudziale w opracowaniu koncepcji, metodyki i prowadzeniu badań, dostarczeniu materiałów do badań, nadzór, a także współudział w pisaniu oryginalnego szkicu a także jego przeglądzie i redagowaniu.

3. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry *(Fragaria x ananassa* Duch.) Fruit Grown in Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571

   Mój udział w przygotowaniu tej publikacji wynosił 6 % i polegał na współudziale w opracowaniu metodyki, przeglądzie i redagowaniu manuskryptu, dostarczeniu materiałów do badań, nadzór.

**należy opisowo przedstawić udział osoby składającej oświadczenie w danej publikacji*

Data 24.06.2025

……………………………………………………………………
(podpis osoby składającej oświadczenie)

Załącznik 2

Oświadczenie współautora publikacji doktoranta

prof. dr hab. Magdalena Frąc
Instytut Agrofizyki im. Bohdana Dobrzańskiego Polskiej Akademii Nauk

W związku z ubieganiem się mgr Małgorzaty Nakielskiej o stopień doktora nauk rolniczych oświadczam, że jestem współautorem publikacji:

1. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Frąc M. 2024. Microbial Biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation. Sustainability 16, 7559, 1-23. https://doi.org/10.3390/su16177559

   Mój udział w przygotowaniu tej publikacji wynosił 5 % i polegał na udziale w opracowaniu koncepcji, udziale w przeglądzie i redakcji publikacji, nadzorze i zarządzaniu projektem, pozyskaniu finansowania.

2. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571

   Mój udział w przygotowaniu tej publikacji wynosił 5 % i polegał na udziale w opracowaniu koncepcji, pozyskaniu finansowania, udziale w opracowaniu metodyki, zarządzaniu projektem, udziale w przeglądzie i redakcji publikacji.

**należy opisowo przedstawić udział osoby składającej oświadczenie w danej publikacji*

data 24.06.2025

Magdalena Frąc
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Załącznik 2

Oświadczenie współautora publikacji doktoranta

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W związku z ubieganiem się mgr Małgorzaty Nakielskiej o stopień doktora nauk rolniczych oświadczam, że jestem współautorem publikacji:

Nakielska M., Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112

Mój udział w przygotowaniu tej publikacji wynosił 20 % i polegał na opracowaniu danych, prowadzeniu analiz, udziale w napisaniu oryginalnego tekstu publikacji, redakcji publikacji .

**należy opisowo przedstawić udział osoby składającej oświadczenie w danej publikacji*

data 24.06.2025r.

Andrzej Madej
(podpis osoby składającej oświadczenie)

Załącznik 2

Oświadczenie współautora publikacji doktoranta

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W związku z ubieganiem się mgr Małgorzaty Nakielskiej o stopień doktora nauk rolniczych oświadczam, że jestem współautorem publikacji:

Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571

Mój udział w przygotowaniu tej publikacji wynosił 4 % i polegał na opracowaniu metodyki, prowadzeniu badań laboratoryjnych, przeprowadzeniu walidacji, udziale w przygotowaniu tekstu publikacji, przeglądzie i redakcji publikacji.

**należy opisowo przedstawić udział osoby składającej oświadczenie w danej publikacji*

data 15.06.2025

Ukalska - Jaruga Aleksandra
(podpis osoby składającej oświadczenie)

3. Wstęp i przegląd literatury

3.1. Charakterystyka gatunku *Fragaria × ananassa* Duch. ze szczególnym uwzględnieniem odmian użytych w badaniu

Historia gatunku truskawki sięga XVIII wieku, kiedy w Europie przypadkowo skrzyżowano poziomkę chilijską (*Fragaria chiloensis* Ehrh.) z poziomką wirginijską (*Fragaria virginiana* Duch.). Mieszańce powstałe z tego połączenia dały początek gatunkowi truskawki (*Fragaria* × *ananassa* Duch). W literaturze spotykana jest również nazwa *Fragaria grandiflora* Duch. czyli poziomka wielokwiatowa [Masny i Żurawicz 2013]. Truskawka należy do gatunków o istotnym znaczeniu gospodarczym. W 2020 roku globalna produkcja tych owoców wynosiła 8,8 miliona ton [Wójcik i in. 2021]. Polska jest jednym z czołowych producentów truskawek - zajmuje drugie miejsce w Europie i dziesiąte na świecie [Kaczmarska i in. 2008; Rochalska i in. 2011; Wójcik i in. 2021]. W 2021 roku powierzchnia uprawy truskawki na świecie wynosiła 389,7 tys. hektarów, z czego 33,9 tys. hektarów przypadało na Polskę [FAOSTAT - źródła internetowe pozycja 1]. W 2020 roku Polska była liderem w Unii Europejskiej w produkcji truskawki w systemie ekologicznym - zarówno pod względem areału (1048 ha), jak i wielkości zbiorów (8013 ton) [EUROSTAT - źródła internetowe pozycja 2].

Owoce truskawki cieszą się dużym uznaniem konsumentów nie tylko ze względu na smak, lecz także na liczne właściwości prozdrowotne wynikające z obecności związków bioaktywnych, takich jak witamina A i C, związki fenolowe, aminokwasy, żelazo, wapń, potas, fosfor, a także karotenoidy, pektyny, błonnik oraz glutation [Kumra i in. 2018; Sharma i Negi 2019; Khunte i in. 2020; Katel i in. 2022; Kilic 2023]. Pukszta i Platta (2017) podkreślają, że polifenole obecne w truskawkach, zwłaszcza antocyjany, oraz witamina C wykazują liczne korzystne właściwości, takie jak: działanie przeciwzapalne, przeciwbakteryjne, przeciwwirusowe i przeciwnowotworowe. Ponadto mogą łagodzić reakcje alergiczne, obniżać poziom cholesterolu we krwi oraz działać przeciwmiażdżycowo i przeciwzakrzepowo [Pukszta i Platta 2017]. Owoce truskawki znajdują szerokie zastosowanie w przemyśle spożywczym do produkcji przetworów, takich jak dżemy, soki i napoje. W procesie tym powstają wytłoki będące odpadem, zawierające nasiona bogate w kwas α-linolenowy oraz elagotianiny. Wytłoki z owoców truskawek są także źródłem licznych związków bioaktywnych, m. in. kwasów tłuszczowych, cukrów, białek, tokoferoli, fenoli i fitosteroli, co sprawia, że znajdują one zastosowanie w przemyśle spożywczym, kosmetycznym i farmaceutycznym [Wójciak i in. 2024]. Zawarte w owocach związki bioaktywne aktywują komórkową ochronę antyoksydacyjną, hamują ekspresję genów zapalnych, neutralizują wolne rodniki, a przez to chronią komórki przed uszkodzeniami spowodowanymi stanami zapalnymi i stresem oksydacyjnym. Z tego względu uznaje się je za cenny składnik diety prewencyjnej w kontekście chorób przewlekłych, takich jak: nowotwory, choroby sercowo-naczyniowe, depresja i choroba Alzheimera [Miller i in. 2019].

W badaniach uwzględniono trzy odmiany truskawki zaliczane do odmian wczesnych (pierwsze owoce dojrzewają na przełomie maja i czerwca), o zróżnicowanych cechach morfologicznych i odporności na patogeny grzybowe. Odmiany te są polecane do upraw ekologicznych.

Odmiana ‘Honeoye’ została wyhodowana w USA przez Cornell University w wyniku skrzyżowania odmiany ‘Vibrant’ z odmianą ‘Holiday’. Rośliny tej odmiany charakteryzują się niezbyt zwartym, raczej wzniesionym pokrojem oraz silnym wzrostem i dużą odpornością na przemarzanie. Owoce odmiany ‘Honeoye’ są przeważnie dużej i średniej wielkości z niewielką tendencją do drobnienia, a ich kształt jest stożkowaty z intensywnie czerwoną skórką o silnym połysku. Miąższ owoców jest jasnoczerwony, jędrny soczysty i aromatyczny. Odmiana ‘Honeoye’ wykazuje odporność na białą plamistość liści oraz czerwoną plamistość liści, a także małą podatność na mączniaka prawdziwego i szarą pleśń. Jest natomiast średnio podatna na zgniliznę korony truskawki i bardzo podatna na werticiliozę [Kupczak 2013].

‘Rumba’ to holenderska odmiana truskawki pochodząca z programu hodowlanego Fresh Forward BV (status CPVR). Jej rodowód jest zastrzeżony. Rośliny tej odmiany mają średnio zwartą budowę i charakteryzują się bujnym wzrostem, dlatego zaleca się sadzenie ich w odstępach co 35 cm. Odmiana ta wykazuje wysoką odporność na niskie temperatury. Owoce są duże (21-23 g), smaczne i aromatyczne. Skórka jest jednolicie jasnoczerwona z wyraźnym połyskiem, a miąższ jędrny i słodki. Odmiana ‘Rumba’ wyróżnia się dobrą odpornością na szereg chorób istotnych w uprawie truskawki: białą i czerwoną plamistość liści, mączniaka prawdziwego oraz zgniliznę korony truskawki, a także wykazuje małą podatność na werticiliozę i szarą pleśń [Kupczak 2013; Łabanowska-Bury 2024]. Owoce dobrze znoszą przechowywanie. Rośliny tej odmiany dobrze sprawdzają się zarówno w uprawie gruntowej, jak i w tunelach. Daje bardzo wysokie plony, przekraczające nawet 900 g/roślinę [Łabanowska-Bury 2024].

Odmiana ‘Vibrant’ została wyhodowana w Stacji Hodowlanej East Malling Research/ Meiosis Ltd. w Anglii. Rośliny tej odmiany charakteryzują się wzniesionym pokrojem oraz średnio silnym wzrostem, a także wykazują odporność na mróz [Kupczak 2013; Łabanowska-Bury 2024]. Na podstawie obserwacji własnych stwierdzono jednak, że taki pokrój roślin oraz kwiatostany wzniesione ponad liście zwiększają podatność na uszkodzenia spowodowane przymrozkami oraz uszkodzenia mechaniczne wynikające ze stosowania agrotkaniny do zabezpieczenia roślin przed przymrozkami. Zjawiska te są szczególnie istotne w pierwszej połowie maja, kiedy truskawka znajduje się w fazie kwitnienia [Nakielska i in. 2024a]. Owoce odmiany ‘Vibrant’ są duże lub bardzo duże, mają kształt sercowaty bądź stożkowaty. Skórka jest jednolicie jasnoczerwona z silnym połyskiem, a miąższ słodkawy, soczysty i jędrny. Odmiana ‘Vibrant’ rozpoczyna owocowanie nieco wcześniej niż ‘Honeoye’ i charakteryzuje się wyższym plonowaniem. W ocenie trwałości pozbiorczej wypada również korzystniej od odmiany ‘Honeoye’. Dobrze wyeksponowane owoce na roślinie sprawiają, że zbiór jest szybszy i łatwiejszy. ‘Vibrant’ wykazuje wysoką odporność na większość najważniejszych chorób truskawki, takich jak: biała plamistość liści, czerwona plamistość liści, mączniak prawdziwy, zgnilizna korony truskawki oraz szara pleśń owoców truskawki. Jest natomiast średnio podatny na werticiliozę [Kupczak 2013; Łabanowska-Bury 2024].

3.2. Najczęściej występujące choroby grzybowe owoców truskawek

3.2.1. Antraknoza truskawki *(Colletotrichum acutatum)*

Grzyby z rodzaju *Colletotrichum spp.* z uwagi na częstotliwość występowania zajmują ósmą pozycję w zestawieniu najważniejszych grzybów patogenicznych roślin [Dean i in. 2012]. Antraknoza powodowana jest przez grzyb z gatunku *Colletotrichum acutatum*. Rozwojowi choroby sprzyja wysoka wilgotność powietrza i temperatura przekraczająca 20°C. Do charakterystycznych objawów należą gnilne plamy na dojrzałych owocach. Na wszystkich etapach występowania choroby pojawiają się jasnobrązowe wodniste plamy, które z czasem stają się ciemnobrązowe o nieregularnym okrągłym kształcie. Przy podwyższonej wilgotności powietrza na powierzchni plam pojawiają się kremowo-łososiowe skupiska zarodników. Kwiaty oraz pąki kwiatowe są szczególnie podatne na porażenie przez *Colletotrichum acutatum* - ciemnieją, zasychają a następnie zamierają. Objawy chorobowe mogą występować także na ogonkach liściowych, rozłogach i szypułkach w postaci wydłużonych ciemnobrązowych, delikatnie zagłębionych w zainfekowanej tkance plam gnilnych. Na przekroju korony zainfekowanej rośliny widoczne są czerwonobrązowe smugi oraz ogniska nekrotyczne [Łabanowska-Bury 2024].

3.2.2. Skórzasta zgnilizna owoców truskawki *(Phytophthora cactorum)*

Skórzasta zgnilizna owoców truskawki to choroba wywoływana przez grzyb *Phytophthora cactorum*. Jej rozwojowi sprzyjają ciepłe i wilgotne warunki pogodowe, a także gleby zwięzłe i słabo przepuszczalne. Choroba ma charakter lokalny, a częstotliwość jej występowania zależy głównie od warunków atmosferycznych, kondycji roślin oraz potencjału inokulacyjnego patogenu. Do charakterystycznych objawów tej choroby należy pojawienie się początkowo jasnobrązowych, a następnie brązowych, suchych, plam gnilnych, które w niektórych przypadkach mogą się rozprzestrzenić na powierzchnię całego owocu. Na owocach dojrzałych infekcja objawia się w postaci szarożółtych, rzadziej fioletowych plam. W przekroju zainfekowanych owoców w jasnobrązowym miąższu widoczne są ciemniejsze wiązki naczyniowe. Porażone owoce mają charakterystyczny, nieprzyjemny zapach i gorzki smak i nie nadają się do spożycia. *Phytophthora cactorum* może porażać zarówno kwiaty, jak i owoce w każdym stadium rozwoju [Łabanowska-Bury 2024].

3.2.3. Szara pleśń truskawki (*Botrytis cinerea*)

Choroba wywoływana przez *Botrytis cinerea* występuje u ponad 200 gatunków roślin [Stachowiak i Ratajkiewicz 2021], a zdaniem innych autorów nawet u ponad 500 różnych gatunków roślin [Hua i in. 2018]. Z uwagi na skalę strat ekonomicznych powodowanych przez *B. cinerea* grzyb ten jest często przedmiotem badań. *B. cinerea* jest uważany za drugi najważniejszy po *Magnaporthe oryzae* grzyb patogeniczny roślin w skali świata [Dean i in.

2012, Hua i in. 2018]. W Polsce powoduje znaczne straty w uprawach warzyw, roślin przemysłowych, ozdobnych, a także na plantacjach krzewów owocowych. Szczególnie podatne na infekcję są m.in. truskawka, porzeczka, fasola, sałata i pomidory [Hua i in., 2018; Stachowiak i Ratajkiewicz 2021].

Szara pleśń powoduje stosunkowo duże straty na plantacjach truskawki [Felczak-Konarska 2021], które w warunkach braku ochrony chemicznej mogą dochodzić do 50-70%, a w sprzyjających warunkach nawet do 80% plonu [Łabanowska-Bury 2024]. Warunki klimatyczne w trakcie sezonu wegetacyjnego w istotnym stopniu wpływają na nasilenie i przebieg choroby. Patogen rozwija się szczególnie intensywnie przy wysokiej wilgotności powietrza i gleby, ograniczonej cyrkulacji powietrza na plantacji, zbyt gęsto rosnących roślinach, a także przy niedostatecznym dostępie światła, zwłaszcza w uprawach pod osłonami [Felczak-Konarska 2021]. Objawy chorobowe mogą występować we wszystkich fazach rozwojowych rośliny na liściach, pędach, szyjce korzeniowej, pąkach, kwiatach oraz owocach. Można do nich zaliczyć: charakterystyczny szaro-biały nalot, brunatne plamy gnilne, nekrozy i lokalne zgorzele. Zmiany chorobowe mogą wystąpić w różnej fazie rozwojowej i są widoczne głównie na kwiatach i owocach. Grzyb przerastający z zainfekowanych kwiatów do szypułki owocu może prowadzić do zamierania całych kwiatostanów. Niedojrzałe zielone owoce często zasychają, a na dojrzałych tworzy się puszysta grzybnia i szary pylący nalot [Łabanowska-Bury 2024]. Zarodniki powstają na obumarłych resztkach roślinnych oraz porażonych organach i z łatwością rozprzestrzeniają się z kroplami wody (deszcz lub deszczowanie plantacji), a także przez prądy powietrza. Sprzyjające warunki mogą doprowadzić do dynamicznego rozprzestrzeniania się tej choroby [Felczak-Konarska 2021].

3.3. Rolnictwo ekologiczne w Polsce

Dynamiczny rozwój intensywnego rolnictwa konwencjonalnego w Europie pod koniec XX wieku przyniósł szereg negatywnych skutków, które dotknęły większość krajów. Do najważniejszych należą: zmniejszenie różnorodności biologicznej, wyczerpywanie się zasobów naturalnych, nasilająca się erozja i spadek naturalnej żyzności gleb, wzrost zagrożeń ze strony nowych chorób i szkodników, a także niedobory wody [Kapela i Majchrowska-Safaryan 2024].

Równolegle w ostatnich trzech dekadach rośnie znaczenie rolnictwa ekologicznego – systemu prawnie uregulowanego w Unii Europejskiej [Regulation 2018]. Zjawisko to jest ściśle związane z rosnącym zainteresowaniem zdrową żywnością wysokiej jakości [Golik i Żmija 2017], postrzeganą jako zdrowszą i będącą źródłem składników bioaktywnych, które odgrywają kluczową rolę w zapobieganiu chorobom cywilizacyjnym [Piotrowska i in. 2013]. Rozwój rynku żywności ekologicznej zależy w dużej mierze od poziomu świadomości ekologicznej społeczeństwa oraz preferencji konsumentów, w tym gotowości do ponoszenia wyższych cen zakupu produktów pochodzących z upraw ekologicznych [Brzozowski i Zmarlicki 2015]. Jednym z najważniejszych wyzwań stojących przed rolnictwem ekologicznym jest zapewnienie wysokiej jakości plonów przy jednoczesnym wykluczeniu stosowania chemicznych środków ochrony roślin [Zmarlicki i Brzozowski 2013]. Dalszy rozwój tego sektora zależy od jego dochodowości oraz konkurencyjności w stosunku do innych systemów rolniczych. Polska ze względu na korzystne warunki glebowe oraz klimatyczne posiada relatywnie wysoki potencjał w sektorze rolnictwa [Paszko 2009]. Należy też do czołowych producentów owoców jagodowych, zajmując wysoką, drugą pozycję w Europie i dziesiątą w skali świata [Paszko i in. 2014; Pawlak i in. 2022].

Rosnące zainteresowanie konsumentów jakością żywności oraz wzrastająca świadomość ekologiczna społeczeństwa stanowią główne czynniki sprzyjające rozwojowi rolnictwa ekologicznego [Staniek i Krejpcio 2013; Zydlik i Zydlik 2016]. W tym systemie produkcji stosuje się zróżnicowane płodozmiany, rezygnując jednocześnie z chemicznych środków ochrony roślin pochodzących z przemysłowej syntezy oraz syntetycznych nawozów mineralnych [Feledyn-Szewczyk i in. 2020]. Rekomenduje się stosowanie naturalnych środków produkcji, które korzystnie wpływają na żyzność gleby oraz umożliwiają uzyskanie plonów o wysokiej jakości biologicznej [Staniak 2014].

Z uwagi na wykluczenie stosowania chemicznych środków ochrony roślin w uprawach ekologicznych [Regulation 2018] konieczne jest poszukiwanie alternatywnych metod ochrony, w tym preparatów biologicznych, które nie tylko zabezpieczą rośliny przed patogenami i szkodnikami, ale również wzmocnią ich odporność na niekorzystne czynniki środowiskowe, które mogą utrudniać prawidłowy wzrost w czasie sezonu wegetacyjnego. Również strategie Wspólnej Polityki Rolnej UE zmierzają do ograniczenia zużycia chemicznych środków produkcji, w związku z czym wzrasta znaczenie agrotechnicznych, mechanicznych oraz biologicznych metod ochrony roślin [Kapela i Majchrowska-Safaryan 2024]. Podejmowana w tej rozprawie tematyka badawcza stanowi zatem odpowiedź na aktualne potrzeby rolnictwa ekologicznego i zrównoważonego.

3.4. Rynek biopreparatów w Polsce

Stosowanie pestycydów niesie ze sobą ryzyko dla środowiska naturalnego, ale także ludzi i zwierząt z uwagi na wysoką toksyczność wielu substancji aktywnych oraz powolne tempo degradacji [Mołoń i Durak 2018]. Potrzeba ochrony środowiska naturalnego oraz zwiększenie popytu na preparaty biologiczne we współczesnym rolnictwie sprawiają, że opracowywane są nowe, a zarazem bezpieczne środki ochrony roślin [Piekutowska 2017]. Jak zauważa Florczak (2024), wzrost zainteresowania biologicznymi metodami zwalczania agrofagów wynika zarówno z coraz większej świadomości społecznej dotyczącej negatywnych skutków nadmiernego stosowania chemicznych środków ochrony roślin, jak i z obowiązujących przepisów prawnych w zakresie ich zrównoważonego stosowania. Dodatkowym powodem poszukiwania nowych metod i narzędzi do zwalczania agrofagów roślin uprawnych jest narastająca odporność patogenów i szkodników na obecnie stosowane substancje aktywne [Barbaś i in. 2023].

Gałąź gospodarki zajmująca się opracowywaniem i wytwarzaniem preparatów mikrobiologicznych jest obecnie jednym z najprężniej rozwijających się segmentów rynku rolno - spożywczego [Gałązka 2024]. Aktualnie w Polsce do stosowania w rolnictwie ekologicznym dopuszczonych jest 92 środki ochrony roślin, z czego niemal 73% zarejestrowano w ciągu ostatnich dwóch lat (2023-2024) [źródła internetowe pozycja 3]. Inne grupy biopreparatów stosowanych w produkcji ekologicznej obejmują nawozy, środki poprawiające właściwości gleby, produkty naturalne oraz mikrobiologiczne preparaty nawozowe, które wspierają wzrost, rozwój, kondycję i zdrowotność roślin, zwiększając ich odporność na stresy abiotyczne i biotyczne [źródła internetowe pozycja 4].

Środki ochrony roślin pochodzenia naturalnego mogą być stosowane nie tylko w systemie ekologicznym, ale również w rolnictwie integrowanym i konwencjonalnym, gdzie ich zastosowanie ma na celu ograniczenie liczby zabiegów z użyciem chemicznych środków ochrony [Piekutowska 2017]. W wielu krajach realizowane są obecnie badania nad poszukiwaniem nowych oraz efektywnym wykorzystaniem już znanych pożytecznych mikroorganizmów w rolnictwie, które oprócz poprawy kondycji i zdrowotności roślin wspierają bioróżnorodność i aktywność biologiczną gleb [Gałązka 2024]. Przykładem takich prac są badania podjęte i opisane w niniejszej rozprawie doktorskiej.

3.5. Wpływ wybranych preparatów mikrobiologicznych i roślinnych na wzrost, zdrowotność i plonowanie roślin uprawnych ze szczególnym uwzględnieniem roślin jagodowych

Na przestrzeni ostatnich lat produkty naturalne pochodzenia roślinnego wzbudzają coraz większe zainteresowanie badaczy jako potencjalne środki w biologicznym ograniczaniu chorób grzybowych roślin, z uwagi na właściwości przeciwgrzybicze niektórych gatunków roślin [Ons i in. 2020; Jiang i in. 2023]. W wielu badaniach podejmowany jest również temat zastosowania olejków eterycznych w ochronie truskawki, m.in. z krwawnika pospolitego (*Achillea millefolium*) i mięty długolistnej (*Mentha longifolia*) do zwalczania antraknozy truskawki [Hosseni i in. 2020]. Analizowano także wpływ olejku tymiankowego na zdrowotność roślin truskawki, plonowanie oraz wybrane cechy sensoryczne owoców [Cato i in. 2024]. Ponadto Déné i in. (2023) oceniali skuteczność ekstraktu z kolendry oraz olejku eterycznego z nasion kolendry w ograniczaniu występowania szarej pleśni truskawki.

W nowoczesnej ochronie roślin coraz większy nacisk kładzie się na indukowanie naturalnych mechanizmów obronnych. Jedną z głównych korzyści stosowania induktorów odporności systemicznej jest ich nieszkodliwość, co jest szczególnie istotne w przypadku roślin przeznaczonych do spożycia. Biopreparaty cechuje większe bezpieczeństwo zarówno dla środowiska, jak i ludzi, oraz osób wykonujących zabiegi ochrony, szybciej ulegają biodegradacji i zwykle są mniej kosztowne w produkcji [Mołoń i Durak 2018].

Preparaty mikrobiologiczne, które nie są klasyfikowane jako środki ochrony roślin, zazwyczaj opierają swoje działanie na zasadzie antagonizmu pomiędzy patogenem a aplikowanym mikroorganizmem pożytecznym [Kowalska i Remlain-Starosta 2013]. Tego typu biopreparaty zawierają w swoim składzie pożyteczne bakterie, grzyby, ekstrakty roślinne, polisacharydy oraz substancje humusowe [Pylak i in. 2019]. Do tej grupy można zaliczyć biostymulatory roślin znane również jako bionawozy, odżywki glebowe, wzmacniacze upraw, fitostymulatory. Ich podstawowym zadaniem jest stymulowanie procesów fizjologicznych i metabolicznych roślin, niezależnie od zawartości składników pokarmowych, w celu poprawy ich ogólnej kondycji. Preparaty te stosuje się najczęściej do materiału nasadzeniowego, podłoży uprawowych oraz w formie aplikacji nalistnych [Tarigan i in. 2022]. Wykazują one zdolność do modyfikowania procesów fizjologicznych roślin, co przekłada się na lepsze pobieranie i wykorzystanie składników odżywczych, intensywniejszy wzrost, a także większą odporność na czynniki stresowe [Yakhin i in 2017; Tarigan i in. 2022]. W literaturze można spotkać badania innych autorów nad wykorzystaniem bakterii *Bacillus sp.* [Sas-Paszt i in. 2020; Sas-Paszt i in. 2023; Furtak 2024], *Bacillus amyloliquefaciens* [Es-Soufi i in. 2020; Sas- Paszt i in. 2020; Sas-Paszt i in. 2023], *Bacillus licheniformis* [Tarigan i in. 2022], *Bacillus thuringiensis* [Florczak 2024], *Paenibacillus polymyxa* [Sas-Paszt i in. 2020; Sas-Paszt i in. 2023], *Bacillus subtilis* [Zhang i in. 2012; Vehapi i in. 2023], *Bacillus safensis* [Li i in. 2021], *Bacillus velezensis* [Hyeon i in. 2009; Popescu i in. 2024] i *Pseudomonas azotoformans* [Popescu i in. 2024], grzyba *Trichoderma harzianum* [Es-Soufi i in. 2020], *Aspergillus niger i Purpureocillum lilacinum* [Sas-Paszt i in. 2020] do stymulacji wzrostu i rozwoju oraz poprawy zdrowotności różnych gatunków roślin uprawnych, w tym sadowniczych [Sas-Paszt i in. 2020; Sas-Paszt i in. 2023].

4. Hipoteza i cel badań

Hipoteza badawcza zakładała, że nowe biopreparaty mikrobiologiczne wzbogacone o ekstrakty ziołowe wpływają pozytywnie na wzrost, zdrowotność, plonowanie i jakość owoców oraz opłacalność ekonomiczną produkcji truskawki w systemie ekologicznym.

Celem badań było określenie wpływu nowych biopreparatów wytworzonych w projekcie EcoFruits (finansowany przez Narodowe Centrum Badań i Rozwoju, BIOSTRATEG3/344433/16/NCBR/2018), zawierających mikroorganizmy pożyteczne i wyciągi roślinne (preparaty objęte zgłoszeniem patentowym, w trakcie procesu komercjalizacji) na:

- wzrost roślin i wielkość plonu owoców,

- zdrowotność owoców, w tym ograniczenie występowania kluczowych patogenów grzybowych truskawki w uprawie ekologicznej, takich jak: *Botrytis cinerea* (szara pleśń owoców truskawki), *Phytophthora cactorum* (skórzasta zgnilizna owoców truskawki) i *Colletotrichum acutatum* (antraknoza truskawki),

- efektywność ekonomiczną produkcji ekologicznej w wariancie nawadnianym i nienawadnianym,

- zawartość makroelementów i mikroelementów oraz metali ciężkich w owocach truskawki.

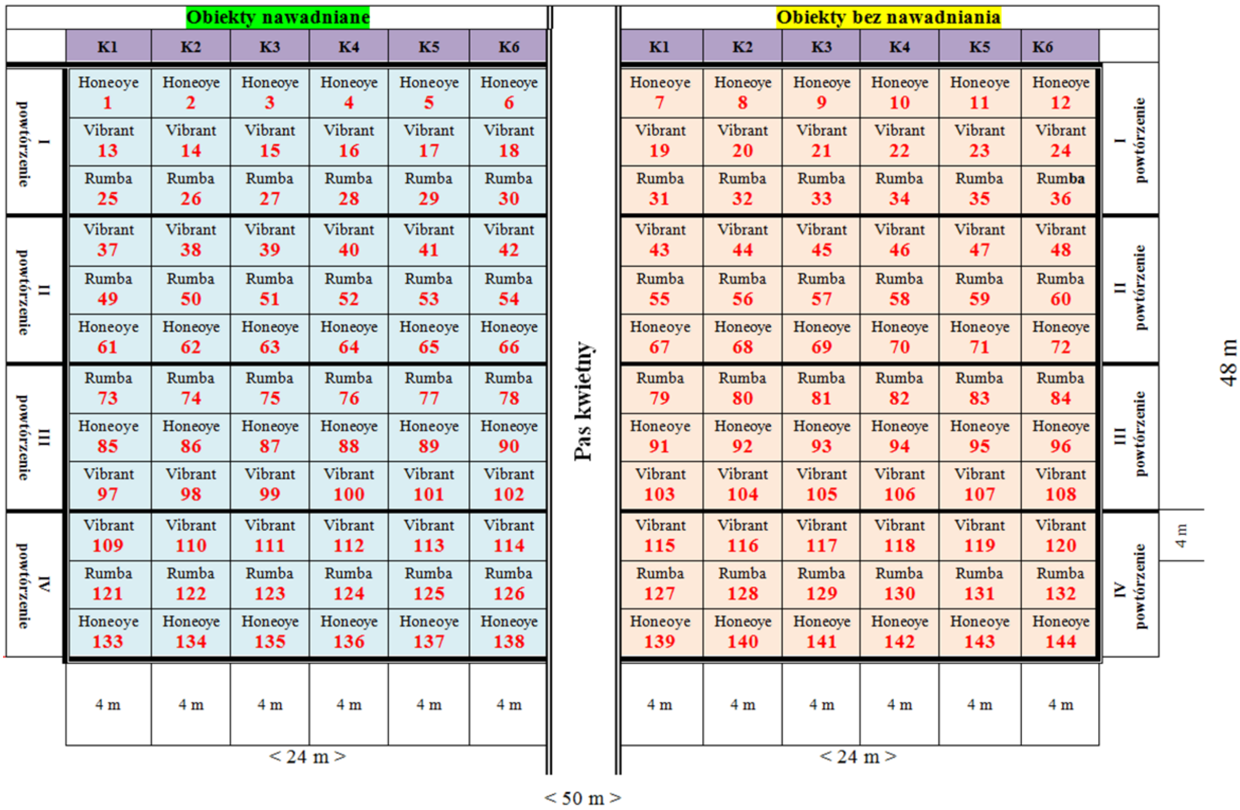
5. Materiał i metody badawcze

5.1. Charakterystyka doświadczenia polowego

Doświadczenie polowe z uprawą truskawki (fot. 1) w systemie ekologicznym założono na certyfikowanym polu Rolniczego Zakładu Doświadczalnego IUNG-PIB w Grabowie nad Wisłą (województwo mazowieckie, powiat zwoleński) [51°21'17.1" N; 21°39'14.0" E]. Plantacja składała się z dwóch identycznych obiektów, z których jeden był nawadniany, a drugi nie nawadniany. Rośliny posadzono w dniach 27 - 29 maja 2019 roku na glebie płowej wytworzonej z piasku gliniastego mocnego na glinie, kompleksu przydatności rolniczej żytniego bardzo dobrego. Do nasadzeń wykorzystano sadzonki truskawki typu frigo, pochodzące ze szkółki ogrodniczej Agronom Plants (Zienki 14, 21-230 Sosnowica). Truskawki były ściółkowane czarną agrotkaniną w celu ograniczenia zachwaszczenia oraz parowania wody z gleby. Przedplonem dla truskawki była koniczyna czerwona (*Trifolium pratense* L.).

Fot. 1. Plantacja doświadczalna truskawki w systemie ekologicznym w Rolniczym Zakładzie IUNG-PIB w Grabowie nad Wisłą (fot. M. Nakielska)

Obiekt doświadczalny z nawadnianiem, jak i bez nawadniania miały powierzchnię po 11,5 a, przy obsadzie 30 052 roślin/ha. Odstępy między rzędami wynosiły 1 m, rozstawa roślin w rzędzie 30 cm. Oba doświadczenia założono na tym samym polu, co zapewniło identyczne warunki glebowe i pogodowe. Obiekty oddzielono od siebie dwumetrowej szerokości pasem kwietnym, na którym wysiano rośliny przyciągające pożyteczne owady. Każdy z obiektów składał się z 72 poletek o powierzchni 16 m^2, przy obsadzie 48 roślin na poletku (rys. 1)



Rys. 1. Schemat doświadczenia z testowaniem biopreparatów w uprawie truskawki w systemie ekologicznym w wariancie nawadnianym i nienawadnianym: K1 - kontrola bez stosowania biopreparatów, K2-K6 – kombinacje biopreparatów, numery 1-144 – kolejne numery poletek.

Czynnikami doświadczenia były:

1) kombinacje preparatów opracowanych w ramach projektu EcoFruits (5 kombinacji K2-K6 oraz obiekt kontrolny K1);
2) odmiany truskawek: ‘Honeoye’, ‘Rumba’, ‘Vibrant’.

Preparaty zawierające pożyteczne mikroorganizmy i wyciągi roślinne stosowano przez trzy sezony wegetacyjne - od 2020 do 2022 roku (tab. 1). W pierwszym roku badań preparaty były stosowane dwukrotnie (29 maja i 29 czerwca 2020 roku) w dawce 35 kg·ha^{-1}, natomiast w kolejnych latach trzykrotnie w ciągu sezonu wegetacyjnego (13, 21, 28 maja 2021 roku oraz 26 kwietnia, 12 i 24 maja 2022 roku) w dawce 50 kg·ha^{-1}. Preparaty mieszano z wodą w ilości 700 l·ha^{-1} i aplikowano za pomocą opryskiwacza z belką typu Fragaria (fot. 2).

Tabela 1. Skład oraz nazwy preparatów na poszczególnych etapach ich opracowywania i trwania projektu.

Nazwa preparatów stosowana w publikacjach	**Nazwa handlowa**	**Nazwa preparatów stosowana w czasie ich opracowywania i testowania**	**Skład**
K1	-	-	Obiekt kontrolny (woda)
K2	BacilRoots	P7	*Bacillus* sp. AF75BC i *Bacillus subtilis* AF75AB2 na nośniku składającym się z suchych kwasów humusowych, gorczycy, oleju rzepakowego i olejku goździkowego w mikronizowanym dolomicie (10^9 CFU/roślinę)
K3	BacilRoots + BacilExtra	P7+P8	*Bacillus* sp. AF75BC i *Bacillus subtilis* AF75AB2 na nośniku składającym się z suchych kwasów humusowych, gorczycy, oleju rzepakowego i olejku goździkowego w mikronizowanym dolomicie (10^9 CFU/roślinę), i *Bacillus subtilis* AF75AB2 i *Bacillus* sp. Sp115AD na nośniku składającym się z ekstraktów roślinnych (pokrzywa, skrzyp, nagietek) oraz kwasów humsowych w mikronizowanym dolomicie (10^5 CFU/cm^2)
K4	BacilRoots + BacilHumus	P7+P9	*Bacillus* sp. AF75BC i *Bacillus subtilis* AF75AB2 na nośniku składającym się z suchych kwasów humusowych, gorczycy, oleju rzepakowego i olejku goździkowego w mikronizowanym dolomicie (10^9 CFU/roślinę), a także *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, kwasy humusowe oraz odciek po produkcji drożdży w mikronizowanym dolomicie (10^5 CFU/cm^2)
K5	BacilRoots + BacilExtra + BacilHumus	P7+P8+P9	*Bacillus* sp. AF75BC i *Bacillus subtilis* AF75AB2 na nośniku składającym się z suchych kwasów humusowych, gorczycy, oleju rzepakowego i oleju goździkowego w mikronizowanym dolomicie (10^9 CFU/roślinę), i *Bacillus subtilis* AF75AB2 i *Bacillus* sp. Sp115AD na nośniku składającym się z ekstraktów roślinnych (pokrzywa, skrzyp, nagietek) oraz kwasów humusowych w mikronizowanym dolomicie (10^5 CFU/cm^2), a także *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, kwasy humusowe oraz odciek po produkcji drożdży w mikronizowanym dolomicie (10^5 CFU/cm^2)
K6	BacilExtra + BacilHumus	P8+P9	*Bacillus subtilis* AF75AB2 i *Bacillus* sp. Sp115AD na nośniku składającym się z ekstraktów roślinnych (pokrzywa, skrzyp, nagietek) oraz kwasów humusowych w mikronizowanym dolomicie (10^5 CFU/cm^2), a także *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, kwasy humusowe oraz odciek po produkcji drożdży w mikronizowanym dolomicie (10^5 CFU/cm^2)

Źródło: Nakielska i in. 2025 (zmodyfikowane)

Fot. 2. Aplikacja biopreparatów przy pomocy opryskiwacza z belką typu Fragaria (fot. M. Nędzi)

Oprócz testowanych biopreparatów na plantacji truskawki stosowano nawożenie środkami dopuszczonymi do stosowania w rolnictwie ekologicznym (tab. 2).

Tabela 2. Preparaty i nawozy stosowane dodatkowo na całości plantacji truskawki

Termin aplikacji	**Preparat**	**Dawka**
	2018	
16.11.2018	Siarczan potasu	250 kg·ha^{-1}
16.11.2018	Sól potasowa	100 kg·ha^{-1}
19.11.2018	Obornik bydlęcy	30,0 t·ha^{-1}
	2019	
11.04.2019	Bioilsa	150 kg·ha^{-1}
17.04.2019	Microcat GOLD	1,0 l·ha^{-1}
	2020	
29.04.2020	Redarom Activstart	2,0 l·ha^{-1}
29.04.2020	Olibio	2,0 l·ha^{-1}
05.08.2020	Siarczan potasu	150 kg·ha^{-1}
21.07.2020	Aminosol	2,0 l·ha^{-1}
	2021	
30.04.2021	Redarom Activstart	1,5 l·ha^{-1}
30.04.2021	Olibio	2,0 l·ha^{-1}
07.05.2021	Aminosol	3,0 l·ha^{-1}
07.07.2021	Nadtlenek wodoru* (jednorazowo do odkażania plantacji po gradobiciu)	0,9 l/100 l wody
20.07.2021	Aminosol	2,0 l·ha^{-1}
20.07.2021	Redarom Activstart	1,5 l·ha^{-1}
20.07.2021	Olibio	2,0 l·ha^{-1}
29.09.2021	Siarczan potasu	250 kg·ha^{-1}
29.09.2021	Sól potasowa	60 kg·ha^{-1}
29.09.2021	Wapno Polcalc	500 kg·ha^{-1}

5.2. Warunki pogodowe

Dane dotyczące opadów i temperatury pochodzą ze stacji meteorologicznej IUNG-PIB w Grabowie zlokalizowanej kilkaset metrów od obiektu doświadczalnego. Średnie opady w okresie od początku kwietnia do końca lipca były w każdym roku trwania eksperymentu niższe niż średnia z wielolecia dla tego okresu. Szczególnie suchymi sezonami były lata 2021 i 2022. W 2020 roku opady w maju i czerwcu były wyższe niż średnia z wielolecia (odpowiednio 53,0 mm i 110,0 mm) i wynosiły odpowiednio 76,5 mm i 157,8 mm (tab. 3). Zwiększone opady mogły z jednej strony korzystnie wpłynąć na wysokość plonu, jednak z drugiej strony, przy temperaturze w czerwcu wyższej o 1,6 °C od średniej mogły sprzyjać większej presji chorób grzybowych. W latach 2021 i 2022 wystąpiły niedobory opadów, zwłaszcza w trzecim roku badań (2022). Temperatury w kwietniu 2021 i 2022 były średnio o 1°C niższe niż średnia z wielolecia, natomiast w pozostałych miesiącach (z wyjątkiem maja 2020 r.) temperatury przekraczały średnie wartości z wielolecia.

Przymrozki w okresie kwitnienia truskawek stanowiły istotny problem jedynie w pierwszym roku badań. U odmiany 'Vibrant', ze względu na wzniesiony pokrój roślin i kwiatostany wyrastające ponad liście, część kwiatów uległa uszkodzeniu na skutek przymrozków oraz uszkodzeń mechanicznych. Zjawisko to miało miejsce w połowie maja, gdy rośliny były zabezpieczone białą agrowłókniną przed nocnymi spadkami temperatur. Tarcie materiału osłaniającego o kwiatostany pod wpływem wiatru powodowało dodatkowe uszkodzenia. W rezultacie część owoców nie wykształciła się prawidłowo lub była zdeformowana. Natomiast w drugim roku badań, wystąpił gwałtowny opad gradu w dniu 24 czerwca, który zniszczył części nadziemne roślin wraz z owocami. Szacowane straty plonu wyniosły niemal 100%, co w praktyce oznaczało konieczność zakończenia zbiorów w tym sezonie.

Tabela 3. Warunki pogodowe w latach 2020-2022 w miesiącach od kwietnia do lipca

miesiąc	**2020**	**2021**	**2022**	**Średnia z wielolecia**
Opady [mm]				
kwiecień	15,6	51,2	42,4	42,0
maj	76,5	49,9	23,3	53,0
czerwiec	157,8	70,1*	31,5	110,0
lipiec	38,3	61,7*	80,6	105,0
Temperatura [°C]				
kwiecień	8,6	6,4	6,5	7,5
maj	11,3	12,5	14,4	12,4
czerwiec	18,3	19,5	19,5	16,7
lipiec	18,6	21,8	19,1	17,8

*wartości opadów mogą odbiegać od rzeczywistych z powodu uszkodzenia deszczomierza w czerwcu 2021 roku.

5.3. Analizy roślinne [Nakielska i in. 2024a]

Zbiory owoców rozpoczynały się na przełomie maja i czerwca, a kończyły w pierwszej dekadzie lipca (łącznie 10 terminów zbiorów), z wyjątkiem roku 2021, kiedy 24 czerwca wystąpiły opady gradu, które spowodowały zakończenie zbiorów w tym sezonie (7 terminów zbiorów). Owoce truskawki były zbierane sukcesywnie, co 2-4 dni, zawsze z tych samych 8 wyznaczonych roślin z każdego poletka. Zbierane owoce liczono, ważono oraz oceniano plon z rośliny i w przeliczeniu na hektar.

Dodatkowo analizowano porażenie owoców przez patogeny wywołujące trzy ważne choroby grzybowe truskawki: szarą pleśń truskawki (*Botrytis cinerea*), antraknozę owoców truskawki (*Colletotrichum acutatum*) oraz skórzastą zgniliznę owoców truskawki (*Phytophthora cactorum*). Przy każdym zbiorze określano udział owoców porażonych przez poszczególne patogeny. Ocenę przeprowadzał zespół 6 przeszkolonych osób, zgodnie z wytycznymi zawartymi w „Metodyce integrowanej ochrony truskawki” (źródła internetowe pozycja 5) oraz „Poradniku sygnalizatora ochrony truskawki” wydane przez Instytut Ogrodnictwa w Skierniewicach (źródła internetowe pozycja 6).

Po zakończeniu owocowania z każdego z poletek pobierano losowo 5 roślin (łącznie część nadziemną i korzeń). Części nadziemne oddzielano od podziemnych i ważono, aby określić ich świeżą masę. Następnie pakowano je osobno do papierowych torebek i suszono w suszarce (fot. 3) przez 7 dni w temperaturze ok. 40°C. Po wysuszeniu próbki ponownie ważono w celu określenia ich powietrznie suchej masy. Dodatkowo określono liczbę koron i rozłogów dla każdej rośliny.

Fot. 3. Suszenie roślin truskawki (fot. M. Nakielska)

5.4. Analizy laboratoryjne [Nakielska i in. 2025]

W każdym roku badań próbki owoców były zamrażane, a następnie przekazywane do analiz laboratoryjnych wykonywanych w Zakładzie Gleboznawstwa Erozji i Ochrony Gruntów (obecnie Zakład Gleboznawstwa i Analiz Środowiskowych) IUNG-PIB w celu oznaczenia zawartości makroelementów (Na, Mg, K, Ca, P) oraz wybranych mikroelementów (Mn, Fe) i metali ciężkich (Cd, Pb, Cu, Zn). Zamrożone owoce poddawano liofilizacji przy użyciu liofilizatora CHRIST Gamma 2-16 LSC. Proces ten polegał na sublimacyjnym usunięciu wody z owoców truskawek w warunkach obniżonego ciśnienia i temperatury. Następnie przeprowadzono analizy chemiczne z wykorzystaniem spektrometru ICP-MS (firmy Agilent quadrupole 7500CE ICP-MS; Santa Clara, CA 95051 United States) w celu oznaczenia zawartości metali, a także analizatora TOC/TN (vario Macro cube CN elementar analyser; Elementar Analysensysteme GmbH; Langenselbold, Germany) do oznaczenia zawartości węgla i azotu. Ekstrakty zostały przygotowane w stężonym kwasie azotowym w wyniku trawienia mikrofalowego. W celu weryfikacji poprawności całego procesu analitycznego analizy przeprowadzono z uwzględnieniem próby ślepej (próby tła), a także certyfikowanego materiału odniesienia (NIST1400 i CRM028-050). Walidacja metod analitycznych obejmowała ocenę odzysku (90 do 97%) oraz dokładności oznaczeń, wyrażonej jako względne odchylenie standardowe (< 3%). Granica wykrywalności (LOD) dla poszczególnych pierwiastków mieściła się w zakresie 0,007 - 0,099 $mg \cdot kg^{-1}$.

5.5. Analizy statystyczne

Analizy statystyczne przeprowadzono przy użyciu programu STATISTICA (Statistica v.10 Statsoft Inc., USA). Dla danych pochodzących z obiektu nienawadnianego (publikacja 1 i 3) zastosowano dwuczynnikową analizę wariancji (ANOVA), w której czynnikiem I rzędu było stosowanie biopreparatów, a czynnikiem II rzędu odmiana truskawki. Różnice między średnimi określono za pomocą testu Fishera, przy poziomie istotności $p < 0{,}05$. Dane dotyczące plonowania oraz porażenia owoców przez patogeny grzybowe analizowano dla każdego roku oddzielnie z uwagi na różną liczbę zabiegów w latach i niewielkie modyfikacje składu biopreparatów w poszczególnych sezonach, wynikające z potrzeby ich dopracowania. Dla danych dotyczących zawartości makro- i mikroelementów oraz metali ciężkich w owocach truskawki (publikacja 3) nie stwierdzono istotnych różnic pomiędzy latami badań, dlatego wyniki przedstawiono jako średnie z dwóch sezonów (2021 i 2022). Przeprowadzono również analizę składowych głównych PCA (Principal Component Analysis) z wykorzystaniem oprogramowania STATISTICA (Statistica v.10 Statsoft Inc., USA).

5.6. Ocena opłacalności ekonomicznej stosowania biopreparatów

[Nakielska i in. 2024b]

Analizę ekonomiczną opłacalności stosowania nowo opracowanych preparatów w ekologicznej uprawie truskawki przeprowadzono dla sezonu 2021, oddzielnie dla doświadczenia nawadnianego i nienawadnianego. W założeniach analizy uwzględniono: koszty pracy, zużycia paliwa, zabiegów agrotechnicznych, nakłady roboczogodzin i ciągnikogodzin, zużycie i ceny nawozów, koszt biopreparatów, koszt wody zużytej do oprysków biopreparatami oraz nawadniania (dla obiektu nawadnianego), a także wartość produkcji. Koszt instalacji nawodnieniowej rozłożono na cztery lata, czyli czas, po którym zazwyczaj plantacja jest likwidowana. Obliczono również wskaźnik nadwyżki bezpośredniej oraz wskaźnik opłacalności produkcji. Nie uwzględniono natomiast kosztu zakupu maszyn.

W obliczeniach uwzględniono minimalne wynagrodzenie netto z 2021 roku, przeliczone na wymiar pracy wynoszący 2200 rbh/rok (wg IERiGŻ), co dało koszt roboczogodziny w wysokości 11,01 zł/rbh. Koszty zużycia paliwa oszacowano dla ciągnika Ursus 4512 (44,5kW) na poziomie 31,87 zł/cnh zgodnie z Harasim (2006), przy średniej cenie oleju napędowego w okresie od stycznia do października 2021 roku wynoszącej 5,30 zł$\cdot$l^{-1}. Koszty zabiegów agrotechnicznych oraz nakłady roboczo i ciągnikogodzin oraz zużycie nawozów, określono na podstawie karty dokumentacyjnej doświadczenia, uwzględniając ceny zakupu z danego okresu. Koszt wody przyjęto na poziomie 3,66 zł$\cdot$m^{-3} (zgodnie z rozporządzeniem gminy Przyłęk odnośnie ceny wody w celu zaopatrzenia ludności na 2021 rok). Koszt biopreparataów oszacowano na 400 zł$\cdot$ha^{-1} za jeden zabieg, przy rekomendowanej liczbie trzech zabiegów w sezonie (łącznie 1200 zł/ha/rok). Koszt preparatów był taki sam we wszystkich kombinacjach doświadczenia. Wartość produkcji ustalono na podstawie średniej ceny skupu netto truskawki deserowej (przeznaczonej do bezpośredniego spożycia) w województwie mazowieckim w 2021 roku (region, w którym znajdował się obiekt doświadczalny) wynoszącej 4,80 zł$\cdot$kg^{-1}.

Ocenę ekonomiczną produkcji truskawki przeprowadzono zgodnie z metodyką IERGiŻ-PIB [Skarżyńska i in. 2017; Żekało 2016], uwzględniając: wartość produkcji, koszty bezpośrednie, nadwyżkę bezpośrednią oraz wskaźnik opłacalności. Wartość produkcji obliczono jako iloczyn masy zebranych owoców i ceny skupu owoców. Nadwyżkę bezpośrednią obliczono jako różnicę wartości plonu (dochód ze sprzedaży owoców) i wartości kosztów bezpośrednich, na które składały się koszty sadzonek, nawozów, środków ochrony roślin oraz wybranych kosztów pośrednich (paliwo zużyte przy wykonywaniu aplikacji preparatów). Wskaźnik opłacalności produkcji obliczono jako iloraz przychodów i kosztów bezpośrednich wyrażony w procentach.

6. Wyniki badań

6.1. Wpływ testowanych biopreparatów na plonowanie truskawki w systemie ekologicznym

Wyniki badań przeprowadzonych na obiekcie nienawadnianym (fot. 4-5) wykazały, że w 2020 roku spośród trzech testowanych odmian truskawki jedynie ‘Honeoye’ zareagowała istotnym wzrostem plonu (o 119,4%) na zastosowanie kombinacji biopreparatów K4 w porównaniu z obiektem kontrolnym (tab. 4). Odmiana ‘Rumba’ charakteryzowała się istotnie wyższym plonem (średnio 504,2 g·roślinę$^{-1}$ tj. 15,2 t·ha^{-1}) w porównaniu do ‘Honeoye’ (383,2 g·roślinę$^{-1}$; tj. 11,5 t·ha^{-1}) i ‘Vibrant’ (320,9 g·roślinę$^{-1}$ tj. 9,6 t·ha^{-1}). W przypadku odmiany ‘Vibrant’, której kwiatostany wystają ponad powierzchnię liści, niższy plon niż u pozostałych odmian był spowodowany uszkodzeniem kwiatów przez wiosenne przymrozki. Średnie plony owoców wszystkich odmian truskawki wahały się od 271,5 g·roślinę$^{-1}$ po zastosowaniu preparatu K2 do 477,5 g·roślinę$^{-1}$ po aplikacji K4.

W 2021 roku odnotowano wzrost plonów odmian ‘Honeoye’ i ‘Rumba’ po zastosowaniu kombinacji preparatów K4 - odpowiednio o 79% i 49% w stosunku do kontroli (tab. 4). Chociaż u odmiany ‘Honeoye’ różnice te nie były statystycznie istotne, zauważono tendencję zwiększenia plonów również po aplikacji pozostałych biopreparatów (K2, K3, K5 i K6).

Tabela. 4. Wpływ badanych biopreparatów na plon owoców truskawki (g·roślina^{-1}) na obiekcie nienawadnianym

Lata i kombinacje preparatów							
2020							
odmiany	**K1**	**K2**	**K3**	**K4**	**K5**	**K6**	**średnia**
‘Honeoye’	240,2 ab (±21,2)	227,30 a (±65,2)	440,2 ab (±79,0)	527,2 b (±184,0)	373,6 ab (±157,6)	419,1 ab (±260,4)	383,2 A (±176,1)
‘Rumba’	621,0 b (±0,70)	370,6 a (±108,2)	374,3 a (±58,6)	512,4 ab (±132,4)	599,0 b (±129,1)	606,6 b (±111,1)	504,2 B (±143,0)
‘Vibrant’	389,1 ab (±255,2)	216,6 a (±25,2)	341,7 ab (±72,2)	393,0 b (±54,3)	358,5 ab (±134,5)	260,7 ab (±62,4)	320,9 A (±109,7)
średnia	416,8 ab (±206,3)	271,5 a (±99,5)	385,4 ab (±76,7)	477,5 b (±137,0)	443,7 b (±171,6)	428,8 b (±211,4)	402,8 (±162,5)
2021							
odmiany	**K1**	**K2**	**K3**	**K4**	**K5**	**K6**	**średnia**
‘Honeoye’	368,9 a (±32,8)	519,3 ab (±56,6)	588,8 ab (±136,1)	660,6 b (±33,8)	496,8 ab (±188,3)	590,6 ab (±148,2)	552,8 A (±135,2)
‘Rumba’	443,9 a (±25,8)	578,8 ab (±89,2)	574,9 ab (±77,4)	661,1 b (±119,4)	560,1 ab (±77,7)	602,3 ab (±84,5)	581,7 A (±95,6)
‘Vibrant’	663,2 ab (±137,6)	576,2 ab (±83,2)	688,5 b (±49,0)	649,9 ab (±122,7)	622,2 ab (±104,0)	503,5 a (±121,7)	613,1 A (±110,4)
średnia	492,0 a (±151,1)	558,1 ab (±75,9)	617,4 bc (±100,7)	657,2 c (±91,3)	559,7 ab (±130,9)	565,5 ab (±118,7)	582,5 (±115,8)

Interakcja biopreparat x odmiana – n.i. Wartości oznaczone różnymi małymi literami oznaczają istotne różnice między kombinacjami preparatów, a wartości oznaczone różnymi dużymi literami oznaczają istotne różnice między odmianami. Wartości w nawiasach oznaczają odchylenie standardowe (SD). Źródło: Nakielska i in. (2024a)

Zarówno w pierwszym jak i w drugim roku badań odmiana ‘Honeoye’ zareagowała największą zwyżką plonu na zastosowane preparaty, a w szczególności na kombinację preparatów K4. Średni plon owoców wszystkich odmian w 2021 roku wynosił od 492,0 g·roślinę$^{-1}$ na obiekcie kontrolnym do 657,2 g·roślinę$^{-1}$ po zastosowaniu kombinacji K4 (tab. 4).

Fot. 4. Plantacja w fazie kwitnienia (fot. M. Nakielska)

Fot. 5. Plantacja w fazie owocowania (fot. M. Nakielska)

Wyniki tych badań są szczegółowo opisane w publikacji 1 składającej się na niniejszą rozprawę doktorską [Nakielska i in. 2024a].

6.2. Wpływ testowanych biopreparatów na choroby grzybowe truskawki

Ocena wpływu nowych biopreparatów na zdrowotność owoców truskawki na obiekcie nienawadnianym wykazała, że skuteczność stosowanych biopreparatów w ograniczaniu występowania sprawców szarej pleśni (*Botrytis cinerea*), antraknozy (*Colletotrichum acutatum*) i skórzastej zgnilizny owoców (*Phytophthora cactorum)* zależała zarówno od odmiany truskawki, jak i od warunków pogodowych w danym roku.

W 2020 r. porażenie owoców truskawki przez *Botrytis cinerea* utrzymywało się na niskim poziomie - średnio 3,32% dla całego obiektu doświadczalnego nienawadnianego. Zaobserwowano tendencję zmniejszenia występowania objawów chorobowych po zastosowaniu biopreparatów, zwłaszcza kombinacji K6 (o 29% mniej owoców z objawami szarej pleśni w porównaniu do obiektu kontrolnego). Różnice te nie były jednak istotne statystycznie, co mogło wynikać z dużej zmienności wyników. U odmiany 'Rumba' w sezonie 2020 zaobserwowano pozytywny trend w ograniczaniu występowania objawów chorobowych szarej pleśni na owocach truskawki po zastosowaniu każdej z kombinacji preparatów. W drugim roku badań (2021) porażenie owoców przez patogen wywołujący szarą pleśń było również na bardzo niskim poziomie - średnio 0,42%. U odmiany 'Honeoye' zauważono tendencję ograniczenia objawów chorobowych po zastosowaniu każdej z kombinacji preparatów, choć różnice te również nie osiągnęły poziomu istotności statystycznej.

W przypadku antraknozy truskawki w 2020 roku nie odnotowano istotnych różnic w stopniu porażenia owoców pomiędzy poszczególnymi kombinacjami biopreparatów. Najmniej podatna na porażenie była odmiana 'Honeoye' (około 7% owoców z objawami chorobowymi), natomiast dla pozostałych dwóch odmian udział owoców prażonych był około trzykrotnie większy. W 2021 roku u odmiany 'Vibrant' zaobserwowano tendencję mniejszego porażenia owoców po zastosowaniu każdej z testowanych kombinacji w porównaniu do obiektu kontrolnego, przy czym najlepszy efekt uzyskano po aplikacji preparatu K5 (o 55,5% niższe porażenie niż na obiekcie kontrolnym).

W obu latach badań kombinacja preparatów K3 okazała się skuteczna w ograniczaniu objawów skórzastej zgnilizny owoców. W 2020 roku udział porażonych owoców był mniejszy o 46%, a w 2021 roku - o 27% w porównaniu do kontroli nie traktowanej biopreparatami (przy czym nie były to różnice istotne statystyczne). W 2021 roku skuteczność w ograniczaniu objawów chorobowych wykazały również kombinacje K2 i K6 (średnio o 25,6 do 30% mniej porażonych owoców niż na obiekcie kontrolnym). Najmniejszą podatność na porażenie przez *Phytophthora cactorum* w 2020 roku wykazała odmiana 'Honeoye', natomiast w 2021 roku odmiana 'Rumba'. W obu sezonach zaobserwowano większe różnice w stopniu porażenia owoców pomiędzy odmianami niż pomiędzy stosowanymi kombinacjami biopreparatów.

Wyniki tych badań są opisane w publikacji 1 [Nakielska i in. 2024a].

6.3. Wpływ testowanych biopreparatów na wzrost i rozwój roślin truskawki

Na doświadczeniu nienawadnianym w 2020 roku wszystkie testowane kombinacje biopreparatów, a w 2021 wszystkie z wyjątkiem K2 sprzyjały zwiększeniu liczby koron na roślinie w porównaniu z obiektem kontrolnym. Ze względu na dużą zmienność między powtórzeniami różnice te nie były jednak istotne statystycznie. W pierwszym roku badań zaobserwowano tendencję wzrostu suchej masy części nadziemnych roślin truskawki w wariantach, gdzie stosowano preparaty w porównaniu do roślin z obiektu kontrolnego.

W 2021 roku efekt ten był zróżnicowany w zależności od odmiany oraz zastosowanej kombinacji preparatów (fot. 6-8).

Fot. 6. Krzew truskawki odmiany ‘Honeoye’ (fot. B. Feledyn-Szewczyk)

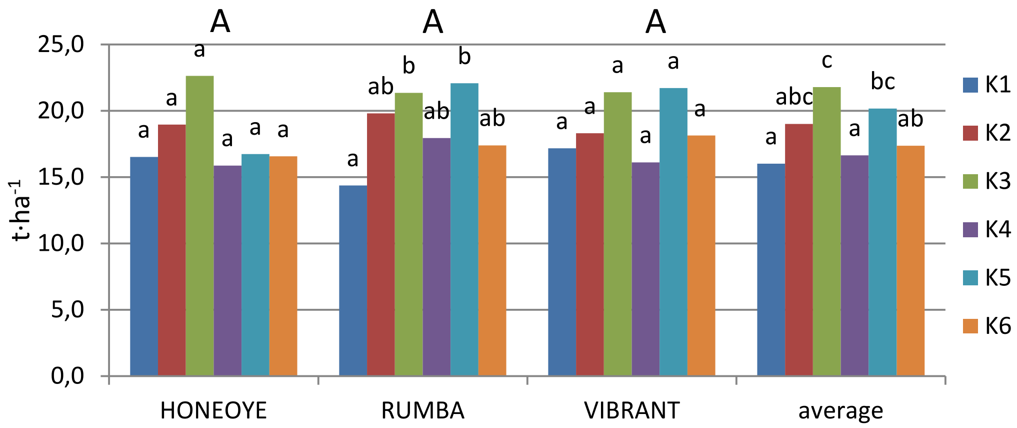
Fot. 7. Krzew truskawki odmiany ‘Rumba’ (fot. B. Feledyn-Szewczyk)

Fot. 8. Krzew truskawki odmiany ‘Vibrant’ (fot. B. Feledyn-Szewczyk)

Wyniki tych badań są opisane w publikacji 1 składającej się na rozprawę doktorską [Nakielska i in. 2024a].

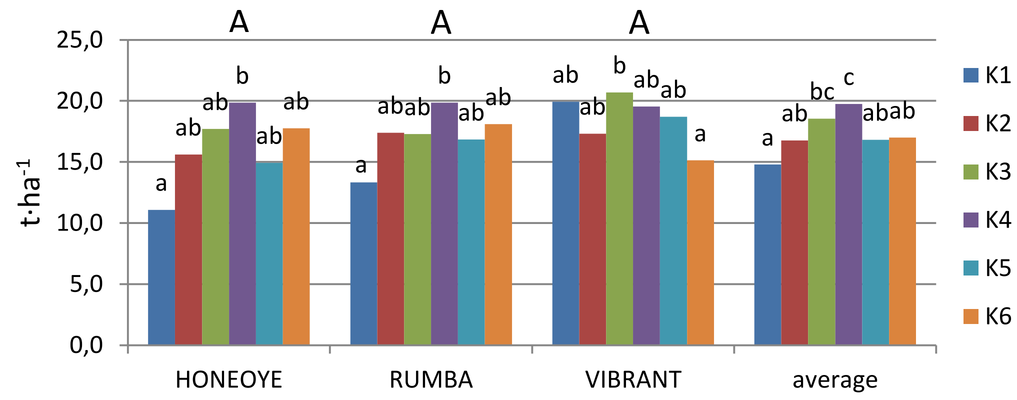
6.4. Porównanie produkcyjności i opłacalności ekonomicznej stosowania testowanych biopreparatów w uprawie truskawki nawadnianej i nienawadnianej

Ocenę ekonomiczną produkcji truskawki w systemie ekologicznym przeprowadzono zarówno dla doświadczenia nawadnianego, jak i bez nawadniania w sezonie 2021. Średni plon owoców na obiekcie nawadnianym wynosił 18,51 t·ha^{-1}, natomiast na obiekcie bez nawadniania był niższy o około 7% i wynosił 17,28 t·ha^{-1} (rys. 2-3, tab. 5).



Rys. 2. Wpływ testowanych biopreparatów na plon owoców odmian ‘Honeoye’, ‘Rumba’, ‘Vibrant’ na obiekcie nawadnianym w 2021 roku.

Duże litery oznaczają różnice między odmianami. Małe litery oznaczają istotne różnice między testowanymi biopreparatami. Interakcja biopreparat x odmiana – n.s.



Rys. 3. Wpływ testowanych biopreparatów na plon owoców odmian ‘Honeoye’, ‘Rumba’, ‘Vibrant’, na obiekcie nienawadnianym w 2021 roku.

Duże litery oznaczają różnice między odmianami. Małe litery oznaczają istotne różnice między testowanymi biopreparatami. Interakcja biopreparat x odmiana – n.s.

Wartość plonu na obiekcie nienawadnianym wynosiła średnio 82 849,50 zł·ha^{-1}. W zależności od zastosowanej kombinacji biopreparatów, wartość ta kształtowała się od 70 918 zł·ha^{-1} (kontrola) do 94 701 zł·ha^{-1} (kombinacja K4), a po zastosowaniu K3 osiągała 88 947 zł·ha^{-1}. Spośród testowanych odmian, najwyższą wartość plonu uzyskano dla

‘Vibranta’ – 88 947,20 zł·ha^{-1}, natomiast najniższą dla ‘Honeoye’ 77 455,30 zł·ha^{-1}. Zdecydowanie najwyższą wartość plonu (99 209 zł·ha^{-1}) odnotowano dla owoców odmiany ‘Vibrant’ po zastosowaniu preparatów K3 (tab. 5).

Tabela 5. Wartość plonu i nadwyżki bezpośredniej dla trzech odmian truskawki traktowanych różnymi kombinacjami biopreparatów (2021)

specyfikacja	**Kombinacje preparatów**						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**średnia**
Obiekt nienawadniany							
Plon (średnia, t·ha^{-1})	14,79	16,77	18,55	19,75	16,82	16,99	17,28
Wartość plonu (PLN)							
‘Honeoye’	53 177	74 850	84 824	95 181	71 589	85 111	77 455,3
‘Rumba’	63 965	83 385	82 858	95 277	80 700	86 790	82 162,5
‘Vibrant’	95 564	83 049	99 209	93 646	89 667	72 548	88 947,2
średnia	70 918	80 412	88 947	94 701	80 652	81 467	82 849,5
Koszty bezpośrednie (PLN)	54 783	56 098	56 098	56 098	56 098	56 098	55 878,8
Nadwyżka bezpośrednia (PLN)							
‘Honeoye’	−1606	18 752	28 726	39 083	15 492	29 013	21 576,7
‘Rumba’	9 182	27 287	26 760	39 179	24 602	30 692	26 283,7
‘Vibrant’	40 781	26 952	43 111	37 549	33 569	16 451	33 068,8
średnia	16 135	24 314	32 849	38 603	24 554	25 369	26 970,7
Średnia nadwyżka bezpośrednia z dotacjami	19 010	27 189	35 724	41 478	27 429	28 244	29 845,7
Obiekt nawadniany							
Plon (średnia, t·ha^{-1})	16,03	19,03	21,81	16,65	20,18	17,37	18,51
Wartośc plonu (PLN)							
‘Honeoye’	79 118	91 105	108 367	76 241	80 077	79 597	85 750,8
‘Rumba’	69 048	94 941	102 613	85 831	105 970	83 433	90 306,0
‘Vibrant’	82 474	87 749	102 613	77 200	104 052	86 790	90 146,3
średnia	76 720	91 105	104 531	79 597	96 859	83 433	88 707,5
Koszty bezpośrednie (PLN)	60 271	61 586	61 586	61 586	61 586	61 586	61 366,8
Nadwyżka bezpośrednia (PLN)							
‘Honeoye’	18 846	29 519	46 781	14 654	18 490	18 011	24 383,5
‘Rumba’	8 777	33 355	41 027	24 244	44 383	21 847	28 938,8
‘Vibrant’	22 203	26 162	41 027	15 613	42 465	25 203	28 778,8
średnia	16 449	29 519	42 945	18 011	35 273	21 847	27 340,7
Średnia nadwyżka bezpośrednia z dotacjami	19 323	32 394	45 820	20 886	38 148	24 722	30 215,5

Źródło: Nakielska i in. 2024b (zmodyfikowane)

Na obiekcie nawadnianym średnia wartość plonu wynosiła 88 707,50 zł·ha^{-1} i była wyższa niż na obiekcie bez nawadniania (tab. 5). Wartość ta, w zależności od kombinacji, mieściła się w przedziale od 76 720 zł·ha^{-1} (kontrola) do 104 531 zł·ha^{-1} (kombinacja K3). Podobnie jak na obiekcie nienawadnianym, dla odmiany ‘Honeoye’ odnotowano niższą średnią wartość plonu (85 750,80 zł·ha^{-1}) w porównaniu do pozostałych odmian. Jednakże po zastosowaniu kombinacji preparatów K3 uzyskano rekordową wartość plonu dla ‘Honeoye’ - 108 367 zł·ha^{-1} (tab. 5).

Koszty bezpośrednie na 1 ha były niższe w uprawie nienawadnianej - od 54 783 zł (kontrola) do 56 098 zł, (dla każdej z kombinacji) niż w uprawie nawadnianej, gdzie wynosiły od 60 271 zł do 61 586 zł. Różnica ta wynikała głównie z kosztów zużycia wody oraz jej transportu z gospodarstwa na plantację.

Średnia wartość nadwyżki bezpośredniej dla całego obiektu nienawadnianego wynosiła 26 970,70 zł·ha^{-1}, a po uwzględnieniu dopłat - 29 845,70 zł·ha^{-1}. W zależności od zastosowanej kombinacji biopreparatów, nadwyżka bezpośrednia mieściła się w przedziale od 16 135 zł (K1) do 38 603 zł (K4). Biorąc pod uwagę poszczególne odmiany, najwyższą nadwyżkę osiągnięto dla ‘Vibranta’ - 33 068,80 zł, a najniższą dla odmiany ‘Honeoye’ - 21 576,70 zł, natomiast dla ‘Rumby‘- 26 283,70 zł. Przy braku stosowania preparatów dla ‘Honeoye’ odnotowano ujemną nadwyżkę na poziomie - 1606 zł i był to jedyny obiekt, na którym uprawa truskawki była nieopłacalna (tab. 5).

Na obiekcie nawadnianym średnia nadwyżka bezpośrednia wynosiła 27 340,70 zł, a z dopłatami 30 215,50 zł. W zależności od zastosowanego wariantu wynosiła od 16 449 zł (K1) do 42 945 zł (K3). Również tutaj ‘Honeoye’ charakteryzowała się niższą opłacalnością niż pozostałe odmiany - średnia nadwyżka wynosiła 24 383,50 zł. Na plantacji bez nawadniania największą opłacalność osiągnięto po zastosowaniu biopreparatów K4 i K3 natomiast w uprawie nawadnianej - K3 i K5. Na tej podstawie można stwierdzić, że najbardziej uniwersalnym i skutecznym ekonomicznie biopreparatem dającym zadowalające efekty w postaci nadwyżki bezpośredniej (bez względu na to czy plantacja jest nawadniana czy też nie) był wariant K3.

Średni wskaźnik opłacalności uprawy przy braku stosowania biopreparatów wynosił 130% dla obiektu nienawadnianego i 127% na plantacji nawadnianej (tab. 6). Zastosowane mikrobiologicznych produktów nawozowych spowodowało wzrost wskaźnika opłacalności do poziomu 143% - 169% w uprawie bez nawadniania oraz 129% - 170% dla plantacji nawadnianej.

Zadowalające efekty ekonomiczne dla szerokich warunków uprawy, czyli dla każdej z testowanych odmian zarówno na obiekcie nawadnianym, jak i bez nawadniania dawało stosowanie kombinacji preparatów K3. W przypadku uprawy bez nawadniania pozytywnie wyróżniała się również kombinacja K4, która może być polecana do uprawy truskawki bez nawadniania. Natomiast wariant K6, mimo pewnych pozytywnych tendencji nie przynosił zadowalających rezultatów, odnotowano w tym przypadku niewielki wzrost nadwyżki bezpośredniej bez względu na odmianę. Minimalny plon owoców, potrzebny do pokrycia bezpośrednich kosztów zastosowania preparatów K2-K6, wynosił 12,8 t·ha^{-1} na obiekcie nawadnianym, i 11,7 t·ha^{-1} na obiekcie bez nawadniania (tab. 6).

Tabela 6. Wskaźnik opłacalności (%) i plon kompensujący koszty bezpośrednie w zależności od kombinacji stosowanych preparatów, nawadniania oraz odmiany truskawki

specyfikacja	**Kombinacja preparatów**					
	K1	**K2**	**K3**	**K4**	**K5**	**K6**
Obiekt nienawadniany						
‘Honeoye’	97	133	151	170	128	152
‘Rumba’	117	149	148	170	144	155
‘Vibrant’	174	148	177	167	160	129
średnia	130	143	159	169	144	145
Zyski kompensujące koszty bezpośrednie (t)	11,4	11,7	11,7	11,7	11,7	11,7
Obiekt nawadniany						
‘Honeoye’	131	148	176	124	130	129
‘Rumba’	115	154	167	139	172	136
‘Vibrant’	137	142	167	125	169	141
średnia	127	148	170	129	157	136
Zyski kompensujące koszty bezpośrednie (t)	12,6	12,8	12,8	12,8	12,8	12,8

Źródło: Nakielska i in. 2024b (zmodyfikowane)

Wyniki tych badań są opisane szczegółowo w publikacji 2 [Nakielska i in. 2024b].

6.5. Wpływ testowanych biopreparatów na zawartość makroelementów i mikroelementów oraz metali ciężkich w owocach truskawki

Wyniki badań wykazały, że zastosowanie testowanych biopreparatów nie miało istotnego wpływu na zawartość węgla w owocach truskawki w doświadczeniu bez nawadniania. Dla większości analizowanych pierwiastków odnotowano zróżnicowaną reakcję odmian na aplikowane biopreparaty. Zawartość azotu całkowitego (tab. 7) była generalnie większa w owocach pochodzących z obiektów, na których stosowano biopreparaty. Niektóre z nich wykazały istotne działanie: u odmiany ‘Honeoye’ preparat K2 przyczynił się do zwiększenia zawartości suchej masy w porównaniu do kontroli natomiast u odmiany ‘Vibrant’ preparaty K3-K6 spowodowały wzrost zawartości azotu w owocach (tab. 7).

Tabela 7. Zawartość azotu całkowitego w owocach truskawki [$g \cdot kg^{-1}$].
Źródło: Nakielska i in. 2025 (zmodyfikowane)

Odmiany	Biopreparaty						
	K1	K2	K3	K4	K5	K6	Średnia
'Honeoye'	14,8a * (±1,3)	16,7a (±2,2)	18,3a (±2,3)	18,2a (±1,7)	17,1a (±1,7)	16,9a (±1,6)	17,1B (±0,7)
'Rumba'	18,6a (±2,4)	17,6a (±2,1)	19,3a (±1,2)	19,2a (±2,1)	18,4a (±1,5)	19,8a (±2,4)	18,8C (±0,7)
'Vibrant'	13,8a (±0,7)	15,2ab (±1,5)	16,3b (±2,3)	16,0b (±1,6)	16,3b (±1,6)	16,2b (±1,5)	15,7A (±0,7)
Średnia	15,7a (±1,1)	16,5ab (±1,1)	18,0b (±1,1)	17,8ab (±1,0)	17,3ab (±0,9)	17,7ab (±1,1)	17,2 (±0,4)

*Małe litery oznaczają istotne różnice między biopreparatami, duże litery różnice między odmianami. Interakcje biopreparat x odmiana nie były statystycznie istotne przy $p<0,05$. Wartości w nawiasach to błąd standardowy średniej (SEM).

U 'Rumby' zastosowanie kombinacji K5 skutkowało niższą zawartością żelaza (tab. 12), natomiast dla odmiany 'Vibrant' biopreparaty K2 i K3 ograniczyły akumulację miedzi względem kontroli (rys. 4). Zastosowanie kombinacji preparatów K6 i K5 obniżyło także zawartość ołowiu w owocach odmiany 'Vibrant' (rys. 5). Wyniki te wskazują na potencjał selektywnego wpływu biopreparatów na gospodarkę makro- i mikroelementami w roślinie. Odmiana 'Vibrant' istotnie zareagowała na zastosowanie biopreparatów wzrostem zawartości azotu całkowitego z 13,8 $g \cdot kg^{-1}$ (kontrola) do 15,2 $g \cdot kg^{-1}$ po zastosowaniu preparatu K2, a nawet 16,3 $g \cdot kg^{-1}$ po zastosowaniu kombinacji K3 i K5, czyli o 10-18% względem kontroli. Zastosowanie preparatów K3 i K5 przyczyniło się do istotnego spadku zawartości żelaza w owocach - odpowiednio o 16,1% oraz 17,9% w porównaniu do obiektu kontrolnego. Najwyższe poziomy żelaza, miedzi, cynku stwierdzono w owocach truskawki 'Vibrant' pochodzących z obiektu kontrolnego, gdzie stosowano jedynie oprysk wodą (tab. 12, rys. 4). Zastosowanie biopreparatów nie wpłynęło istotnie na zawartość magnezu, wapnia, sodu ani fosforu (tab. 8–11).

Tabela 8. Zawartość magnezu w owocach truskawki [$mg \cdot kg^{-1}$].
Źródło: Nakielska i in. 2025 (zmodyfikowane)

Odmiany	Biopreparaty						
	K1	K2	K3	K4	K5	K6	Średnia
'Honeoye'	1488a* (±109)	1437a (±97)	1432a (±100)	1467a (±81)	1422a (±102)	1388a (±104)	1436A (±38)
'Rumba'	1793a (±130)	1613a (±125)	1720a (±179)	1695a (±135)	1573a (±47)	1632a (±64)	1664B (±47)
'Vibrant'	1912a (±113)	1798a (±148)	1582a (±104)	1794a (±158)	1856a (±105)	1951a (±111)	1810C (±52)
Średnia	1731a (±82)	1616a (±77)	1578a (±77)	1652a (±77)	1617a (±65)	1657a (±76)	1637 (±31)

*Małe litery oznaczają różnice między biopreparatami, duże litery różnice między odmianami. Interakcje biopreparat x odmiana nie były statystycznie istotne przy $p<0,05$. Wartości w nawiasach to błąd standardowy średniej (SEM).

Tabela 9. Zawartość wapnia w owocach truskawek [$mg \cdot kg^{-1}$].
Źródło: Nakielska i in. 2025 (zmodyfikowane)

Odmiany	Biopreparaty						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Średnia**
'Honeoye'	2899a * (±142)	2536a (±264)	2575a (±263)	3176a (±106)	2935a (±222)	2792a (±381)	2814A (±105)
'Rumba'	3092a (±434)	2542a (±182)	2604a (±351)	2470a (±261)	2796a (±369)	2824a (±109)	2700A (±115)
'Vibrant'	3792a (±406)	3507a (±269)	3014a (±166)	3487a (±352)	3861a (±381)	3905a (±329)	3583B (±132)
Średnia	3261a (±217)	2862a (±172)	2731a (±155)	3045a (±175)	3198a (±213)	3174a (±204)	3032 (±78)

*Małe litery oznaczają różnice między biopreparatami, duże litery różnice między odmianami. Interakcje biopreparat x odmiana nie były statystycznie istotne przy $p<0,05$. Wartości w nawiasach to błąd standardowy średniej (SEM).

Tabela 10. Zawartość sodu w owocach truskawki [$mg \cdot kg^{-1}$].
Źródło: Nakielska i in. 2025 (zmodyfikowane)

Odmiany	Biopreparaty						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Średnia**
'Honeoye'	13,2a * (±2,1)	14,2a (±2,4)	13,2a (±2,1)	18,5a (±3,4)	16,0a (±1,5)	14,9a (±1,8)	15,1A (±0,9)
'Rumba'	33,9a (±4,1)	24,3a (±2,1)	34,0a (±7,4)	24,7a (±6,2)	24,3a (±2,8)	31,4a (±5,9)	28,5C (±2,1)
'Vibrant'	31,2a (±10,0)	26,9a (±4,7)	21,3a (±2,8)	21,9a (±1,8)	21,2a (±2,5)	24,8a (±4,2)	24,2B (±1,7)
Średnia	26,1a (±4,3)	21,8a (±2,2)	22,9a (±3,3)	21,7a (±2,3)	20,5a (±1,5)	23,7a (±2,9)	22,6 (±1,1)

*Małe litery oznaczają różnice między biopreparatami, duże litery różnice między odmianami. Interakcje biopreparat x odmiana nie były statystycznie istotne przy $p<0,05$. Wartości w nawiasach to błąd standardowy średniej (SEM).

Tabela 11. Zawartość fosforu w owocach truskawki [$mg \cdot kg^{-1}$].
Źródło: Nakielska i in. 2025 (zmodyfikowane)

Odmiany	Biopreparaty						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Średnia**
'Honeoye'	2074a * (±111)	2339a (±340)	2112a (±119)	2234a (±221)	2122a (±227)	2003a (±123)	2152A (±84)
'Rumba'	2310a (±331)	2498a (±244)	2579a (±277)	2647a (±331)	2741a (±349)	2457a (±281)	2552B (±117)
'Vibrant'	2284ab (±336)	2285ab (±176)	1905a (±164)	2150ab (±193)	2252ab (±264)	2518b (±278)	2229A (±94)
Średnia	2223a (±150)	2374a (±144)	2199a (±127)	2343a (±148)	2372a (±167)	2326a (±141)	2311 (±59)

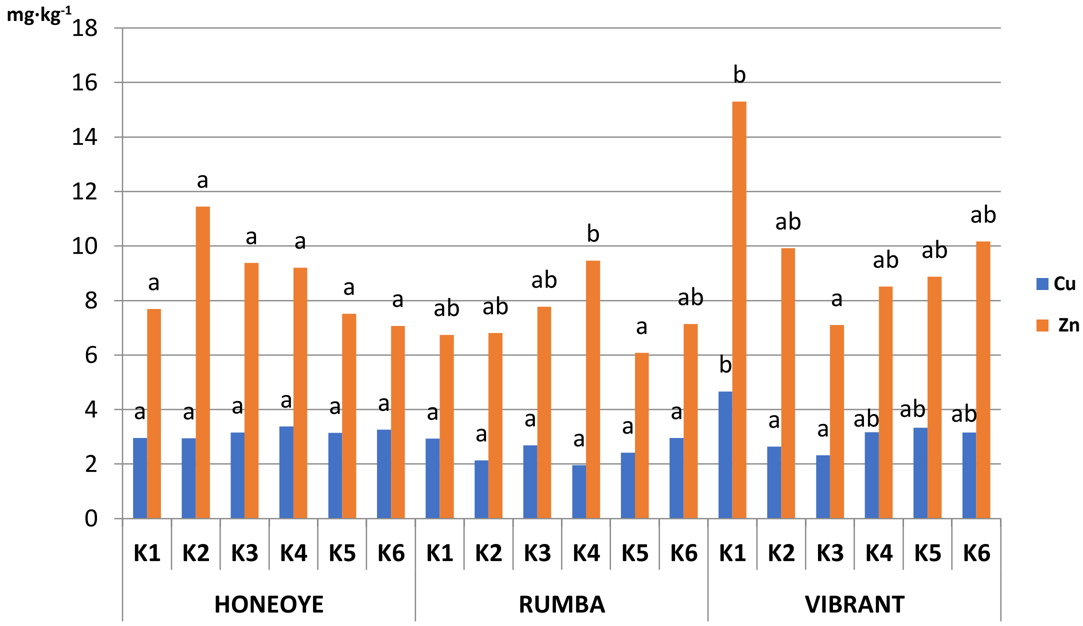
*Małe litery oznaczają różnice między biopreparatami, duże litery różnice między odmianami. Interakcje biopreparat x odmiana nie były statystycznie istotne przy $p<0,05$. Wartości w nawiasach to błąd standardowy średniej (SEM).

Tabela 12. Zawartość żelaza w owocach truskawki [mg·kg^{-1}].
Źródło: Nakielska i in. 2025 (zmodyfikowane)

Odmiany	Biopreparaty						
	K1	K2	K3	K4	K5	K6	Średnia
'Honeoye'	32,7a * (±3,4)	34,1a (±4,7)	31,3a (±0,4)	34,6a (±4,5)	30,4a (±1,3)	34,7a (±1,6)	33,0A (±1,2)
'Rumba'	38,4b (±5,6)	32,4ab (±2,2)	36,6ab (±4,6)	35,3ab (±3,5)	30,6a (±1,5)	37,2ab (±1,5)	34,9A (±1,3)
'Vibrant'	46,4b (±11,1)	35,4 ab (±4,8)	30,5a (±1,6)	35,7ab (±2,4)	35,3ab (±1,2)	34,9ab (±2,4)	35,8A (±1,7)
Średnia	39,1b (±4,2)	33,9ab (±2,2)	32,8a (±1,7)	35,2ab (±1,9)	32,1a (±0,9)	35,6ab (±1,1)	34,5 (±0,8)

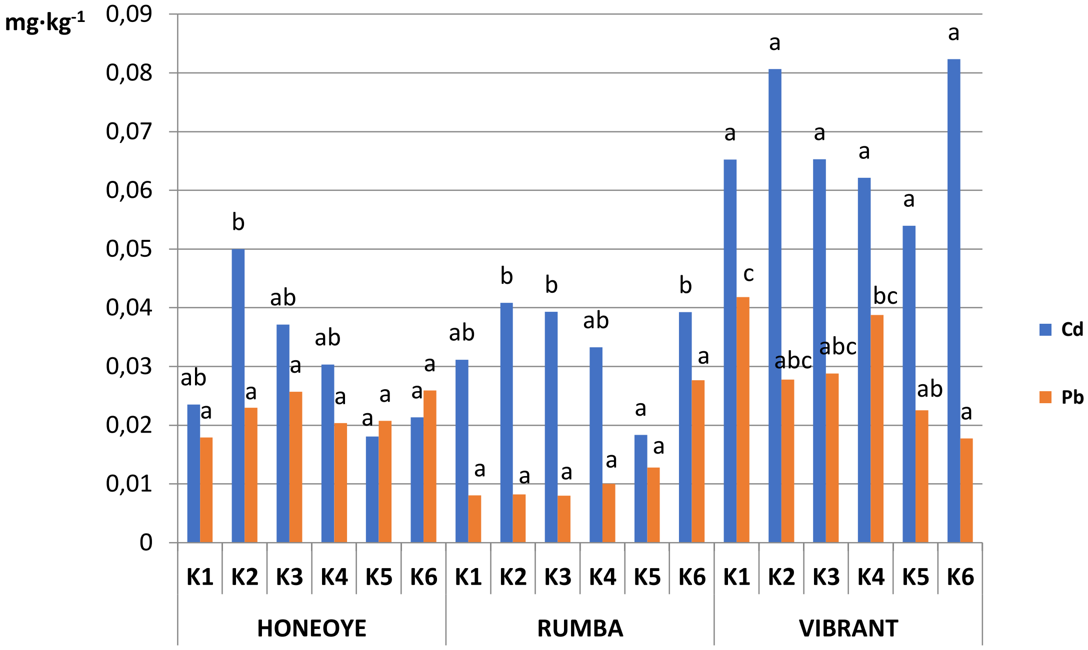
*Małe litery oznaczają różnice między biopreparatami, duże litery różnice między odmianami. Interakcje biopreparat x odmiana nie były statystycznie istotne przy $p<0,05$. Wartości w nawiasach to błąd standardowy średniej (SEM).

W żadnej z analizowanych próbek nie stwierdzono przekroczenia dopuszczalnych norm dla zawartości metali ciężkich w owocach (rys. 4-5). Podsumowując wpływ testowanych biopreparatów na zawartość wybranych mikro- i makroelementów w owocach był on uzależniony od odmiany i zastosowanej kombinacji preparatów, bez wyraźnej ogólnej tendencji.



Rys. 4. Zawartość cynku i miedzi w owocach truskawki [mg·kg^{-1}].

Małe litery (a, b, c) oznaczają istotne różnice między biopreparatami [Źródło: Nakielska i in. 2025].



Rys. 5. Zawartość kadmu i ołowiu w owocach truskawki [mg·kg^{-1}].

Małe litery (a, b, c) oznaczają istotne różnice między biopreparatami [źródło: Nakielska i in. 2025].

Wyniki tych badań są opisane szczegółowo w publikacji 3 [Nakielska i in. 2025]

7. Dyskusja

Cykl publikacji składający się na niniejszą rozprawę doktorską dotyczy aktualnego i istotnego zagadnienia dotyczącego poszukiwania bezpiecznych biopreparatów do zastosowania w uprawie roślin jagodowych, ze szczególnym uwzględnieniem truskawki. Regularne spożywanie roślin jagodowych może przynieść szereg korzyści zdrowotnych, co uzasadnia potrzebę intensyfikacji badań nad rozwiązaniami wspierającymi ich uprawę, zwłaszcza w systemie ekologicznym, w którym nie stosuje się syntetycznych nawozów mineralnych i chemicznych środków ochrony roślin. Przeprowadzone badania własne pozwoliły zweryfikować skuteczność testowanych nowych biopreparatów wytworzonych w projekcie EcoFruits oraz dały możliwość ich udoskonalenia w trakcie realizacji projektu. W rezultacie potwierdzono zasadność ich dalszego rozwoju oraz przygotowania do komercjalizacji. Kombinacje preparatów oznaczone jako K2-K6, zawierające wyselekcjonowane szczepy bakterii z rodzaju *Bacillus spp*., ekstrakty roślinne oraz mikronizowany dolomit, zostały objęte zgłoszeniem patentowym, przypisano im też nazwy handlowe i znajdują są na etapie przygotowania do wprowadzenia na rynek. Seria trzech publikacji powstałych jako efekt realizacji projektu EcoFruits i składających się na rozprawę doktorską zawiera wyniki badań polowych i laboratoryjnych, w których testowano wpływ nowo opracowanych biopreparatów na plon i zdrowotność owoców truskawki, skład chemiczny owoców oraz efektywność ekonomiczną produkcji.

Pierwsza z publikacji [Nakielska i in. 2024a] koncentruje się na ocenie wpływu badanych biopreparatów na plonowanie oraz występowanie chorób grzybowych, stanowiących główne zagrożenie dla uprawy truskawki, takich jak szara pleśń, skórzasta zgnilizna oraz antraknoza owoców truskawki. Ocenie poddano również cechy biometryczne roślin, w tym masę części nadziemnych oraz liczbę koron na roślinie. Artykuł ten odnosi się do jednej z hipotez przyjętych w pracy, zgodnie z którą nowe biopreparaty mikrobiologiczne wzbogacone o ekstrakty roślinne z ziół wpływają korzystnie na wzrost, zdrowotność, plon i jakość owoców.

W badaniu własnym najwyższy, statystycznie istotny wzrost plonu owoców truskawki (33% wyższe plony w porównaniu do kontroli) odnotowano w drugim roku badań (2021) po zastosowaniu kombinacji K4, zawierającej m.in.: płynne i suche kwasy humusowe, odciek z hodowli drożdży, mikronizowany dolomit, gorczycę, olej rzepakowy oraz bakterie: *Bacillus sp.* Sp116AC*, *Bacillus sp.*115AD, *Bacillus sp.* AF75BC oraz *Bacillus subtilis* AF75AB2. Szczególnie korzystną reakcję na zastosowane preparaty wykazała odmiana ‘Honeoye’, u której zaobserwowano istotny wzrost plonowania [Nakielska i in. 2024a]. Na podstawie przeprowadzonych analiz można wnioskować, że pozytywny wpływ testowanych biopreparatów może się kumulować w czasie, sprzyjając stabilizacji zespołów mikroorganizmów i utrwaleniu korzystnej struktury mikroflory glebowej. Warto również zaznaczyć, że w sezonie 2021 zwiększono zarówno dawki, jak i częstotliwość aplikacji biopreparatów w porównaniu do wcześniejszego sezonu [Nakielska i in 2024a]. Badania o podobnej tematyce prowadzili Mikciuk i in. (2019), którzy odnotowali korzystny wpływ stosowania biopreparatów mikoryzowych na wielkość plonów truskawek oraz masę pojedynczych owoców. Apu i in. (2022) w badaniach nad wpływem dodatków organicznych (wermikompost, biowęgiel) oraz arbuskularnych grzybów mikoryzowych (AMF) na truskawkę odmiany BARI Strawberry-2 stwierdzili, że najlepsze efekty uzyskano w wariancie T6 (162 g wermikompostu + 162 g AMF), który istotnie zwiększał plon, masę pojedynczych owoców, liczbę kwiatów i owoców, wysokości roślin, liczbę liści na roślinie oraz ich powierzchnię, długość i masę korzeni (świeżą i suchą), a także masę części nadziemnych rośliny. Ten sam wariant powodował również zwiększenie w owocach zawartości wapnia, magnezu i potasu, a także kwasu askorbinowego i cukrów ogółem [Apu i in. 2022]. Według Déné i in. (2023) naturalne substancje o działaniu hamującym rozwój grzybów patogenicznych odgrywają istotną rolę w zwalczaniu patogenów o dużym znaczeniu gospodarczym do których zalicza się między innymi grzyb wywołujący szarą pleśń – *Botrytis cinerea*. W swoich badaniach autorzy wykorzystali olejek eteryczny z nasion kolendry oraz ekstrakt z kolendry. Najlepsze efekty przeciwgrzybicze, zarówno w warunkach in vitro, jak i na roślinach truskawki uzyskano po zastosowaniu olejku eterycznego [Déné i in. 2023].

W badaniach własnych [Nakielska i in. 2024a] na owocach truskawki odmiany ‘Vibrant’ odnotowano ograniczenie objawów skórzastej zgnilizny owoców po zastosowaniu nowo wyprodukowanych w projekcie EcoFruits biopreparatów w porównaniu do kontroli, przy czym najlepsze efekty uzyskano po zastosowaniu kombinacji K3 w 2020 r. Podobne badania prowadziła Kowalska (2011), oceniając efektywność grzyba *Trichoderma asperellum* [T1] w ekologicznej uprawie truskawki. Po zastosowaniu preparatu handlowego zawierającego *T. asperellum* trzykrotnie w ciągu sezonu wegetacyjnego już w pierwszym roku badań zaobserwowano zwiększony przyrost biomasy części nadziemnych roślin. Objawy szarej pleśni zarówno na roślinach, jak i owocach występowały sporadycznie. W drugim roku eksperymentu odnotowano istotny, 30% wzrost plonów owoców truskawki w porównaniu do obiektu kontrolnego, co jest zbieżne z wynikami badań własnych zawartych w niniejszej rozprawie doktorskiej. Ponadto rośliny wytwarzały więcej rozłogów, a masa części nadziemnych była o 24% większa w porównaniu do kontroli [Kowalska 2011]. Zbliżone tematycznie badania przeprowadziły również Kowalska i Remlain-Starosta (2013), oceniając wpływ Efektywnych Mikroorganizmów (EM) na truskawkę odmiany ‘Honeoye’ (ta sama odmiana została użyta w badaniu własnym). Sześciokrotna nalistna aplikacja 5% roztworu EM powodowała znaczący wzrost masy części nadziemnych roślin truskawki, natomiast zwiększenie liczby zabiegów do 10 aplikacji lub podwyższenie stężenia preparatu nie wpłynęło korzystnie na rozwój roślin. W badaniu własnym dla tej samej odmiany stwierdzono tendencję pozytywnego działania preparatów K3-K6. Zwłaszcza preparat K5 spowodował zwiększenie suchej masy części nadziemnych roślin truskawki o około 90% w porównaniu do roślin z obiektu kontrolnego. Różnice te, mimo wyraźnej tendencji, nie były jednak istotne statystycznie [Nakielska i in. 2024a].

W badaniach przeprowadzonych przez tych samych autorów (Kowalska i Remlein-Starosta 2013) sprawdzono rolniczą przydatność dostępnych na rynku biopreparatów zawierających *Trichoderma asperellum*, *Cryptoccocus albidus*, ProBioEM oraz *Aureobasidium pullans*. Badania nad wykorzystaniem *Trichoderma asperellum* w ekologicznej uprawie truskawek odmiany ‘Senga-Sengana’ oraz ‘Honeoye’ (odmiana użyta w badaniu własnym) wykazali, że 0,5% roztwór preparatu zawierającego *T. asperellum* stymulował wzrost roślin oraz poprawiał ich zdolność do przezimowania. Najlepsze rezultaty uzyskano, gdy mikroorganizm aplikowano na etapie zakładania plantacji, a następnie regularnie nanoszono go na liście w czasie sezonu wegetacyjnego [Kowalska i in. 2012].

Druga publikacja [Nakielska i in. 2024b] miała na celu ocenę efektywności ekonomicznej testowanych biopreparatów w ekologicznej uprawie truskawki. Opłacalność ekonomiczna upraw, a tym samym decyzje dotyczące doboru gatunków, czasu trwania uprawy, zastosowanych metod i środków produkcji, mają podstawowe znaczenie dla przetrwania i rozwoju gospodarstwa. W obecnych czasach rolnik musi funkcjonować w dużej mierze jako przedsiębiorca, który przed podjęciem kluczowych decyzji produkcyjnych powinien dokonać analizy ich opłacalności. W badaniach własnych [Nakielska i in. 2024b] spośród wszystkich testowanych kombinacji nieopłacalna była jedynie uprawa odmiany ‘Honeoye’ na obiekcie kontrolnym (K1) bez nawadniania i bez aplikacji biopreparatów. Na plantacji nienawadnianej najwyższy wskaźnik opłacalności średnio dla zabiegów uzyskano po zastosowaniu preparatu K3 (159%) oraz K4 (169%). Z kolei na plantacji nawadnianej najbardziej dochodowe były zabiegi K3 oraz K5, dla których średni wskaźnik opłacalności wynosił odpowiednio 170% i 157%. Dla porównania, w przypadku braku stosowania biopreparatów (K1), wskaźnik opłacalności wynosił 127% .

Pod względem ekonomicznym jabłka i truskawki stanowią dwa kluczowe gatunki upraw sadowniczych w Polsce. Różnice w cenach sprzedaży pomiędzy owocami pochodzącymi z upraw ekologicznych i konwencjonalnych mogą zachęcać producentów do przejścia na ekologiczny system produkcji [Brzozowski i Zmarlicki 2012]. Dubey i in. (2020) oraz Kuźniar i in. (2021) podkreślają, że wyniki badań nad zastosowaniem mikroorganizmów w technologiach agroekologicznych mogą sprzyjać osiąganiu wysokiej efektywności produkcji przy jednoczesnej dbałości o środowisko naturalne [Dubey i in. 2020; Kuźniar i in. 2021].

Trzecia publikacja [Nakielska i in. 2025] dotyczy wpływu testowanych preparatów na skład chemiczny owoców truskawki. Głównym celem badań było określenie, czy zastosowanie biopreparatów nie ma negatywnego wpływu na jakość tych owoców, w tym czy nie prowadzi do akumulacji metali ciężkich. Podobne badania przeprowadzili Bebek Markovinović i in. (2022), analizując zawartość mikroelementów w owocach truskawki odmiany ‘Albion’, soku z nich otrzymanym, a także w produktach ubocznych powstałych podczas produkcji tego soku. Stężenia oznaczanych pierwiastków wynosiły odpowiednio: Cu 0,077-0,415 $mg \cdot kg^{-1}$, Zn - 0,988-3,12 $mg \cdot kg^{-1}$, Pb – poniżej 0,03 do 0,076 $mg \cdot kg^{-1}$ [Bebek Markovinović i in. 2022]. W badaniach własnych odnotowano wyższe wartości tych pierwiastków: zawartość Cu mieściła się w zakresie od 1,95 $mg \cdot kg^{-1}$ (K4 Rumba) do 4,66 $mg \cdot kg^{-1}$ (K1 Vibrant), Zn od 6,08 $mg \cdot kg^{-1}$ (K5 Rumba) do 15,30 $mg \cdot kg^{-1}$ (K1 Vibrant), Pb od 0,008 $mg \cdot kg^{-1}$ (K1, K2, K3 Rumba) do 0,042 $mg \cdot kg^{-1}$ (K1 Vibrant) [Nakielska i in 2025]. Badania o podobnej tematyce przeprowadzili Hallmann i in. (2016), którzy oceniali wpływ efektywnych mikroorganizmów w ekologicznej uprawie truskawek odmiany ‘Honeoye’ i stwierdzili, że zastosowanie preparatów istotnie wpłynęło na zawartość kwasu kawowego i p-kumarynowego, a także luteiny, kwercetyny i jej glukozydu [Hallmann i in. 2016].

Kowalska i Remlein-Starosta (2013) zwracają uwagę na praktyczne ograniczenia produktów opartych na mikroorganizmach, takie jak: brak szybkiego efektu, potrzebę wielokrotnego powtarzania zabiegów, konieczność prowadzenia nadzoru upraw, stadiów rozwoju szkodników oraz bezwzględnego przestrzegania terminów ich zastosowania. Ponadto ich skuteczność jest uzależniona od warunków pogodowych: silne opady deszczu mogą prowadzić do wypłukania mikroorganizmów, a niskie temperatury hamują ich aktywność biologiczną [Kowalska i Remlein-Starosta 2013].

Uzyskane wyniki wskazują, że choć biopreparaty mikrobiologiczne mogą mieć wpływ na parametry jakościowe oraz zawartość poszczególnych składników w owocach truskawek, to efekt ich działania jest w dużej mierze uzależniony od odmiany. Zaobserwowano pewne tendencje, jednak efekty w większości przypadków nie były jednolite we wszystkich odmianach i wariantach zabiegów. Obrazuje to złożone mechanizmy interakcji pomiędzy biopreparatami, genotypem rośliny a warunkami środowiskowymi w uprawach ekologicznych. Brak jednoznacznych wzorców wskazuje na potrzebę kontynuacji badań w celu wyjaśnienia mechanizmów odpowiadających za zmienne reakcje odmian i składu preparatów oraz optymalizacji stosowania biopreparatów mikrobiologicznych w uprawach ekologicznych. Warto, aby badania poszerzono o dodatkowe odmiany truskawek najczęściej uprawianych w Polsce oraz by przeprowadzono je w różnych lokalizacjach oraz warunkach glebowych i siedliskowych. Istotne byłoby także wydłużenie okresu testowania do czterech sezonów, ponieważ pewne obserwacje wykazują, że korzystne efekty wynikające ze stosowania biopreparatów mikrobiologicznych mogą narastać w czasie. Zasadne byłoby również zbadanie potencjalnego zastosowania tych preparatów w uprawach konwencjonalnych i integrowanych, jako elementu ograniczającego ilość lub częstotliwość stosowania innych konwencjonalnych preparatów.

8. Podsumowanie i wnioski

1. Testowane odmiany truskawki (‘Honeoye’, ‘Vibrant’ i ‘Rumba’) reagowały w różny sposób na zastosowane nowo opracowane biopreparaty, zawierające pożyteczne mikroorganizmy oraz ekstrakty roślinne, zarówno pod względem plonowania, jak i podatności na patogeny grzybowe.
2. Odmiana ‘Honeoye’ najlepiej reagowała na testowane biopreparaty mikrobiologiczne w postaci zwiększenia plonowania. Wykazywała też największą odporność na *Colletotrichum acutatum*, sprawcę antraknozy truskawki.
3. Największy wzrost plonu (średnio o 33%) zaobserwowano w 2021 roku na plantacji nie nawadnianej po zastosowaniu biopreparatu K4, zawierającego szczepy bakterii: *Bacillus* sp. AF75BC i *Bacillus subtilis* AF75AB2 na nośniku składającym się z suchych kwasów humusowych, gorczycy, oleju rzepakowego i olejku goździkowego w mikronizowanym dolomicie, a także *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, kwasy humusowe oraz odciek po produkcji drożdży w mikronizowanym dolomicie.
4. Skuteczność biopreparatów w ograniczaniu występowania objawów chorób grzybowych owoców truskawki zależała od odmiany oraz warunków pogodowych w danym sezonie wegetacyjnym. W 2020 roku zastosowanie kombinacji preparatów K6 ograniczyło występowanie szarej pleśni (*Botrytis cinerea)* na owocach truskawki. Dla odmiany ‘Vibrant’ stwierdzono zmniejszenie porażenia owoców przez patogena wywołującego skórzastą zgniliznę owoców truskawki (*Phytophthora cactorum*), szczególnie po zastosowaniu kombinacji K3. W 2021 roku zaobserwowano zmniejszenie objawów tej choroby po zastosowaniu kombinacji K2, K3 i K6 o 26-30% w stosunku do kontroli.
5. Większość zastosowanych kombinacji biopreparatów (z wyjątkiem K2 w 2021 r.) sprzyjało zwiększeniu liczby koron na roślinach truskawki w porównaniu do kontroli, co wskazuje pośrednio na znaczenie biopreparatów w stymulowaniu wzrostu i rozwoju.
6. Zastosowanie biopreparatów wpłynęło na zwiększenie opłacalności produkcji. Na plantacjach nienawadnianych wartość tego wskaźnika wzrosła średnio z 130% dla kontroli do 143-169% po aplikacji biopreparatów, a na plantacjach nawadnianych odpowiednio z 127% do 129-170% w zależności od zastosowanej kombinacji preparatów.
7. Efektywność działania biopreparatów może być modyfikowana przez obecność nawadniania. Kombinacja biopreparatów K3 zapewniła korzystne efekty ekonomiczne dla wszystkich badanych odmian w szerokich warunkach uprawy, zarówno na plantacji nawadnianej, jak i bez nawaniania, co wskazuje na jej uniwersalny charakter. Kombinacja biopreparatów K4 przyniosła wysoką efektywnością ekonomiczną w uprawie truskawki bez nawadniania, co pozwala rekomendować go do tego typu plantacji.

8. Zastosowane biopreparaty mikrobiologiczne wpłynęły na skład chemiczny owoców truskawki (zawartość suchej masy oraz azotu, żelaza, manganu, miedzi, cynku, kadmu, ołowiu). Biopreparaty nie wpłynęły natomiast istotnie na zawartość wapnia, magnezu i sodu w owocach truskawki. W żadnej z analizowanych prób nie stwierdzono przekroczenia dopuszczalnych zawartości metali ciężkich.
9. Stwierdzono istotne różnice w zawartości pierwiastków: N, Mn, Na, Mg, Ca, K, P oraz metali ciężkich: Cu, Zn, Pb, Cd w owocach truskawki między odmianami. Odmiana 'Honeoye' cechowała się mniejszą zawartością Na, K, P, Mg, Mn w owocach w porównaniu do pozostałych odmian. Natomiast odmiana 'Vibrant' charakteryzowała się wyższą zawartością Mg, Zn, Mn, Ca, Cd i Pb niż pozostałe odmiany. Z kolei w owocach odmiany 'Rumba' stwierdzono najniższe poziomy zawartości metali ciężkich: Cu, Zn, Pb, oraz wapnia, a jednocześnie najwyższą zawartość N całkowitego, K, P, Na w porównaniu do pozostałych odmian.
10. Wyniki badań wskazują, że stosowanie biopreparatów, zawierających pożyteczne mikroorganizmy i wyciągi roślinne, może korzystnie wpływać na plonowanie oraz efektywność ekonomiczną uprawy truskawki w systemie ekologicznym. Jednak przy doborze preparatu należy uwzględnić zarówno specyfikę odmiany, jak i warunki prowadzenia plantacji (nawadnianie lub jego brak).
11. Testowane biopreparaty mają potencjał do poprawy jakości owoców truskawki w rolnictwie ekologicznym, ale na podstawie przeprowadzonych badań stwierdzono, że ich stosowanie wymaga dopasowania do warunków uprawy i konkretnej odmiany. Zaobserwowano pewne tendencje, jednak większość efektów nie była jednoznaczna ani powtarzalna we wszystkich wariantach czy odmianach. Potwierdza to złożoność interakcji pomiędzy preparatami mikrobiologicznymi, genotypem rośliny a warunkami środowiskowymi w uprawach ekologicznych. Brak jednoznacznych zależności wskazuje na potrzebę kontynuacji badań w celu poznania mechanizmów odpowiedzialnych za zróżnicowane reakcje odmian oraz dopracowania optymalnych strategii stosowania biopreparatów.

9. Literatura

1. Apu S.C., Biswas M.S., Bhuiyan M.A.B., Gomasta J., Esmin S., Kayesh E. 2022. Effect of organic amendments and arbuscular mycorrhizal fungi on plant growth, yield and quality of strawberry. Ann. Bangladesh Agric. 26(2), 71-82. www.doi.org/10.3329/aba.v26i2.67867
2. Barbaś P., Aslan H., Aslan I., Skiba D., Otekunrin O.A., Sawicka B., 2023. Prospects for using pesticides in agriculture. Agronomy Science LXXVIII(1), 97-120. https://doi.org/10.24326/as.2023.5078
3. Bebek Markovinović A., Putnik P., Duralija B., Krivohlavek A., Ivešić M., Mandić Andačić I., Palac Bešlić I., Pavlić B., Lorenzo J.M., Bursać Kovačević D. 2022. Chemometric valorization of strawberry (*Fragaria x ananassa* Duch.) cv. 'Albion' for the production of functional juice: The impact of physiochemical, toxicological, sensory and bioactive value. Foods 11, 640, 1-22. https://doi.org/10.3390/foods11050640.
4. Brzozowski P., Zmarlicki K. 2012. Economics of the 2009-2012 organic apple, strawberry, and sour cherry production in Poland. Journal of Fruit and Ornamental Plant Research 20(2), 63-70. DOI: 10.2478/v10290-012-0016-6
5. Brzozowski P., Zmarlicki K. 2015. Zmiany kosztów jednostkowych produkcji ekologicznej truskawek w latach 2009–2013. Stowarzyszenie Ekonomistów Rolnictwa i Agrobiznesu Roczniki Naukowe XVII, 1, 9–13.
6. Cato A.J., McWhirt A.L., Rojas A. 2024. Impact of Soil-Applied Thyme Oil on Strawberry Yield and Disease Abundance. International Journal of Fruit Science 24, 1, 130-141. https://doi.org/10.1080/15538362.2024.2339219
7. Dean R., Van Kan J.A.L., Pretorius Z.A., Hammond-Kosack K.E., Di Pietro A., Spanu P.D., Rudd J.J., Dickman M., Kahmann R., Ellis J., Foster G.D. 2012. The Top 10 fungal pathogens in molecular plant pathology. Molecular Plant Pathology 13(4), 414-430. DOI: 10.1111/J.1364-3703.2011.00783.X
8. Déné L., Laužiké K., Rasiukevičiūté N., Chrapačiené S., Brazaityté A., Viršilé A., Vaštakaité-Kariené V., Miliauskiené J., Sutuliené R., Samuoliené G., Valiuškaité A. 2023. Defense response of strawberry plants against *Botrytis cinerea* influenced by coriander extract and essential oil. Frontiers in Plant Science 13:1098048, 1-10. Doi: 10.3389/fpls.2022.1098048
9. Dubey A., Malla M.A., Kumar A., Dayanandan S., Khan M.L. 2020. Plants endophytes: unveiling hidden agenda for bioprospecting toward sustainable agriculture. Critical Reviews in Biotechnology 40, 8, 1-22. https://doi.org/10.1080/07388551.2020.1808584
10. Es-Soufi R., Tahiri H., Azaroual L., El Oualkadi A., Martin P., Badoc A., Lamarti A. 2020. Biocontrol Potential of *Bacillus amyloliquefaciens* Bc2 and *Trichoderma harzianum* TR against Strawberry Anthracnose under Laboratory and Field Conditions. Agricultural Sciences 11, 260-277. DOI: 10.4236/as. 2020.113017
11. Felczak-Konarska K. 2021. Choroby truskawki. Kraków: Wydawnictwo Plantpress Sp. z o.o., str. 25-48.
12. Feledyn-Szewczyk B., Cacak-Pietrzak G., Lenc L., Stalenga J. 2020. Rating of Spring Wheat Varieties (*Triticum aestivum* L.) According to Their Suitability for Organic Agriculture. Agronomy 10, 1900, 1-13. doi:10.3390/agronomy10121900
13. Florczak L. 2024. Od bakterii do biopreparatu – *Bacillus thuringiensis* w ochronie roślin. Progress in Plant Protection 64(4), 204-217. DOI: 10.14199/ppp-2024-020
14. Furtak K. 2024. Bakterie z rodzaju *Bacillus* jako składniki biopreparatów o szerokim spektrum zastosowania w rolnictwie. W: Gałązka A., Podleśny J. (red.), Preparaty mikrobiologiczne w rolnictwie i ochronie środowiska. Puławy: Wydawnictwo IUNG-PIB, Monografie i Rozprawy Naukowe, 66, str. 89-104.

15. Gałązka A. 2024. Preparaty mikrobiologiczne potrzeby, szanse i znaczenie. W: Gałązka A., Podleśny J. (red.), Preparaty mikrobiologiczne w rolnictwie i ochronie środowiska. Puławy: Wydawnictwo IUNG-PIB, Monografie i Rozprawy Naukowe, 66, str. 9–27.
16. Golik D., Żmija D. 2017. Rolnictwo ekologiczne i perspektywy jego rozwoju w Polsce w świetle doświadczeń unijnych. Zeszyty Naukowe Uniwersytet Ekonomiczny w Krakowie 1(961), 117-129. DOI: 10.15678/ZNUEK.2017.0961.0108
17. Hallmann E., Piotrowska A., Świąder K. 2016. The effect of organic practices on the bioactive compounds content in strawberry fruits. Journal of Research and Applications in Agricultural Engineering 61(3), 176-179.
18. Harasim A. 2006. Przewodnik Ekonomiczno-Rolniczy w Zarysie. Puławy: Wydawnictwo IUNG-PIB .
19. Hosseni S., Amini J., Rafei J.N., Khorshidi J. 2020. Management of Strawberry Anthracnose Using Plant Essential Oils as Bio-fungicides, and Evaluation of Their Effects on Quality of Strawberry Fruit. Journal of Oleo Science 69(4), 377-390. doi: 10.5650/jos.ess19119
20. Hua L., Yong Ch., Zhanquan Z., Boqiang L., Guozheng Q., Shiping T. 2018. Pathogenic mechanisms and control strategies of *Botrytis cinerea* causing post-harvest decay in fruits and vegetables. Food Quality and Safety 3, 111-119. doi: 10.1093/fqsafe/fyy016
21. Hyeon N.M., Park M.S., Kim H.G., Yoo S.J. 2009. Biological Control of Strawberry *Fusarium* Wilt Caused by *Fusarium oxysporum* f. sp. *fragariae* Using *Bacillus velezensis* BS87 and RK1 Formulation. J. Microbiol. Biotechnol. 19(5), 520-524. doi: 10.4014/jmb.0805.333
22. Jiang M., Wang T., Simal-Gandara J., Siddaiah Ch.N. Dai X.F., Chen J.Y.,Wang D., Kong Z.Q. 2023. Overview of the control of plant fungal pathogens by natural products derived from medicinal plants. Plant Protection Science 59 (4), 303-316. https://doi.org/10.17221/17/2023-PPS
23. Kaczmarska E., Dobrowolska A.M., Hortyński J.A. 2008. The influence of pollen viability on seed set and fruit mass in strawberry (*Fragaria x ananassa* Duch.). Acta Agrobotanica 61(1), 79-84.
24. Kapela K., Majchrowska-Safaryan A. 2024. Mechaniczne i biologiczne metody ochrony roślin przed agrofagami w kontekście strategii Europejskiego Zielonego Ładu. Progres in Plant Protection 64(3), 135-144. DOI: 10.14199/ppp-2024-013
25. Katel S., Mandal H.R., Kattel S., Yadav S.P.S., Lamshal B.S. 2022. Impacts of plant growth regulators in strawberry plant: A review. Heliyon 8, e11959, 1-5. https://doi.org/10.1016/j.heliyon.2022.e11959.
26. Khunte S.D., Kumar A., Ansari N., Saravanan S. 2020. Effect of Different Levels of PGRs with Organic Manure on Growth Characters and Economics of Strawberry (*Fragaria x ananassa* Duch.) *cv.* Chandler in Northern region. Int. J. Curr. Microbiol. App. Sci. 9(1), 1633–1638. https://doi.org/10.20546/ijcmas.2020.901.180.
27. Kilic N. 2023. Synergistic Effect of Organic and Biofertilizers on Strawberry Cultivation. Sustainability 15, 8206, 1-11. https://doi.org/10.3390/su15108206.
28. Kowalska J. 2011. Effects of *Trichoderma asperellum* [T1] on *Botrytis cinerea* [Pers.: Fr.], growth and yield of organic strawberry. Acta Sci. Pol., Hortorum Cultus 10(4),107-114.
29. Kowalska J., Remlein-Starosta D., Drożdżyński D. 2012. Wykorzystanie *Trichoderma asperellum* w ekologicznej uprawie truskawek. Progress in Plant Protection 52(2), 351-353.
30. Kowalska J., Remlein-Starosta D. 2013. Zastosowanie efektywnych mikroorganizmów (EM) w uprawie truskawki. Zagadnienia Doradztwa Rolniczego 3, 46-55.

31. Kumra R., Saravanan R.S., Bakshi P., Kumar A., Singh M., Kumar V. 2018. Influence of plant growth regulators on strawberry: A review. International Journal of Chemical Studies 6(1), 1236-1239.
32. Kupczak K. 2013. Odmiany truskawki. Kraków: Wydawnictwo Plantpress Sp. z o.o., str. 4, 5, 14, 19, 21.
33. Kuźniar A., Włodarczyk K., Gromadzka P., Siara A., Wolińska A. 2021. Aktualny stan wiedzy na temat biopreparatów stosowanych w rolnictwie. Lublin: Wydawnictwo KUL, str.1-29. ISBN 978-83 - 8061-964-7.
34. Li X., Zhang M., Qi D., Zhou D., Qi Ch., Li Ch., Liu S., Xiang D., Zhang L., Xie J., Wang W. 2021. Biocontrol Ability and Mechanism of a Broad-Spectrum Antifungal Strain *Bacillus safensis* sp. QN1NO-4 Against Strawberry Anthracnose Caused by *Colletotrichum fragariae*. Frontiers in Microbiology 12:735732, 1-14. doi: 10.3389/fmicb.2021.735732
35. Łabanowska-Bury D. (red.) 2024. Truskawka. Zeszyt uprawowy. Kraków: Wydawnictwo Plantpress Sp. z o.o., str.19-22, 133-134, 143.
36. Masny A., Żurawicz E. 2013. Uprawa truskawek z uwzględnieniem zasad integrowanej ochrony. Kraków: Wydawnictwo Plantpress Sp. z o. o., str. 8.
37. Mikciuk G., Sas-Paszt L., Mikciuk M., Derkowska E., Trzciński P., Głuszek S., Lisek A., Wera-Bryl S., Rudnicka J. 2019. Mycorrhizal frequency, physiological parameters, and yield of strawberry plants inoculated with endomycorrhizal fungi and rizosphere bacteria. Mycorrhiza 29, 489-501. https://doi.org/10.1007/s00572-019-00905-2
38. Miller K., Feucht W., Schmid M. 2019. Bioactive Compounds of Strawberry and Blueberry and Their Potential Health Effects Based on Human Intervention Studies: A Brief Overview. Nutrients 11, 1510, 1-12. doi: 10.3390/nu11071510
39. Mołoń A., Durak R. 2018. Biopestycydy jako stymulatory odporności roślin. Polish Journal for Sustainable Development 22(1), 69-74. DOI: 10.15584/pjsd.2018.22.1.9
40. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Frąc M. 2024a. Microbial Biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation. Sustainability 16, 7559: 1-23. https:// doi.org/ 10.3390/su16177559
41. Nakielska M., Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024b. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112
42. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in an Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571
43. Ons L., Bylemans D., Thevissen K., Cammue B.P.A. 2020. Combining Biocontrol Agents with Chemical Fungicides for Integrated Plant Fungal Disease Control. Microorganisms 8, 1930, 1-19. doi:10.3390/microorganisms81121930
44. Paszko D. 2009. Opłacalność produkcji truskawek deserowych i przemysłowych w Polsce. Zeszyty Naukowe Instytutu Sadownictwa i Kwiaciarstwa im. Szczepana Pieniążka 17, 67-78.
45. Paszko D., Pawlak J., Wróblewska W. 2014. Yield of two strawberry cultivars depending on the cropping method on the example of a commercial plantation in a specialized horticultural farm. Acta Sci. Pol., Hortorum Cultus 13(6), 149–159.
46. Pawlak J., Wróblewska W., Paszko D. 2022. Production and economic efficiency in the cultivation of strawberry (*Fragaria* × *ananassa* Duch.) depending on the method of production - case study. Agronomy Science LXXVII(1), 15–26. https://doi.org/10.24326/as.2022.1.2

47. Piekutowska M. 2017. Potencjał naturalnych preparatów pochodzenia roślinnego dla poprawy zdrowotności i żywotności materiału siewnego roślin rolniczych. Problemy Drobnych Gospodarstw Rolnych, 3, 43-59. DOI: http://dx.doi.org/10.15576/PDGR/2017.3.43
48. Piotrowska A., Góralczyk M., Żebrowska-Krasuska M. 2013. Owoce jagodowe i ich przetwory jako źródła przeciwutleniaczy®. Postępy Techniki Przetwórstwa Spożywczego, 2, 98-103.
49. Popescu I., Loganathan A.K., Graham H.R., Avis T.J. 2024. Antifungal activity of *Bacillus velezensis* and *Pseudomonas azotoformans* isolated from compost tea against anthracnose (*Colletotrichum spp.*) on strawberry fruit. Plant Pathology 73, 2419-2428. DOI: 10.1111/ppa.13983
50. Pukszta T.; Platta A. 2017. Truskawki jako źródło składników bioaktywnych wspomagających profilaktykę chorób nowotworowych. Bromat. Chem. Toksykol. 3, 234-240.
51. Pylak M., Oszust K., Frąc M. 2019. Review report on the role of bioproducts, biopreparations, biostimulants and microbial inoculants in organic production of fruit. Rev. Environ. Sci. Biotechnol. 18, 597–616. https://doi.org/10.1007/s11157-019-09500-5
52. Regulation (EU) 2018/848 of The European Parliament and of the Council of 30 May 2018 on Organic Production and Labelling of Organic Products and Repealing Council Regulation (EC) No 834/2007. OJ L 150, 14 June 2018, p. 1. Dostęp online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02018R0848-20220101 (dostęp na dzień 4 stycznia 2024).
53. Rochalska M., Orzeszko-Rywka A., Czapla K. 2011. Zawartość substancji odżywczych w truskawkach w zależności od systemu uprawy. Journal of Research and Applications in Agricultural Engineering 56(4), 84-86.
54. Sas-Paszt L., Sumorok B., Grzyb Z.S., Głuszek S., Lisek A., Derkowska E., Trzciński P., Stępień W., Przybył M., Frąc M., Górnik K. 2020. Effect of microbiologically enriched fertilizers on the yielding of strawberry plants in container-based cultivation at different levels of irrigation. Journal of Research and Applications in Agricultural Engineering 65(1), 21-29.
55. Sas-Paszt L., Sumorok B., Górnik K., Grzyb Z.S., Lisek A., Głuszek S., Trzciński P., Derkowska E., Frąc M., Treder W., Podlaska B. 2023. Influence of beneficial soil microorganisms and mineral fertilizers enriched with them on the flowering, fruiting, and physical and chemical parameters of the fruit of three-year-old strawberry plants in field cultivation. Horticultural Science (Prague) 50(2), 112-126. https://doi.org/10.17221/90/2021-HORTSCI
56. Sharma K., Negi M. 2019. Effect of organic manures and inorganic fertilizers on plant growth of strawberry (*Fragaria x ananassa*) cv. Shimla delicious under mid-hill conditions of Uttarakhand. Journal of Pharmacognosy and Phytochemistry 8(2), 1440–1444.
57. Skarżyńska A., Abramczuk Ł., Czułkowska M. 2017. Wyniki ekonomiczne produktów rolniczych w 2016 roku. Warszawa: Wydawnictwo IERiGŻ-PIB, str. 112.
58. Stachowiak B., Ratajkiewicz H. 2021. Możliwość wykorzystania szczepów gatunku *Bacillus circulans* w ochronie roślin przed szarą pleśnią i fuzariozą. Zagadnienia Doradztwa Rolniczego 3(105), 30-44. ISSN 1232-3578, e-ISSN 2719-8901.
59. Staniak S. 2014. Charakterystyka żywności produkowanej w warunkach rolnictwa ekologicznego. Polish Journal of Agronomy 19, 25-35.
60. Staniek H., Krejpcio Z. 2013. Ocena zawartości Cd i Pb w wybranych produktach ekologicznych i konwencjonalnych. Probl Hig Epidemiol 94(4), 857-861.
61. Tarigan S.I., Toth Sz., Szalai M., Kiss J., Turoczi G., Toepfer S. 2022. Biological control properities of microbial plant biostimulants. A review. Biocontrol Science and Technology 32, 12, 1351-1371. https://doi.org/10.1080/09583157.2022.2129589

62. Vehapi M., Inan B., Kayacan-Cakmakoglu S., Sagdic O., Özçimen D. 2023. Production of *Bacillus subtilis* soil isolate as biocontrol agent under bioreactor conditions. Archives of Microbiology 205, 52, 1-9. https://doi.org/10.1007/s00203-022-03381-z
63. Wójcik D., Markiewicz M., Matysiak B., Sowik I. 2021. Effect of LED light irradiation on morphology, chlorophyll content and photosynthetic activity of strawberry (*Fragaria x ananassa* Duch.) cuttings. Sci. J. Inst. Hortic. 29, 59-70.
64. Wójciak W., Żuk M., Sowa I., Mazurek B., Tyśkiewicz K., Wójciak M. 2024. Recovery of Bioactive Components from Strawberry Seeds Residues Post Oil Extraction and Their Cosmetic Potential. Applied Sciences 14, 783, 1-11. https://doi.org/10.3390/app14020783
65. Yakhin O.I., Lubyanov A.A., Yakhin I.A., Brown P.H. 2017. Biostimulants in Plant Science: A Global Perspective. Frontiers in Plant Science. 7: 2049, 1-32. doi: 10.3389/fpls.2016.02049
66. Zhang Y., Fan T., Jia W., Zhang W., Liu Q., Li B., Zhang L. 2012. Identification and characterization of a *Bacillus subtilis* strain TS06 as bio-control agent of strawberry replant disease (*Fusarium* and *Verticilum* wilts). African Journal of Biotechnology 11(3), 570-580. DOI: 10.5897/AJB11.1131
67. Zmarlicki K., Brzozowski P. 2013. Porównanie cen hurtowych owoców z produkcji konwencjonalnej i ekologicznej. Stowarzyszenie Ekonomistów Rolnictwa i Agrobiznesu Roczniki Naukowe XV, 2, 386–390.
68. Zydlik P., Zydlik Z. 2016. Sadownicze uprawy ekologiczne w Polsce – dynamika zmian oraz perspektywy rozwoju. Nauka Przyroda Technologie 10, 2, #25, 1-9. DOI: 10.17306/J.NPT.2016.2.25
69. Żekało M. (red.), 2016. Produkcja, koszty i dochody wybranych produktów rolniczych w latach 2014–2015. Warszawa: Wydawnictwo IERiGŻ-PIB, str. 89.

Źródła internetowe:

1. FAOSTAT. Dostęp online: https://www.fao.org/faostat/en/#data/QCL (dostęp na dzień 4 stycznia 2024).
2. EUROSTAT. Organic Crop Area by Agricultural Production Methods and Crops; Organic Crop Production by Crops. Dostęp online: https://ec.europa.eu/eurostat/databrowser/view/ORG_CROPPRO$DEFAULTVIEW/default/table (dostęp na dzień 26 stycznia 2023).
3. https://www.ior.poznan.pl/2240,wykaz-srodkow-ochrony-roslin
4. https://www.iung.pl/wp-content/uploads/2025/02/Wykaz_-ekologia_-17.02.2025.pdf
5. https://www.inhort.pl/files/sor/metodyki_ior/Metodyka_int_ochrony_truskawki_doradcy.pdf
6. https://www.inhort.pl/files/sor/poradniki_sygnalizatora/Poradnik_sygnalizatora_truskawka.pdf

10. Wykaz skrótów:

GUS - Główny Urząd Statystyczny

EUROSTAT- Statistical Office of the European Union (Urząd Statystyczny Unii Europejskiej)

FAOSTAT - Food and Agriculture Organization Statistical Database (Statystyczna Baza Danych Organizacji Narodów Zjednoczonych do spraw Wyżywienia i Rolnictwa)

K1 – obiekt kontrolny

K2 – BacilRoots

K3 – BacilRoots + BacilExtra

K4 – BacilRoots + BacilHumus

K5 – BacilRoots + BacilExtra + BacilHumus

K6 – BacilExtra + BacilHumus

UE - Unia Europejska

11. Streszczenie rozprawy doktorskiej w języku polskim

Wpływ biopreparatów na zdrowotność, wybrane cechy morfologiczne i plonowanie truskawki (*Fragaria x ananassa* Duchesne) uprawianej w systemie ekologicznym

Truskawka to gatunek o dużym znaczeniu gospodarczym szczególnie w Polsce, która należy do czołowych producentów tych owoców w Unii Europejskiej i jest liderem w ich produkcji w systemie ekologicznym. Obowiązujące strategie Unii Europejskiej w zakresie polityki rolnej zmierzają do ograniczenia stosowania chemicznych środków ochrony roślin i syntetycznych nawozów, co sprzyja rozwojowi niechemiczych metod ochrony roślin, w tym opartych na biopreparatach.

Celem podjętych badań była ocena wpływu nowo opracowanych biopreparatów, opartych na pożytecznych mikroorganizmach i wyciągach roślinnych, na wielkość plonu owoców truskawki, występowanie chorób grzybowych (szara pleśń, skórzasta zgnilizna owoców truskawki i antraknoza), cechy biometryczne roślin, jak również opłacalność ekonomiczną stosowania biopreparatów i ich wpływ na zawartość makroelementów i mikroelementów oraz metali ciężkich w owocach.

Badania przeprowadzono w latach 2020-2022 na certyfikowanym polu ekologicznym należącym do Rolniczego Zakładu Doświadczalnego IUNG-PIB w Grabowie nad Wisłą. Doświadczenie z uprawą truskawki o łącznej powierzchni 23a podzielono na dwa obiekty: nawadniany i bez nawadniania. Uwzględniono pięć kombinacji biopreparatów (K2-K6) zawierających szczepy bakterii z rodzaju *Bacillus spp.* oraz ekstrakty roślinne oraz trzy odmiany truskawki (‘Honeoye’, ‘Rumba’ i ‘Vibrant’).

Testowane odmiany truskawki (‘Honeoye’, ‘Vibrant’ i ‘Rumba’) reagowały w różny sposób na zastosowane nowo opracowane biopreparaty, zawierające pożyteczne mikroorganizmy oraz ekstrakty roślinne, zarówno pod względem plonowania, jak i podatności na patogeny grzybowe. Odmiana ‘Honeoye’ najlepiej reagowała na testowane biopreparaty mikrobiologiczne w postaci zwiększenia plonowania. Wykazywała też największą odporność na *Colletotrichum acutatum*, sprawcę antraknozy truskawki. Największy wzrost plonu w sezonie 2021 (średnio o 33%) zaobserwowano po zastosowaniu biopreparatu K4, zawierającego szczepy bakterii: *Bacillus* sp. AF75BC i *Bacillus subtilis* AF75AB2 na nośniku składającym się z suchych kwasów humusowych, gorczycy, oleju rzepakowego i olejku goździkowego w mikronizowanym dolomicie, a także *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, kwasy humusowe oraz odciek po produkcji drożdży w mikronizowanym dolomicie. Skuteczność biopreparatów w ograniczaniu występowania objawów chorób grzybowych owoców truskawki zależała od odmiany oraz warunków pogodowych w danym sezonie wegetacyjnym. W 2020 roku zastosowanie kombinacji preparatów K6 ograniczyło występowanie szarej pleśni (*Botrytis cinerea)* na owocach truskawki. W odmianie ‘Vibrant’ natomiast stwierdzono zmniejszenie porażenia owoców przez patogena wywołującego skórzastą zgniliznę owoców truskawki (*Phytophthora cactorum*), szczególnie po zastosowaniu kombinacji K3. W 2021 roku zaobserwowano zmniejszenie objawów tej choroby po zastosowaniu kombinacji K2, K3 i K6 o 26 - 30% w stosunku do kontroli.

Większość zastosowanych kombinacji biopreparatów (z wyjątkiem K2 w 2021 r.), sprzyjały zwiększeniu liczby koron na roślinach truskawki w porównaniu do kontroli, co wskazuje pośrednio na znaczenie biopreparatów w stymulowaniu wzrostu i rozwoju krzewów.

Na podstawie uzyskanych wyników stwierdzono, że efektywność działania biopreparatów mogła być modyfikowana przez obecność nawadniania. Kombinacja biopreparatów K3 zapewniła korzystne efekty ekonomiczne dla wszystkich badanych odmian w szerokich warunkach uprawy, zarówno na plantacji nawadnianej, jak i bez nawaniania, co wskazuje na jej uniwersalny charakter. Kombinacja biopreparatów K4 przyniosła wysoką efektywność ekonomiczną w uprawie truskawki bez nawadniania, co pozwala rekomendować go do tego typu plantacji.

Zastosowane biopreparaty mikrobiologiczne wpłynęły na skład chemiczny owoców truskawki (zawartość suchej masy oraz azotu, żelaza, manganu, miedzi, cynku, kadmu, ołowiu), a ich działanie było uzależnione od odmiany. Biopreparaty nie wpłynęły natomiast istotnie na zawartość wapnia, magnezu i sodu w owocach truskawki. W żadnej z analizowanych prób nie stwierdzono przekroczenia dopuszczalnych zawartości metali ciężkich. Stwierdzono istotne różnice w zawartości pierwiastków: N, Mn, Na, Mg, Ca, K, P oraz metali ciężkich: Cu, Zn, Pb, Cd w owocach truskawki między odmianami. Odmiana ‘Honeoye’ cechowała się mniejszą zawartością Na, K, P, Mg, Mn, Fe w owocach w porównaniu do pozostałych odmian. Natomiast odmiana ‘Vibrant’ charakteryzowała się wyższą zawartością Mg, Zn, Mn i Pb, Cd, Ca niż pozostałe odmiany. Z kolei w owocach odmiany ‘Rumba’ stwierdzono najniższe poziomy zawartości metali ciężkich: Cu, Zn, Pb oraz wapnia, a jednocześnie najwyższą zawartość N całkowitego, K, P, Na w porównaniu do pozostałych odmian. Nie stwierdzono jednakowej tendencji działania biopreparatów, co świadczy o złożoności interakcji pomiędzy odmianą, biopreparatem a warunkami środowiska.

Wyniki badań wskazują, że stosowanie biopreparatów, zawierających pożyteczne mikroorganizmy i wyciągi roślinne, może korzystnie wpływać na plonowanie oraz efektywność ekonomiczną uprawy truskawki w systemie ekologicznym. Jednak przy doborze preparatu należy uwzględnić zarówno odmianę, jak i warunki prowadzenia plantacji (nawadnianie lub jego brak). Biopreparaty mają potencjał do poprawy jakości owoców w rolnictwie ekologicznym, ale ich stosowanie wymaga indywidualnego dopasowania do warunków uprawy i konkretnej odmiany.

Słowa kluczowe: biopreparaty, rolnictwo ekologiczne, patogeny grzybowe, mikrobiologiczne preparaty nawozowe , makroelementy, mikroelementy, metale ciężkie, efektywność ekonomiczna, wskaźnik opłacalności, truskawka, plon

12. Streszczenie rozprawy doktorskiej w języku angielskim

The Influence of Biopreparations on Plant Health, Selected Morphological Traits, and Yield of Strawberry (*Fragaria x ananassa* Duchesne) Cultivated Under Organic Farming Conditions

Strawberries are a crop of significant economic importance, particularly in Poland, one of the leading producers of this fruit within the European Union and the foremost in organic strawberry production. Current EU agricultural policies aim to reduce the use of chemical plant protection products and synthetic fertilizers, which supports the development of non-chemical crop protection methods, including those based on biopreparations.

The objective of this study was to evaluate the effects of newly developed biopreparations – based on beneficial microorganisms and plant extracts – on strawberry fruit yield, incidence of fungal diseases (gray mold, leather rot, and anthracnose), plant biometric traits, as well as the economic viability of their application and their influence on the content of macro- and micronutrients and heavy metals in the fruit.

The research was conducted between 2020 and 2022 on a certified organic field at the Agricultural Experimental Station of IUNG-PIB in Grabów nad Wisłą. The strawberry trial, covering a total area of 2,300 m^2, was divided into two treatment groups: irrigated and non-irrigated. Five biopreparation combinations (K2-K6) containing strains of *Bacillus spp.* and various plant extracts were applied, and three strawberry cultivars – 'Honeoye', 'Rumba', and 'Vibrant' – were included in the experiment.

The tested cultivars responded differently to the applied biopreparations, both in terms of yield and susceptibility to fungal pathogens. 'Honeoye' showed the most positive response, with a notable increase in yield and the highest resistance to *Colletotrichum acutatum*, the causal agent of anthracnose. The highest yield increase in the 2021 season (on average by 33%) was observed following the application of the K4 formulation, which contained bacterial strains *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on carrier contained dry humic acids, mustard, rapeseed oil and clove oil in micronized dolomite, as well as *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, humic acids and yeast culture filtrate in micronized dolomite.

The effectiveness of the biopreparations in reducing the incidence of fungal disease in strawberry fruit depended on the cultivar and weather conditions during the growing season. In 2020, the K6 preparation combination effectively limited the occurrence of gray mold (*Botrytis cinerea*) on strawberry fruit. In the cultivar 'Vibrant', a reduction in fruit infection caused by the pathogen responsible for leather rot (*Phytophthora cactorum)* was noted, particularly after treatment with the K3 combination. In 2021, a reduction in disease symptoms ranging from 26% to 30% compared to the control was observed after applying combinations K2, K3, and K6.

Most of the biopreparation combinations used (with the exception of K2 in 2021) promoted an increase in the number of crowns per plant compared to the control, indirectly

indicating the stimulatory effect of these preparations on strawberry plant growth and development.

The results suggest that the effectiveness of biopreparations may have been influenced by the presence or absence of irrigation. The K3 combination proved to deliver consistent economic benefits across all tested cultivars and under both irrigated and non-irrigated conditions, highlighting its broad applicability. The K4 combination showed high economic effectiveness specially under non-irrigated conditions, supporting its recommendation for use in such cultivation systems.

The microbial biopreparations applied also influenced the chemical composition of strawberry fruit, including dry matter content and the levels of nitrogen, iron, manganese, copper, zinc, cadmium, and lead. These effects were cultivar-dependent. However, no significant changes were noted in the calcium, magnesium, or sodium content of the fruit. None of the tested samples exceeded permissible levels for heavy metals. Significant differences in the concentration of elements- N, Mn, Na, Mg, Ca, K, P-and heavy metals - Cu, Zn, Pb, Cd - were found among the cultivars. The 'Honeoye' cultivar had lower levels of Na, K, P, Mg, Mn, and Fe in its fruit compared to the others. In contrast, 'Vibrant' showed higher concentrations of Mg, Zn, Mn, Pb, Cd and Ca. Meanwhile, the 'Rumba' cultivar exhibited the lowest levels of heavy metals (Cu, Zn, Pb) and calcium, but the highest content of total nitrogen, K, P, and Na. No uniform pattern in the effects of biopreparations was observed, underscoring the complexity of interactions between cultivar, biopreparation, and environmental conditions.

Overall, the results indicate that the use of biopreparations containing beneficial microorganisms and plant extracts can have a positive impact on yield and economic performance of organic strawberry production. However, the choice of preparation should take into account both the cultivar and cultivation conditions (presence or absence of irrigation). Biopreparations show potential for improving fruit quality in organic farming systems, but their use requires careful adaptation to specific growing conditions and cultivar characteristics.

Keywords: biopreparations, organic farming, fungal pathogens, microbial biofertilizers, macronutrients, micronutrients, heavy metals, economic efficiency, profitability index, strawberry, yield.

13. Kopie publikacji wchodzące w skład rozprawy doktorskiej

1. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Frąc M. 2024. Microbial Biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation. Sustainability 16, 7559, 1-23. https://doi.org/10.3390/su16177559

2. Nakielska M., Berbeć A.K., Madej A., Feledyn-Szewczyk B. 2024. Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars. Horticulturae 10, 1112, 1-17. https://doi.org/10.3390/horticulturae10101112

3. Nakielska M., Feledyn-Szewczyk B., Berbeć A.K., Ukalska-Jaruga A., Frąc M. 2025. The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria x ananassa* Duch.) Fruit Grown in an Organic Farming System. Sustainability 17, 2571, 1-20. https://doi.org/10.3390/su17062571

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Article

Microbial Biopreparations and Their Impact on Organic Strawberry (*Fragaria x ananassa* Duch.) Yields and Fungal Infestation

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Abstract: Growing consumer awareness of the importance of food quality on their health is the main driving force for increasing the market for sustainable agricultural products. This makes sustainable, environmentally friendly production methods into non-chemical plant protection products against pathogens, including microbial biopreparations, increasingly important among farmers. Strawberry fruits (*Fragaria x ananassa* Duch.) are often negatively affected by fungal pathogens. The aim of this study was to evaluate the impact of five combinations of newly developed microbial biopreparations (from K2 to K6) on fungal pathogens and the yield of three strawberry cultivars. The research was conducted on a certified organic strawberry plantation in Poland in 2020–2021. In the first year of the study, no statistically significant positive impact of tested treatments on strawberry yields have been found. At the same time, yields of 'Honeoye' treated with K4 combination showed a tendency (with no statistical significance) to have higher yields than the control object by about 33%. In the second year of the study, yields of 'Honeoye' and 'Rumba' treated with K4 combination (containing *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2, humic acids, yeast culture effluent, micronized dolomite, and mustard and rapeseed oil) significantly increased by 79% and 49%, respectively. Fruit infestation by fungal pathogens was reduced under some microbial treatments; however, the effect varied between years, cultivars, and tested biopreparations. The K2 combination showed a tendency (with no statistical significance) to limit *B. cinerea* infestation rate by 23% in 2020 and 21% in 2021, *C. acutatum* by 16% in 2021, and *P. cactorum* infestation rate by 30% in 2021. Tested microbial biopreparations showed a positive impact on the yield of strawberries and (to some extent) on disease infestation, with an impact on pathogen infestation strongly dependent on the year, variety, and biopreparation tested.

Keywords: microbial pathogens; organic agriculture; plant health; productivity

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1. Introduction

The strawberry (*Fragaria x ananassa* Duch.) is a species that originated about 250 years ago after crossing the *Fragaria chiloensis* L. with *Fragaria virginana* Duch. [1]. It is cultivated mostly in temperate and cool, sometimes in subtropical, climates. It grows best and has the highest yield on fertile soils with regulated water relations, in well-sunned sites [1]. The quality of strawberry fruits is reflected by the presence of health-promoting active substances [2,3]. Flavonols, flavonoids (responsible for fruits' aroma), phenols, ellagic acid, and anthocyanins [4–8] can contribute to the anti-inflammatory [5,9,10], anti-neurodegenerative [5], and anticancer [6,8,10–13] properties of strawberry fruits. The global production of strawberries reached 8.8 million tons in 2020 [14]. Currently, Poland is the second largest producer of strawberries in the EU and is among the top ten producers worldwide [1,14,15]. Globally, nearly 10% of all strawberry plantations are located in

Poland [14]. The high volume of production as well as the crop value makes it one of the most important berry crops in the country [16–18]. In 2021, there were 389.7 thousand hectares of strawberry plantations worldwide, while in Poland, they were grown on 33.9 thousand hectares. Moreover, the importance of strawberries in Poland seems to be increasing, as in 2021, the cultivated area increased year by year by 900 hectares [19]. In 2022, the harvest of strawberries was 185.1 thousand tons. In the same year, the largest cultivation area of strawberries was found in the Mazowieckie voivodeship (15.8 thousand ha), which is the region were the present study has been carried out. The second largest strawberry producer was Lubelskie region (3.8 thousand ha) [20,21]. Lubelskie is one of the regions with the highest yields of strawberries, reaching an average of 8.21 t ha^{-1} in 2020 [22]. According to PIORIN (Table 1) data [23], the most popular certified strawberry cultivars in 2021 included 'Camarosa', 'Nabila', 'Flair', 'Honeoye', and 'Grandarosa'. Moreover, Poland was the largest producer of certified organic strawberries in the European Union in 2020 in terms of both the cultivated area (1048 ha) and production volume of organic strawberries (8013 tons) [24].

Table 1. A list of acronym names used in the text.

Acronym Names	Explanation
EM	Effective microorganisms
GA_3	Gibbelleric acid
K1	Control
K2	Combination with P3 preparation only
K3	Combination of preparations P3 and P1
K4	Combination of preparations P3 and P2
K5	Combination of preparations P3 and P1 and P2
K6	Combination of preparations P1 and P2
n.s.	Non-significant
P1	Preparation containing: *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD, on a carrier consists of plant extracts (nettle, horsetail, calendula), humic acids in liquid formulation in 2020 and in micronized dolomite (Inco S.A.) in 2021,
P2	Preparation containing: *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, humic acids, yeast culture effluent in liquid formulation in 2020 and in micronized dolomite (Inco S.A.) in 2021,
P3	Preparation containing: In 2020: *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2, on a carrier consists of wheat bran, dry humic acids, mustard, rapeseed oil, clove oil in a pellet formulation and on micronized dolomite (Inco S.A.) instead of wheat bran in 2021.
PIORIN	Plant Health and Seed Inspection Service
SD	Standard deviation

The growing ecological awareness of the society, as well as the increasing demands of consumers regarding food quality, are important reasons for the development of sustainable agricultural management strategies, like organic farming system [25,26]. Organic farming is a production system based on few environmentally friendly principles, including the use of diversified crop rotation, the abandonment of the use of synthetic mineral fertilizers, and chemical plant protection products [27]. Biodiversity conservation, protection of the environment, and the prevention of water, soil, and air pollution are also important goals of the organic agriculture [28]. Under this system, the use of natural, technologically unprocessed inputs that create a positive impact on soil fertility and ensure yields of high biological quality is preferred [29]. Preventive measures to reduce the occurrence of diseases, pests, and weeds are also recommended. Certified plant protection products, which are based on the natural substances, are allowed to be used if other means are unsuccessful [30,31]. Organic agriculture is gaining importance as an alternative, sustainable food source due to its ability to improve ecosystem service delivery, reduce environmental pollution, lower carbon footprints, mitigate greenhouse gas emissions, and produce safe food of high quality [32,33]. Studies have shown that organic agriculture is in line with sustainable development principles by providing not only private goods, such as organic food, but also environmental public goods, such as landscape preservation and biodiversity conservation [34]. In 2022, the total number of organic farms in Poland (both in conversion process and certified) was 21,193, and the total area of organic farmlands reached 554,632 hectares [20].

Organic food is gaining importance because of its high nutritional value, which can be beneficial for human health due to higher content of bioactive substances (polyphenols, antioxidants) compared to fruits cultivated on conventional plantations [35–37]. Organic farming principles excludes the use of chemical plant protection products [31], so farmers have to look for new management strategies, including biological preparations (biopreparations), to maintain plantation quality and control pathogen infestations. Biopreparations are products that contain natural microorganisms and/or naturally occurring compounds to support agricultural production. Grzyb et al. [38] defines biopreparations as '*consortia of microorganisms with species composition and activity adapted to carry out a specific process*'. According to Pylak et al. [39], biopreparations may contain plant extracts, polysaccharides, humic substances, and beneficial bacteria and fungi.

Microbial biopreparations can be utilized as a measure to lower the risk of pathogenic bacteria or fungi infection; however, they are not always registered as plant protection products (PPPs). Such products can still have a beneficial impact on plant growth and development and hence lower the risk of the pathogen infestation of plantations [40]. Recently, the use of this type of product in integrated and conventional agriculture has also been increasing due to the restrictions introduced by the EU to the list of authorized active substances of PPPs and the significant increase in the price of mineral fertilizers and chemical plant protection products. This resulted in a greater demand for alternative products [41,42].

According to Pylak et al. [39], in many cases, biopreparations can be at least as effective as commercially available chemical PPPs; however, their effectiveness varies and is highly dependent on environmental factors such as precipitation, soil moisture content, and air humidity. Kosicka et al. [43] states numerous advantages of using biopreparations, such as improvements in the humus-forming capacity, a reduction in decay processes, improvements in the growth and quality of agricultural crops, and an increase in the availability of hard-to-access nutrients for plants and the elimination of pathogens. All this makes microbial preparations highly effective in improving the overall quality of fruits. In the last two decades, numerous scientific articles have been published on strawberry cultivation and pest control, including those concerning the effect of microbial fertilizers on the vegetative growth of strawberry [44,45]; applications of nanofertilizers [46] and nanotechnology in strawberry cultivation [47]; the effects of the composition of the growing medium enriched with biofertilizer on the growth and quality of strawberry plants [48]; the effect of growing media on growth, flowering, and fruit weight of strawberry [49]; the effect of zinc preparations on strawberry biomass [50,51]; and silicon preparations on growth and yield [52]. Moreover, some authors studied the effects of biostimulants [53], biopreparations and biocontrol agents [54–58], protective and stimulating effects of selected microorganisms [59], the nutrient and health-promoting content of strawberry fruits [1,60], and leaf diseases [54,55] in strawberry cultivation. At the same time, relatively few papers deal with organic strawberry cultivation [61–63]. According to Feledyn-Szewczyk et al. [64], one of the most important factors influencing both the quantity and quality of the crop yield in an organic system is the selection of cultivars (crop genotype). This is also the reason why the selection of the best possible genotype has an impact on farmers' agricultural income and food security. The development and testing of new formulations of biopreparations can help farmers to increase the yields and provide consumers with healthy and safe food. The aim of the research was to determine the effect of newly developed biopreparations containing beneficial microorganisms and plant extracts on the yield and health of selected strawberry cultivars grown under the organic farming system conditions. In addition, the authors wanted to investigate whether there is an interaction between biopreparations and cultivars.

While previous studies have evaluated multiple aspects of strawberry cultivation and the use of microbial preparations, there is still a gap in our understanding of how the newly developed microbial biopreparations affect organic strawberry production, particularly in terms of the yield and pathogen infestation of different cultivars. It was hypothesized that the newly developed microbial biopreparations will significantly improve the strawberry yield and reduce pathogen infestation under organic farming conditions, with effects varying among cultivars. This study is unique in that it focuses on organic farming practices, the specific combination of beneficial microorganisms and plant extracts in our biopreparations, and the study of cultivar-specific responses.

2. Materials and Methods

2.1. Characteristics of the Experiment

The field study was conducted at the Institute of Soil Science and Plant Cultivation-State Research Institute in Puławy at the Agricultural Experimental Station in Grabów (51°21′17.1″ N 21°39′14.0″ E) (Poland, Mazowieckie region). The experiment with strawberry cultivation was established in 2019 on a certified organic field with area of 1150 m^2. The experimental factors were (1) combinations of biopreparations with beneficial microorganisms and plant extracts and (2) three strawberry cultivars with different susceptibility to fungal pathogens: 'Honeoye', 'Vibrant', and 'Rumba'. The experiment was set up in a split-block design in 4 replication (3 cultivars × 6 combination of biopreparations × 4 replications, n = 72 plots). The experiment was set up on Luvisols on a gray-brown podzolic soil made of strong loamy sands on light loam. The forecrop for strawberries was red clover (*Trifolium pratense* L.). The experiment was set up in the third decade of May 2019. The experimental area was covered with fleece to reduce weed growth and evaporation, and no irrigation was used in this part of the experiment. Plants were planted at 30 cm × 100 cm spacing at a density of 30,000 plants·ha^{-1}. The area of each single plot of strawberries was 16 m^2 (4 × 4 m) and 48 strawberry plants were planted on it. Certified frigo strawberry seedlings from the professional Agronom Plants horticultural and nursery farm were grown. In addition to the tested biopreparations, fertilizers approved for organic farming were applied before (2018–2019) and during the years of research (2020–2021) (Table 2).

Table 2. Fertilizers and other means of production used on strawberry plantation in organic system.

Trade Name	Manufacturer	Chemical Composition	Application Date	Dose Applied
		2018		
Cattle manure	-	-	19,11,2018	30 t·ha^{-1}
Patentkali®	K+S Polska Sp. z o.o., Poland	Potassium sulphate with magnesium: SO_3 42.5%, K_2O 30% water-soluble potassium	16,11,2018	250 kg·ha^{-1}
Potassium salt	K+S Minerals and Agriculture GmbH, Germany	60% K_2O	16,11,2018	100 kg·ha^{-1}
		2019		
Bioilsa N 12.5	NaturalCrop Poland Sp. z o.o., Poland	12.5% organic nitrogen, 40% organic carbon, SO_3 4.4%, B 100 mg·kg^{-1}, Zn 61 mg·kg^{-1}, Cu 20 mg·kg^{-1}, Mn 18 mg·kg^{-1}, other mineral compounds (P, K, Ca, Mg, Fe)	11,04,2019	150 kg·ha^{-1}

Table 2. *Cont.*

Trade Name	Manufacturer	Chemical Composition	Application Date	Dose Applied
		2020		
Redarom Activstart	Biodevas Laboratoires ZA de l' L'Épine, France,	Aromatic plant extract. Mixture of micronutrients, guaranteed zinc content 0.7%.	29,04,2020	1.5 L·ha^{-1}
Olibio	Biodevas Laboratoires ZA de l' L'Épine, France	Silicon extracts from field horsetail (Equisetum arvense) and nettle (Urtica dioica): B 0.02%, Cu 0.5%, Fe 0.5%, Mn 0.5%, Mo 0.1%	29,04,2020	2.0 L·ha^{-1}
Patentkali®	K+S Polska Sp. z o.o., Poland	Potassium sulphate with magnesium: SO_3 42.5%, K_2O 30% water-soluble potassium	05,08,2020	150 kg·ha^{-1}
Aminosol	AZELIS POLAND Sp. z o. o., Poland	N 9.4%, K_2O 1.1 %, S 0.25%, Na 1.28%, 66.3% organic matter (56–58% aminoacids and peptides)	21,07,2020	2.0 L·ha^{-1}
		2021		
Redarom Activstart	Biodevas Laboratoires ZA de l' L'Épine, France,	Aromatic plant extract. Mixture of micronutrients, guaranteed zinc content 0.7%.	30,04,2021	1.5 L·ha^{-1}
Olibio	Biodevas Laboratoires ZA de l' L'Épine, France	Silicon extracts from field horsetail (Equisetum arvense) and nettle (Urtica dioica): B 0.02%, Cu 0.5%, Fe 0.5%, Mn 0.5%, Mo 0.1%	30,04,2021	2.0 L·ha^{-1}
Aminosol	AZELIS POLAND Sp. z o. o., Poland	N 9.4%, K_2O 1.1%, S 0.25%, Na 1.28%, 66.3% organic matter (56–58% aminoacids and peptides)	07,05,2021	3.0 L·ha^{-1}

Table prepared on the basis of product/fertilizer labels and IUNG-PIB fertilizer search engine.

2.2. Biopreparations

The strawberries were treated with five organic biopreparations containing beneficial microorganisms and plant extracts, established as a result of ECOFRUITS project (BIOSTRATEG3/344433/16/NCBR/2018) (Table 3).

The P3 preparation was applied to the treatments: K2, K3, K4, and K5. Biopreparation P1 was applied in treatments K3, K5, and K6, while biopreparation P2 was used in treatments K4, K5, and K6 by spraying the plants. On the same dates, plants in control objects were sprayed with water (K1) at a rate equivalent to the water used to dissolve the biopreparations. In 2021, the biopreparations were improved compared to 2020 (the carrier was changed from organic (bran) to mineral (dolomite)). In 2020, growing season biopreparations were used twice during the growing season, whereas in 2021, they were used three times to increase the effect. In 2020, the preparations were applied at a rate of 35 kg·ha^{-1} of preparation diluted in 700 L·ha^{-1} of water, whereas in 2021, the preparations were applied at a rate of 50 kg·ha^{-1} of preparation dissolved in 700 L·ha^{-1} of water to improve the effect on plants. On the next development stage of the products, market product will be 10 times more concentrated for ease of use by farmers. The tested products were applied using a tractor sprayer with a Fragaria type boom (spraying both from above and from sides).

Table 3. Composition of biopreparations. Source: Drobek et al., modified [65].

Components	**Biopreparation Combinations Used in the Experiment**					
	K1	**K2**	**K3**	**K4**	**K5**	**K6**
	Control (sprayed with water)					
(P1) *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD, on a carrier consists of plant extracts (nettle, horsetail, calendula), humic acids in liquid formulation in 2020 and in micronized dolomite in 2021.			x		x	x
(P2) *Bacillus* sp. Sp116AC*. *Bacillus* sp. Sp115AD, humic acids, yeast culture effluent in liquid formulation in 2020 and in micronized dolomite in 2021.				x	x	x
(P3) In 2020: *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2, on a carrier consists of wheat bran, dry humic acids, mustard, rapeseed oil, clove oil in a pellet formulation and on micronized dolomite instead of wheat bran in 2021.		x	x	x	x	

The "x" sign indicates the presence of the preparation component.

2.3. Strawberry Fruit Analysis

Strawberry fruits were harvested during the second (2020) and third (2021) seasons of strawberry growth. Fruits were picked up successively every 3–4 days from the marked 8 plants in each plot. The fruits from each plot were counted and weighed. Total yield of strawberries was calculated per plant and per 1 ha.

At each harvest, an assessment of fruit infection by fungal pathogens, such as strawberry fruit leathery rot (*Phytophthora cactorum*), strawberry fruit gray mold (*Botrytis cinerea*), and strawberry anthracnose (*Colletotrichum acutatum*), was carried out. The percentage share of infested fruits in each combination was calculated. The percentage of fruit infected by individual pathogens was determined in each sample. Four train people were assigned to carry out fruit infestation assessment. The training took place directly before 1st season of harvest and 2nd season of harvest (2020 and 2021). No other inter-rater reliability measures have been undertaken.

2.4. Analysis of Biometric Parameters of Strawberry Plants

The assessment of the impact of tested biopreparations on the selected morphological features and biometric parameters of strawberry plants were carried out. This included the determination of the number of crowns developed by strawberry plants and dry weight of aboveground parts of plants. The analyses were conducted postharvest, in the first decade, in July of each year of the study. The measurement was performed on 5 randomly selected plants collected from each of 72 plots tested.

2.5. Meteorological Conditions

Average monthly temperatures in spring (April and May) in both years of the study were close to the multi-year average, while average temperatures for June and July were above the multi-year average (Table 4). Year 2020 was characterized by an uneven distribution of the precipitation. Rainfall in May and June was higher compared to the multi-year average and 2021 season, while April and July 2020 were dry with a precipitation of about 37% and 36.5% of average multiannual precipitation. July 2021 was especially warm, with a mean temperature 4 °C higher than the multi-year average. With the exception of April, the 2021 season was warmer than the 2020.

Table 4. Meteorological conditions at experiment location in 2020–2021 growing seasons.

Month	Average Temperature [°C]			Precipitation [mm]		
	2020	2021	Multi-Annual Average	2020	2021	Multi-Annual Average
April	8.6	6.4	7.5	15.6	51.2	42.0
May	11.3	12.5	12.4	76.5	49.9	53.0
June	18.3	19.5	16.7	157.8	70.1	110.0
July	18.6	21.8	17.8	38.3	61.7	105.0

2.6. Statistical Analysis

The data were analyzed using STATISTICA software (Statistica v.10, Statsoft Inc., Tulsa, OK, USA). In order to compare the influence of biopreparations (n = 6) and cultivars (n = 3) and their interaction effects on strawberry yield and health status, a one-way analysis of variance ANOVA was made. The significance of the mean differences of the study factors was evaluated using a post hoc Fisher's test at a significance level of $\alpha = 0.05$.

In order to check the normality of the distributions, the Shapiro–Wilk test was used. Since the data on pathogen infestation did not meet the requirements for parametric tests, a logarithmic transformation log (x + 0.1) of the data was carried out before the analysis of variance.

For the purpose of this study, no method was used to fill in missing data (there were no missing data for all included parameters).

3. Results and Discussion

3.1. The Influence of Biopreparations on Strawberry Yielding

Among three tested strawberry cultivars in 2020, only 'Honeoye' responded positively by increasing the fruit yield under the K4 combination treatment; the yield was 119.4% higher when compared to the control (Table 5). On average, 'Rumba' yielded significantly higher (504.2 g·plant^{-1}; i.e., 15.2 t·ha^{-1}) than 'Honeoye' (383.2 g·plant^{-1}; i.e., 11.5 t·ha^{-1}) and 'Vibrant' (320.9 g·plant^{-1}; 9.6 t·ha^{-1}). A low level of the 'Vibrant' yield was linked with flower damage by frost in May 2020. 'Vibrant' flowers raised high above the plant resulted in a high risk of direct contact with frost on the surface of the white agro-textile that covered the field to protect it from local spring frost damage. Interestingly, K2 and K3 treatment in the 'Rumba' cultivar resulted in a significant yield loss compared to the control object.

In 2021, the 'Honeoye' and 'Rumba' cultivars yielded significantly higher when treated with the K4 biopreparations (by 79% and 49% higher than the control) (Table 5). Although there was no significant impact, a tendency was visible for the 'Honeoye' cultivar to have higher yields when treated with the K3 and K6 biopreparations. In 2021, the impact of the tested combinations of biopreparations on the strawberry yield of the tested cultivars was positive or, at the worst, neutral (there was no negative impact on the yield for any of the tested treatments). In both years of the study, 'Honeoye' was the cultivar that was under the strongest positive influence of biopreparation, with significant yield increases for the K4 combination in 2021 and a visible tendency for a yield increase (however, not proven statistically) for the other tested treatments.

The results correspond with Kuś et al.'s [66] research, who found that using effective, beneficial microorganisms (EM biopreparations) resulted in an increase in the winter wheat yield in a conventional monoculture, whereas in an organic system, the effect of EM preparations was insignificant. It suggests that biopreparations with beneficial microorganisms work best in difficult, problematic habitats. An organic farming system may have higher initial biodiversity than other farming systems, and thus, the impact of introduced biopreparations might be lower compared to the conventional system. Soltaniband et al. [3], comparing the performance of six biostimulants under conventional cultivation in a high tunnel and greenhouse and in organic greenhouse conditions found that biostimulant use resulted in an increased productivity in the conventional high tunnel, while the highest yields were obtained in the conventional greenhouse after the application of citric acid. The authors hypothesized that the different impacts of biopreparations in 2020 and 2021 may be due to habitat stabilization, as the positive impact of microbial-based biopreparations can build up over time, stabilizing the microbial community. Moreover, the doses of biopreparations and the frequency of usage were increased in 2021 compared with 2020. Similarly, Mikiciuk et al. [67] reported a positive effect of the tested mycorrhizal biopreparations on the strawberry yield and fruit weight.

Table 5. The influence of the tested biopreparations on yields (g·plant^{-1}).

Years and Combinations							
2020							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	240.2 ab (±21.2)	227.30 a (±65.2)	440.2 ab (±79.0)	527.2 b (±184.0)	373.6 ab (±157.6)	419.1 ab (±260.4)	383.2 A (±176.1)
'Rumba'	621.0 b (±0.70)	370.6 a (±108.2)	374.3 a (±58.6)	512.4 ab (±132.4)	599.0 b (±129.1)	606.6 b (±111.1)	504.2 B (±143.0)
'Vibrant'	389.1 ab (±255.2)	216.6 a (±25.2)	341.7 ab (±72.2)	393.0 b (±54.3)	358.5 ab (±134.5)	260.7 ab (±62.4)	320.9 A (±109.7)
average	416.8 ab (±206.3)	271.5 a (±99.5)	385.4 ab (±76.7)	477.5 b (±137.0)	443.7 b (±171.6)	428.8 b (±211.4)	402.8 (±162.5)
2021							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**average**
'Honeoye'	368.9 a (±32.8)	519.3 ab (±56.6)	588.8 ab (±136.1)	660.6 b (±33.8)	496.8 ab (±188.3)	590.6 ab (±148.2)	552.8 A (±135.2)
'Rumba'	443.9 a (±25.8)	578.8 ab (±89.2)	574.9 ab (±77.4)	661.1 b (±119.4)	560.1 ab (±77.7)	602.3 ab (±84.5)	581.7 A (±95.6)
'Vibrant'	663.2 ab (±137.6)	576.2 ab (±83.2)	688.5 b (±49.0)	649.9 ab (±122.7)	622.2 ab (±104.0)	503.5 a (±121.7)	613.1 A (±110.4)
average	492.0 a (±151.1)	558.1 ab (±75.9)	617.4 bc (±100.7)	657.2 c (±91.3)	559.7 ab (±130.9)	565.5 ab (±118.7)	582.5 (±115.8)

Biopreparation × cultivar interaction—n.s. Values marked with different lowercase letters indicate significant differences between combinations. Values marked with uppercase letters indicate significant differences between cultivars. Values in brackets indicated standard deviation (SD).

According to Mohamed et al. [68], the yield of strawberries and its quality depends on nutrient provision, soil fertility, and water availability during the growing season. Hindersah et al. [48] cite growth media compositions among the factors affecting yield, which while influencing seedling quality, also affect the yield. Ahmed et al. [69], in a 3-year study conducted in Bangladesh, obtained yields averaging from 6.88 to 9.59 t·ha^{-1} depending on the fertilization rate when grown in a conventional farming system. Those yields were lower than the results obtained in the present study in organic conditions (average yields of 12.1 t·ha^{-1} in 2020 and 17.3 t·ha^{-1} in 2021), which suggest that the level of crop yields in an organic system can reach or even increase the yield of conventional crops [70]. Mohamed et al. [68] indicated significantly higher yields (65.5 t·ha^{-1}) after the application of 50% mineral N + 100% organic N and the foliar spray of Ca+B in comparison to the control (44 t·ha^{-1}). You et al. [71] obtained a 40% increase in yield as well as a prolongation of fruiting time and an increase in the share of high quality fruits after the application of a fermented biofertilizer containing straw, cattle manure, antagonistic actinomycetes, and solar disinfection.

Yields per plant in 2020 ranged from about 271.5 g per plant (K2) to 477.5 g (K4), while in 2021, they ranged from 492.0 g (control) to 657.2 g (K4) (Table 5). In both years of the study, the highest yields were obtained in the combination with the K4 formulation (477.5 g·plant^{-1} and 657.2 g·plant^{-1} on average for all cultivars). Interestingly, the yield of the control treatment in 2021 was greater than the yield of the best treatments of 2021. This shows the importance of local weather conditions for strawberry productivity. Wójcik-Seliga et al. [18] assessed the production potential of 23 strawberry cultivars and average yields for individual cultivars ranging from 45 g·plant^{-1} for the 'Plahuelfre' cultivar to 580 g·plant^{-1} for the 'Alfa Centauri' cultivar. 'Honeoye' yields were on average 320 g·plant^{-1}. In the present study, 'Honeoye' yielded, on average for all combinations, 383.2 g·plant^{-1} in 2020 and 552.8 g·plant^{-1} in 2021. 'Honeoye' yielded the highest when treated with K4, 660.6 g·plant^{-1} in 2021.

Similar levels of yields were obtained by Sener and Turemis [72], who studied the effect of different types of mulch on the yield of several strawberry cultivars grown under organic farming conditions. The authors observed the highest yields from plants mulched with agro-textile (486.11 g·plant^{-1}), while among the cultivars, 'Monterey' yielded significantly the highest (696.90 g·plant^{-1}).

Kalnina et al. [73] in a field experiment conducted in Latvia obtained 'Rumba' cultivar yields of 245.9 g·plant^{-1} (2010), 710.7 g·plant^{-1} (2011), and 433.0 g·plant^{-1} (2012). In the present experiment with the same cultivar, the average yield for all tested bioformulations was at 504.2 g·plant^{-1} in 2020 and 581.7 g·plant^{-1} in 2021. In contrast, in the experiment described in the same paper [73] conducted in 2015 in Germany in a tunnel where strawberry plants were mulched with black plastic mulch, yields of 249.3 g·plant^{-1} for 'Honeoye' and 208.1 g·plant^{-1} for 'Rumba' were obtained. Those yields were lower than obtained in the present study for both 'Honeoye' and 'Rumba' under organic conditions in both the years of the study (Table 5).

Kilic et al. [74] tested the effect of different fertilizers on strawberries grown under an organic system and reported lower levels of strawberry yields than in the present experiment. The highest yield of 190.61 g·plant^{-1} was obtained after vermicompost application and slightly lower after humic–fulvic acid application (182.92 g·plant^{-1}), while a significantly lower yield was obtained after manure application (95.30 g·plant^{-1}). The authors concluded that the fertilization with vermicompost and humic–fulvic acids in organic strawberry cultivation had a positive effect on yields. Develi et al. [75] recorded that after the application of vermicompost at a rate of 45 g per plant, strawberries yielded 972.8 g, which was 153.2% higher than the control (384.2 g). Filipczak et al. [52] obtained the highest increase in strawberry yielding after the application of silicic acid on plants of the 'Elkat' cultivar (1300 g of fruit per plant—15% more than the control), while the 'Elsanta' cultivar yielded 850 g per plant after the application of calcium silicate (70% more than the control).

In comparison to organic systems, Khunte et al. [12] recorded the highest yields of strawberries in the conventional system—330.18 g·plant^{-1} after the application of poultry manure at 5.50 t·ha^{-1} and triacontanol (150 ppm). Singh et al. [50] found that three applications of 0.2% $FeSO_4$ + 0.3% $ZnSO_4$ at monthly intervals on the strawberry cultivar 'Chandler' resulted in the highest total yield of 236.57 g·plant^{-1}.

Some authors studied the effect of gibberellic acid application on the yield and strawberry fruit quality. Sharma and Singh [76] reported a decrease in the number of deformed fruits and increase in the total yield and marketable yield in relation to the control. Treatment with GA_3 resulted in yields of 529.2 g·plant^{-1}, which was 256% more than yields on the control object. Similarly, Saima et al. [77], who tested the effect of plant bioregulators on strawberry yield traits, noted that the 'Chandler' cultivar yielded the most after the application of GA_3 in an amount of 75mg L^{-1} (356.56 g·plant^{-1}). According to Kosicka et al. [43], biopreparations are less effective and take longer to act on pathogens than pesticides, but unlike pesticides, they do not cause biotic imbalances and improve the humus-forming properties of the soil, resulting in higher crop yields.

3.2. The Influence of Biopreparations on Fungus Infestation of Strawberry Fruits

Strawberry yields, as any crop, are significantly influenced by various pathogens. The impact of a pathogen infestation can cause a major yield loss in strawberry fruits. The primary pathogens affecting strawberry plants include fungi such as *Botritis cinerea*, *Colletotrichum acutatum*, *Phytophtora cactorum*, *Fusarium oxysporum*, and *Verticillium dahliae*, which are known to cause diseases that can reduce yields by as much as 20–80% depending on the pathogen and environmental conditions [78–81]. Most fungal pathogens can accumulate in the soil on plantations where strawberries are grown repeatedly in the same location for a long time, leading to increased disease pressure, reduced plant health, and, in turn, yield and economic losses [82,83]. Plant diseases caused by some fungus species are recognized as one of the most important drivers of yield losses worldwide, including strawberry plantations. Depending on the region, host plant or fungus species, losses range from 8 to as much as 41% [78]. Ziedan [84] reports that crop losses of even up to 50–75% are due to soil-borne pathogenic fungi, such as *Rhizoctonia* spp., *Fusarium* spp., *Verticillum* spp., *Sclerotinia* spp., *Phytium* spp., and *Phytophtora* spp. The most common strawberry pathogens are fungi of the genera: *Botrytis*, *Verticillium*, *Phytophthora*, *Colletotrichum*, *Penicillium*, *Alternaria*, *Cladosporium*, *Rhizopus*, *Aureobasidium*, and *Cryptococcus* [85]. Infections of fruit leading to rotting can occur between flowering and maturity or even at the harvest stage. The use of microorganisms for plant protection requires the disruption of one of the stages of the disease or the life cycle of the pathogen. This mostly means the prevention of infection by the reduction of cell colonization or sporulation and survival of the pathogen. In order to effectively prevent infection by phytopathogenic fungi, the antagonist should be on the surface before the infection occurs [86].

A review of the literature shows that some biopreparations, especially those containing microorganisms, have a potential to improve the health of strawberry plants and fruits [52,87–90]. In the present study, preparations containing *Bacillus* spp., *Paenibacillus* spp. bacterial strains, plant extracts, humic acids, ground mustard, xanthan gum, bran, and vegetable oils were tested to improve the health of strawberry fruits in an organic system.

In the present study, on average for all tested cultivars, there was no positive effect on decreasing significantly the infestation rate of Botritis cinerea, Colletotrichum acutatum, or Phytophthora cactorum in relation to the control treatment. The effectiveness of the tested combinations in relation to each other depended significantly on both used combinations, the tested cultivar, and the year of the experiment. Although the results of the statistical analysis did not show a statistically significant effect on the reduction of disease infestation, some trends were visible on their impact on the reduction of the infestation rate. Some of the tested treatments showed trends (statistically non-significant) of the reduction of the infestation rate often exceeding 30% compared to the control object.

3.2.1. *Botrytis cinerea* (Gray Mold)

Botrytis cinerea, commonly known as gray mold, is one of the most common fungal pathogens of many crops. This pathogen is notorious for causing extensive damage to strawberries, both the plant and the flowers and fruits. It also can damage fruits during postharvest storage, leading to substantial economic losses for producers. Nutrient-rich strawberry fruits, with high moisture content, make strawberries an ideal host for the pathogen [91–94]. The pathogen's high reproduction capabilities are reflected by its ability to produce a large number of conidia. In turn, its genetic variability contributes to its general resilience and capacity to develop resistance to fungicides—which makes effective management an issue [95,96].

In 2020, there was a tendency to reduce the incidence of *Botrytis cinerea* on strawberry fruits by the tested microbiological preparations, especially in combination of K6 (by 29.5% in comparison with the control), but the differences were not significant (Table 6). In 2020, *Botrytis cinerea* remained at a low level, with an average of 3.32% for the experiment. A positive trend in reducing the infestation of fruit by gray mold for the 'Rumba' cultivar after using all combinations of preparations was found. In 2021, there was no clear effect of biopreparations in reducing fruit infestation by *Botrytis cinerea*, with a generally very low pressure of this pathogen at an average of 0.42% for the whole experimental site (Table 6). A positive trend of all tested biopreparations on protection against this pathogen was observed on the 'Honeoye' plantation, but the differences were not significant.

Table 6. The influence of biopreparations on the *Botrytis cinerea* (gray mold) infestation rate (% of fruit infected).

Years and Combinations							
2020							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	1.49 a (±0.98)	2.07 a (±1.34)	4.47 a (±3.75)	2.79 a (±0.60)	3.19 a (±3.11)	1.93 a (±2.21)	2.76 A (±2.33)
'Rumba'	4.85 a (±3.22)	2.80 a (±2.54)	4.49 a (±2.28)	3.38 a (±1.00)	4.03 a (±1.84)	3.58 a (±2.97)	3.77 A (±2.12)
'Vibrant'	4.43 ab (±1.13)	3.48 ab (±1.41)	5.10 b (±3.20)	2.69 ab (±0.82)	3.33 ab (±1.53)	2.08 a (±1.63)	3.44 A (±1.93)
average	3.59 ab (±2.28)	2.78 a (±1.78)	4.69 b (±2.85)	2.96 a (±0.81)	3.52 ab (±2.09)	2.53 a (±2.25)	3.32 (±2.14)
2021							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**average**
'Honeoye'	1.10 ab (±1.55)	0.13 a (±0.15)	0.29 ab (±0.28)	1.06 b (±1.00)	0.17 ab (±0.14)	0.26 ab (±0.32)	0.45 A (±0.67)
'Rumba'	0.12 a (±0.17)	0.50 a (±0.56)	0.20 a (±0.07)	0.15 a (±0.19)	0.30 a (±0.32)	0.31 a (±0.22)	0.28 A (±0.30)
'Vibrant'	0.20 a (±0.28)	0.49 a (±0.56)	0.36 a (±0.59)	0.74 a (±0.69)	0.57 a (±0.93)	0.69 a (±0.86)	0.54 A (±0.65)
average	0.47 a (±0.86)	0.37 a (±0.46)	0.28 a (±0.35)	0.65 a (±0.75)	0.34 a (±0.55)	0.42 a (±0.53)	0.42 (±0.57)

Biopreparation × cultivar interaction—n.s. Values marked with different lowercase letters indicate significant differences between combinations. Values marked with uppercase letters indicate significant differences between cultivars. Values in brackets indicated standard deviation (SD).

Due to the high variability of the results, there were few significant statistical differences in terms of the ability of the tested combinations of biopreparations to reduce the *Botritis cinerea* infestation. At the same time, some of the tested combinations may have the potential to reduce this infestation—which is indicated by the percentage of reduced infestation rate compared to the control object: the *Botritis cinerea* infestation rate was reduced by 29% by the K6 treatment in 2020 (11% in 2021), while in 2021, the use of the K3 combination resulted in a 40% decrease in the infestation rate of *Botritis cinereal* (interestingly, the K3 treatment in 2020 resulted in an increase in the infestation rate of 31%; however, in this year, the infestation of *Botritis cineral* on the whole field was very low, with an average of only 0.42%). The use of the K2 combination resulted in a decreased infestation rate of *Botritis cinerea* of 23% in 2020 and 21% in 2021. This shows how important the weather conditions of a given year are for the development of pathogens and the effectiveness of their control by microbiological agents.

According to Stachowiak and Ratajczyk [78], gray mold can cause up to a 60% loss in the strawberry yield. The authors noticed that the growth of phytopathogens in the presence of cultures and *Bacillus circulans* supernatants added to the nutrient solution was reduced by 53% to almost 90%. This leads to the conclusion that *B. circulans* may prove to be a promising alternative to chemical fungicides [78]. In a study by Kowalska [87], a preparation containing a strain of *Trichoderma asperellum* was tested for the protection of strawberries grown in an organic system and the symptoms of gray mold on the harvested and stored fruits as well as the plants itself were found sporadically. In the second year of the experiment, significantly higher yields were recorded on the objects where the preparation of *T. asperellum* was applied compared to the control object. According to Kowalska [87], biopreparations with *Trichoderma* spp. may be useful to organic processors and producers as an alternative to synthetic protection agents, the use of which is prohibited in certified organic farms.

Laboratory studies on the effect of *Bacillus subtilis* BS-2 and peppermint oil as a biocontrol agent against the pathogen *Botrytis cinerea* showed that supernatants obtained from *Bacillus subtilis* BS-2 inhibited the mycelial growth of *B. cinerea* by up to 57%, while the application of peppermint oil at the highest concentration (4%) reduced mycelial growth by 32% [57]. Biological methods of protection against *Botrytis* sp., such as the use of microorganisms or metabolites as well as plant extracts or essential oils, can be an effective alternative or supplement to conventional disease control methods [57]. In a study by Meszka and Bielenin [88] laminarin, a compound extracted from the brown alga *Laminaria digitata* used to stimulate plant resistance reduced the severity of strawberry gray mold by up to 50 to 80%, depending on the severity of the disease. In a study by Filipczak et al. [52], it was shown that the soil application of silicic acid also inhibited *Botritis cinerea.* The authors concluded that fertilization with silicic acid preparations is economically viable, effective, and safe in strawberry cultivation. The study of Wachowska et al. [89] showed that all of the preparations, Signum 33 WG, Vaxiplant SL, and a solution of cells of the fungus *Aureobasidium pullulans*, reduced the infestation of flowers by *Botrytis cinerea*. The application of Vaxiplant SL also reduced leaf infestation. In contrast, none of the tested preparations significantly reduced the infestation of strawberry fruits and had no effect on the increase in plant yields. On the other hand, Oliveira Filho et al. [90] found that an inhibition of *Botrytis cinerea* on strawberries of up to 100% and 83% after the application of *M. spicata* and *C. martini* essential oils, respectively. Aquilar-Gonzàlez et al. [97], when they tested the antifungal activity of mustard (*Brassica nigra*) and clove (*Syzygium aromaticum*) essential oils against gray mold on strawberry fruits, found that the application of vapors of these oils together or individually inhibited the growth of *B. cinerea* both in vitro and in vivo. At the same time, they found that the combined use of clove and mustard oil produced a synergistic antifungal effect. The combined use of these two oils may be an alternative to synthetic antimicrobials.

3.2.2. *Colletotrichum acutatum* (Anthracnose of Strawberry, Black Spot of Strawberry)

Colletotrichum acutatum can cause anthracnose disease across a cultivar of crops, including strawberries. This pathogen is particularly notorious for its ability to induce severe fruit rot, root necrosis, and crown rot [98–100]. The disease manifests as black spots on leaves and brown, collapsed spots on the fruits, which can severely affect both the yield amount and marketability of fruits [99,101]. Effective management strategies for *C. acutatum* include the use of plant protection products and management practices aimed at reducing humidity and improving air circulation around the plants [102,103].

Anthracnose of strawberries is caused by three fungi of the species *Colletotrichum: C. acutatum* J.H. Simmonds, *C. fragariae* A.N. Brooks, and *C. Gloeosporoides* (Penz.) Penz. and Sacc [101]. It manifests itself by the appearance of brown dry or rot spots on the fruit and by the browning and drying of the flowers and shoots [104,105]. According to Miller-Butler et al. [101], the cultivation of cultivars resistant to anthracnose is a promising way to reduce fungicides on strawberry plantations, especially in organic farming.

Colletotrichum acutatum was, in general, poorly controlled by tested combinations in both years of the study. However, in 2021, the K5 treatment shows a tendency to limit by a 27% infestation rate of *C. acutatum*. However, in 2020, the same combination showed a 20% increase in the infestation rate (average for all tested cultivars). The use of the K4 combination resulted in moderately good results with a 12% increase in the infestation rate (2nd best score of the year) in 2020 and a 16% decrease in the infestation rate of *C. acutatum* in 2021.

In 2020, there were no significant differences in infestation between different combinations (Table 7). In 2020, the least infected cultivar was 'Honeoye' (6.7% of infected fruit), whereas the infestation rate of 'Vibrant' and 'Rumba' was about three times higher than 'Honeoye'. In 2021, 'Vibrant' was the only cultivar to show a trend of reduction in the infestation for all tested combinations in relation to the control. The lowest infection rate was recorded after the K5 treatment; on the 'Vibrant' plantation, a 55.5% lower infection was noted after the K5 application compared to the control. Similarly, on average for all cultivars, formulation K5 was the most effective in reducing anthracnose infection (27.1% lower than in the control).

Table 7. The influence of biopreparations on the *Colletotrichum acutatum* (anthracnose) infestation rate (% of fruit infested).

Years and Combinations							
2020							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	3.0 a (±4.24)	7.7 a (±11.26)	8.0 a (±3.90)	9.4 a (±8.45)	4.8 a (±2.93)	5.4 a (±7.44)	6.7 A (±6.68)
'Rumba'	17.0 ab (±0.01)	26.5 b (±10.83)	18.7 ab (±7.16)	14.2 a (±9.15)	18.9 ab (±3.61)	11.8 a (±3.80)	17.9 B (±8.00)
'Vibrant'	16.2 a (±0.58)	21.4 a (±8.37)	16.0 a (±3.75)	17.2 a (±2.96)	20.0 a (±7.80)	18.6 a (±5.91)	18.4 B (±5.57)
average	12.1 a (±7.29)	18.5 a (±12.42)	14.2 a (±6.67)	13.6 a (±7.48)	14.6 a (±8.64)	11.9 a (±7.74)	14.3 (±8.65)
2021							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**average**
'Honeoye'	7.4 a (±7.12)	9.4 a (±4.17)	5.5 a (±3.66)	4.7 a (±1.83)	4.0 a (±2.10)	9.0 a (±5.50)	6.6 A (±4.13)
'Rumba'	8.0 a (±0.24)	11.7 a (±5.19)	13.0 a (±4.77)	9.1 a (±1.99)	10.0 a (±2.34)	9.8 a (±2.18)	10.5 B (±3.41)
'Vibrant'	10.1 ab (±2.29)	9.7 b (±2.29)	9.7 b (±3.92)	7.4 ab (±2.21)	4.5 a (±1.34)	9.9 b (±4.59)	8.4 AB (±3.38)
average	8.5 abc (±3.57)	10.2 b (±3.83)	9.4 bc (±4.94)	7.1 ac (±2.61)	6.2 a (±3.33)	9.6 bc (±3.93)	8.5 (±3.94)

Biopreparation × cultivar interaction—n.s. Values marked with different lowercase letters indicate significant differences between combinations. Values marked with uppercase letters indicate significant differences between cultivars. Values in brackets indicated standard deviation (SD).

According to Marian et al. [106], anthracnose is considered one of the most important and, unfortunately, also most common diseases of strawberries, causing more than 50% of yield losses in production plantations and even up to 80% of strawberry plant deaths in nurseries. The authors concluded that the *Streptomyces* sp. MBFA-172 isolate has a great potential for use as an alternative or complement to conventional chemical fungicides in the protection of strawberries against anthracnose. The application of the *Streptomyces* sp. MBFA—172 isolates resulted in a significant reduction in the frequency and severity of strawberry anthracnose, and the results obtained were statistically comparable to those obtained after the application of the chemical fungicide Propineb [106]. Alijani et al. [107] reported a positive effect of *Bacillus* spp. bacterial isolates in reducing postharvest fruit anthracnose, with the highest inhibition found for the isolate MarD40 (86% of reduction) and MarD35 (82% of reduction).

3.2.3. *Phytophthora cactorum* (Leather Rot)

Phytophthora cactorum, a fungal-like oomycete pathogen, can infect various parts of the strawberry plant, including roots, crowns, and fruits [108,109]. The disease often manifests rapidly as wilting, stunting, and ultimately plant collapse, particularly in susceptible cultivars [110,111]. The pathogen's adaptability and ability to overcome host defenses complicate management strategies, making an integrated approach—including the utilization of resistant cultivars, effective plant protection, and soil and water management—a key in controlling this pathogen in strawberry cultivation [112,113].

Phytophtora cactorum (Lebert and Cohn) J. Schröt. is one of the most important pathogens in strawberry cultivation [114]. The appearance of this pathogen in the plantation can result in a significant yield and economic losses. Meszka and Michalecka [115] concluded that the *P. cactorum* is the most common accidental infection agent of strawberries in Poland. At temperatures above 20 °C and high humidity, it causes whole-plant rot and significant losses in strawberry fruit yields.

Phytophthora cactorum infestation showed a tendency to be well managed by K3 treatment in both years of the study. The infestation rate was reduced by this treatment by 46% in 2020 and 27% in 2021. Moreover, the K2 combination showed a tendency to limit the *P. cactorum* infestation rate by 30% in 2021 (and to increase the infestation rate by 17% in 2020). In 2020, the most effective combination in reducing *P. cactorum* on strawberry fruits was K3 (Table 8). In 2021, the combination K2, K3, and K6 were found to be highly effective in reducing the infestation of strawberry fruits by *P. cactorum* (by 26–30% on average compared to the control). Although in both years of the study there were no significant differences between combinations of tested biopreparations and control object, generally, the infestation level was low (below 5.5% of infested fruits). The least infested cultivar was 'Honeoye' in 2020 and 'Rumba' in 2021.

Table 8. The influence of biopreparations on the *Phytophthora cactorum* (leather rot) infestation rate (% of fruit infested).

Years and Combinations							
2020							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	1.84 a (±1.03)	2.33 a (±2.64)	0.92 a (±1.21)	2.01 a (±2.07)	1.80 a (±1.84)	1.37 a (±1.38)	1.70 A (±1.69)
'Rumba'	3.70 a (±2.02)	5.38 a (±1.64)	3.07 a (±1.92)	3.46 a (±0.40)	3.09 a (±2.10)	4.11 a (±2.36)	3.81 B (±1.81)
'Vibrant'	4.99 a (±4.07)	4.58 a (±3.41)	1.68 a (±1.38)	2.99 a (±1.58)	2.45 a (±2.96)	4.53 a (±4.85)	3.40 B (±3.03)
average	3.51 ab (±2.52)	4.10 b (±2.76)	1.89 a (±1.67)	2.82 ab (±1.51)	2.45 ab (±2.20)	3.34 ab (±3.25)	2.97 (±2.41)
2021							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**average**
'Honeoye'	3.29 ab (±2.29)	2.05 ab (±0.70)	1.34 a (±1.24)	1.95 ab (±1.18)	3.96 b (±0.90)	2.35 ab (±2.12)	2.42 B (±1.52)
'Rumba'	2.00 a (±0.97)	1.02 a (±0.69)	1.16 a (±1.05)	1.89 a (±2.21)	1.95 a (±1.36)	1.12 a (±1.01)	1.48 A (±1.25)
'Vibrant'	2.83 ab (±0.38)	2.60 a (±0.36)	3.40 ab (±0.55)	4.67 b (±2.32)	2.78 a (±0.49)	2.57 a (±1.15)	3.17 B (±1.29)
average	2.70 a (±1.27)	1.89 a (±0.87)	1.97 a (±1.39)	2.84 a (±2.24)	2.90 a (±1.24)	2.01 a (±1.52)	2.36 (±1.51)

Biopreparation × cultivar interaction—n.s. Values marked with different lowercase letters indicate significant differences between combinations. Values marked with uppercase letters indicate significant differences between cultivars. Values in brackets indicated standard deviation (SD).

The combinations of microbial biopreparations tested in this study included *Bacillus* spp., particularly *Bacillus subtilis*; humic acids; and some other organic compounds (Table 3). All of those were present in the K4 combination, which proved to be one of the most universal combinations among the tested ones. *Bacillus* species are recognized for their plant growth-promoting properties, among them, enhancing the nutrient availability, stimulating root development, and releasing phytohormones (indole-3-acetic acid and gibberellins) [116,117]. These mechanisms can positively impact not only plant flowering but also fruit size and, in turn, the overall yield of strawberries [118,119]. *Bacillus* spp. have been proven to have the potential to control *Botrytis cinerea* and *Phytophthora cactorum*, which are the major threats to strawberry crops. The antimicrobial properties of *Bacillus*, attributed to the production of secondary metabolites and enzymes, help suppress these pathogens, thereby reducing disease incidence and enhancing plant health [120,121]. Humic acids can positively impact strawberries by improving the soil structure, enhancing the nutrient uptake, and stimulating the microbial activity in the rhizosphere [122]. The synergistic effect of *Bacillus* spp. and humic acids can lead to improved resilience against environmental stresses and pathogens to promote the yield quantity and better fruit quality [117].

Other authors have investigated the efficacy of preparations containing *Bacillus strains* on strawberry plant diseases. Pastrana et al.'s [123] study showed that two commercial microbial-based preparations: the Prodygy® (AMC Chemical, Sevilla, Spain) formulation with *Trichoderma asperellum* T18 and the Fusbact® (AMC Chemical, Sevilla, Spain) formulation with two strains of the *Bacillus* (*B. megaterium* and *B. laterosporus*) were found to be effective in controlling strawberry sclerotial rot (charcoal rot). Dipping strawberry roots in the formulation with *T. asperellum* reduced the incidence of crown and root rot caused by *Fusarium solani* by 81% under field conditions and even up to 100% in the greenhouse.

Filipczak et al. [53] concluded that biostimulators can be used as an effective, safe, and economically viable alternative to mineral nitrogen fertilization and plant protection measures against pathogenic microorganisms such as *Salmonella* sp., *Escherichia coli*, and *Listeria monocytogenes*, which pose a direct threat to human health.

3.3. The Influence of Biopreparations on Biometric Parameters of Strawberry Plants

All treatment combinations showed a positive trend to increase the number of crowns per plant compared to the control in both years of the study (with the exception of the K2 treatment in 2021), but due to high variability between replications, this effect was not statistically significant when compared to the control (Table 9).

In the first year of the experiment, the use of all the tested biopreparations resulted in a trend towards the increased dry weight of the aboveground parts of strawberries in relation to the control, but due to high variability between replications, this effect was not statistically significant (Table 10). In the second year, this effect was highly dependent on the cultivar and biopreparation used. This can be important information, as the observed increase in strawberry fruit yields may have been supported by a higher crown number and weight of the aboveground parts of the strawberry.

The present study corresponds with the results of Kowalska [87], which noted that an increased biomass of the plants was recorded after the application of a preparation containing a strain of *Trichoderma asperellum*. Jamiołkowska et al. [124] reported an increase of 11–15% in the number of tomato leaves per plant after root inoculation with mycorrhizal fungi (*Rhizophagus intraradices, Claroideoglomus etunicatum*). The authors found that the treatments applied did not have a significant effect on marketable yields but, by improving plant health, reduced the share (ratio) of infested fruits [124]. In recent years, there has been a growing interest among both scientists and farmers in natural, pro-ecological methods of cultivation and plant protection, with an emphasis on increasing plant resistance to pathogens, pests, and stress conditions caused by unfavorable weather conditions, drought, or frosts. This is due to the growing awareness and demands of consumers to use the best quality products [125–127] with positive impacts on human health [125,126]. It is believed that quality food is supposed to provide consumers with their energy needs, but it is also supposed to provide the necessary macro- and micronutrients and keep consumers healthy without the need for the additional supplementation of essential vitamins and minerals in the form of tablets. Food should also be safe and therefore not contain residues of chemical pesticides or fertilizers used during plant cultivation, which could then negatively affect the health and longevity of consumers. In addition, the increased interest in seeking more natural, often innovative solutions for agriculture and horticulture is linked to the adoption of the European Green Deal strategy by the European Commission, and the consequent introduction of measures in member states aimed at increasing care for the environment and climate as well as increasing the share of organic farming [128]. The list of active substances permitted for use in agriculture has also been reduced, which creates the need to look for new solutions, substances, preparations, and fertilizers that will enable farmers to produce food that is healthy and safe for consumers while at the same time being economically viable [129–131].

Table 9. The effect of biopreparations on the number of crowns developed by strawberry plants.

Years and Combinations							
2020							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	4.5 a (±0.71)	4.5 a (±1.00)	4.8 a (±1.50)	7.5 a (±3.00)	5.8 a (±2.75)	5.3 a (±2.06)	5.5 A (±2.15)
'Rumba'	7.5 a (±3.54)	8.5 a (±4.36)	9.5 a (±6.24)	6.3 a (±2.50)	6.3 a (±1.50)	5.8 a (±2.22)	7.3 B (±3.59)
'Vibrant'	5.0 a (±1.41)	7.8 a (±0.96)	6.5 a (±2.08)	5.3 a (±1.89)	5.8 a (±2.22)	6.5 a (±1.29)	6.2 AB (±1.77)
average	5.7 a (±2.25)	6.9 a (±3.00)	6.9 a (±4.08)	6.3 a (±2.46)	5.9 a (±2.02)	5.8 a (±1.80)	6.3 (±2.69)
2021							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**average**
'Honeoye'	6.5 ab (±2.12)	4.5 a (±2.08)	7.8 ab (±1.71)	9.8 b (±2.63)	6.0 a (±1.83)	6.8 ab (±3.50)	6.9 B (±2.72)
'Rumba'	3.5 a (±0.71)	5.3 a (±2.63)	5.8 a (±2.22)	7.5 a (±3.11)	6.3 a (±1.89)	5.5 a (±1.91)	5.8 AB (±2.30)
'Vibrant'	6.5 a (±2.12)	5.3 a (±1.89)	5.0 a (±3.46)	4.5 a (±0.58)	5.5 a (±1.91)	5.5 a (±2.52)	5.3 A (±2.05)
average	5.5 ab (±2.07)	5.0 a (±2.04)	6.2 ab (±2.62)	7.3 b (±3.11)	5.9 ab (±1.73)	5.9 ab (±2.54)	6.0 (±2.44)

Biopreparation × cultivar interaction—n.s. Values marked with different lowercase letters indicate significant differences between combinations. Values marked with uppercase letters indicate significant differences between cultivars. Values in brackets indicated standard deviation (SD).

Table 10. Effect of biopreparations on dry weight of aboveground parts of plants (g·plant^{-1}).

Years and Combinations							
2020							
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	61.5 a (±13.08)	59.5 a (±14.95)	81.5 a (±43.86)	108.1 a (±59.31)	116.9 a (±86.11)	106.9 a (±49.69)	91.6 A (±52.43)
'Rumba'	113.4 a (±45.32)	115.0 a (±64.96)	118.8 a (±58.65)	105.0 a (±34.16)	133.6 a (±58.14)	146.0 a (±61.24)	122.7 B (±50.85)

Table 10. *Cont.*

'Vibrant'	100.4 a (±22.84)	112.0 a (±40.19)	126.7 a (±51.37)	118.3 a (±30.03)	102.1 a (±42.98)	96.8 a (±27.15)	110.2 AB (±35.38)
average	91.7 a (±33.66)	95.5 a (±48.58)	109.0 a (±51.05)	110.5 a (±39.49)	117.5 a (±60.24)	116.6 a (±48.86)	108.2 (±47.90)
				2021			
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**average**
'Honeoye'	35.5 a (±14.59)	31.6 a (±12.03)	44.9 a (±15.77)	48.1 a (±12.16)	31.5 a (±6.05)	35.5 a (±10.16)	38.1 B (±12.40)
'Rumba'	34.1 ab (±11.42)	51.1 b (±23.52)	32.4 ab (±10.57)	47.8 b (±2.09)	33.6 ab (±12.95)	26.5 a (±10.09)	37.9 B (±15.10)
'Vibrant'	38.5 a (±23.20)	22.0 a (±8.44)	26.1 a (±11.64)	23.6 a (±3.62)	27.5 a (±7.62)	22.3 a (±3.84)	25.6 A (±9.46)
average	36.0 ab (±13.43)	34.9 ab (±19.23)	34.5 ab (±14.22)	39.8 b (±13.74)	30.9 ab (±8.85)	28.1 a (±9.64)	33.8 (±13.67)

Biopreparation × cultivar interaction—n.s. Values marked with different lowercase letters indicate significant differences between combinations. Values marked with uppercase letters indicate significant differences between cultivars. Values in brackets indicated standard deviation (SD).

4. Conclusions

The cultivars of strawberries reacted differently to the tested biopreparations in terms of the yield and infestation rate. The largest significant increase in the strawberry fruit yield was obtained in 2021 with the combination of K4 containing *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2, liquid and dry humic acids, yeast culture effluent, micronized dolomite, mustard, and rapeseed oil (33% higher yield compared to the control). Yields of the 'Honeoye' cultivar were showing the increase when treated with microbial biopreparations. 'Honeoye' was also the most resistant to *Colletotrichum acutatum* (anthracnose) in both years of the study. With the exception of the K2 and K3 treatments in 'Rumba' in 2020, none of the tested bioformulations caused a significant decrease in strawberry yields. In 2020, all biopreparation combinations reduced infestation by the fruit leathery rot pathogen of the 'Vibrant' cultivar in relation to the control, with the K3 combination being the most effective. All treatment combinations showed a positive trend to increase the number of crowns per plant compared to the control in both years of the study, with the exception of the K2 treatment in 2021. The research on microbial organic biopreparations needs to be continued in subsequent years in order to select the combination of preparations with the most beneficial effect on plant health and yields to support sustainable food production. Future studies should be carried out with more years included and with verification of how microbial preparations affect the diversity of microorganisms in the soil, especially in the root zone of plants.

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Conflicts of Interest: The authors declare the following financial interests/personal relationships, which may be considered potential competing interests: Magdalena Frac reports that financial support was provided by National Science Centre Poland. Magdalena Frąc and Beata Feledyn-Szewczyk have patents: (1) Method for obtaining a bacterial biopreparation and a bacterial biopreparation for maintenance and/or improving soil microbial biodiversity while controlling pathogens: *Botrytis* sp., *Colletotrichum* sp., *Phytophthora* sp., *Verticillium* sp. in soft fruit cultivation (in Polish), P.445051; (2) Method for obtaining a microbial fertilizing product and a microbial fertilizing product for conditioning seedlings, maintaining and/or improving the microbiological quality of the soil, while allowing for the control of phytopathogens in the cultivation of soft fruit (in Polish), P.445052; (3) A method of obtaining a microbiological fertilizing product and a microbiological fertilizing product for maintaining and/or improving the microbiological quality of the soil, allowing at the same time to control the phytopathogens *Botrytis* sp., *Colletotrichum* sp., *Phytophthora* sp., *Verticillium* sp. in the cultivation of soft fruit (in Polish), P.445053; (4) Method for obtaining a microbial fertilizing product and a microbial fertilizing product for soil conditioning and improving its biological properties while controlling *pathogens Botrytis* sp., *Colletotrichum* sp., *Phytophthora* sp., *Verticillium* sp. in soft fruit cultivation (in Polish), P.445054. All four patents are pending with the Institute of Agrophysics Polish Academy of Sciences in Lublin and Institute of Soil Science and Plant Cultivation-State Research Institute in Puławy, Poland.

Patents: Magdalena Frac and Beata Feledyn-Szewczyk have patents: (1) Method for obtaining a bacterial biopreparation and a bacterial biopreparation for maintenance and/or improving soil microbial biodiversity while controlling pathogens: *Botrytis* sp., *Colletotrichum* sp., *Phytophthora* sp., *Verticillium* sp. in soft fruit cultivation (in Polish), P.445051; (2) Method for obtaining a microbial fertilizing product and a microbial fertilizing product for conditioning seedlings, maintaining and/or improving the microbiological quality of the soil, while allowing for the control of phytopathogens in the cultivation of soft fruit (in Polish), P.445052; (3) A method of obtaining a microbiological fertilizing product and a microbiological fertilizing product for maintaining and/or improving the microbiological quality of the soil, allowing at the same time to control the phytopathogens *Botrytis* sp., *Colletotrichum* sp., *Phytophthora* sp., *Verticillium* sp. in the cultivation of soft fruit (in Polish), P.445053; (4) Method for obtaining a microbial fertilizing product and a microbial fertilizing product for soil conditioning and improving its biological properties while controlling pathogens *Botrytis* sp., *Colletotrichum* sp., *Phytophthora* sp., *Verticillium* sp. in soft fruit cultivation (in Polish), P.445054. All four patents are pending with the Institute of Agrophysics Polish Academy of Sciences in Lublin and Institute of Soil Science and Plant Cultivation-State Research Institute in Puławy, Poland.

References

1. Rochalska, M.; Orzeszko-Rywka, A.; Czapla, K. The content of nutritive substances in strawberries according to cropping system. *J. Res. Appl. Agric. Eng.* **2011**, *56*, 84–86.
2. Kim, S.K.; Kim, D.S.; Kim, D.Y.; Chun, C. Variation of bioactive compounds content of 14 oriental strawberry cultivars. *Food Chem.* **2015**, *184*, 196–202. [CrossRef] [PubMed]
3. Soltaniband, V.; Brégard, A.; Gaudreau, L.; Dorais, M. Biostimulants Promote Plant Development, Crop Productivity, and Fruit Quality of Protected Strawberries. *Agronomy* **2022**, *12*, 1684. [CrossRef]
4. Avetisyan, A.; Hokhanyan, M.; Herdt, K.; Lund, L.; Hykkerud, A.L.; Jaakola, L.; Martinussen, I. Effect of organic fertilizer on growth of strawberry cultivar Sonata. In Proceedings of the ISHS Acta Horticulturae 1309: IX International Strawberry Symposium, Rimini, Italy, 1–5 May 2021; p. 1309. [CrossRef]
5. Katel, S.; Mandal, H.R.; Kattel, S.; Yadav, S.P.S.; Lamshal, B.S. Impact of plant growth regulators in strawberry plant: A review. *Heliyon* **2022**, *8*, e11959. [CrossRef] [PubMed]
6. Khunte, S.D.; Kumar, A.; Ansari, N.; Saravanan, S. Effect of Different Levels of PGRs with Organic Manure on Growth Characters and Economics of Strawberry (*Fragaria x ananassa* Duch.) *cv.* Chandler in Northern region. *Int. J. Curr. Microbiol. Appl. Sci.* **2020**, *9*, 1633–1638. [CrossRef]
7. Kumra, R.; Saravanan, S.; Bakshi, P.; Kumar, A.; Singh, M.; Kumar, V. Influence of plant growth regulators on strawberry: A review. *Int. J. Chem. Stud.* **2018**, *6*, 1236–1239.
8. Sudha, G.; Saravanan, S.; Subash Chandra Bose, B. Effect of micronutrients on quality and shelf-life of strawberry (*Fragaria x ananasa Duch.*) cv. Chandler. *J. Pharmacogn. Phytochem.* **2018**, *7*, 2239–2241.

9. Giamperi, F.; Tulipani, S.; Alvarez-Suarez, J.M.; Quiles, J.L.; Mezzetti, B.; Battino, M. Review The strawberry: Compositon, nutritional quality, and impact on human helth. *Nutrition* **2012**, *28*, 9–19. [CrossRef] [PubMed]
10. Janurianti, N.M.D.; Utama, I.M.S.; Gunam, I.B.W. Colour and Quality of Strawberry Fruit (*Fragaria x ananasa* Duch.) at Different Levels of Maturity. *Sustain. Environ. Agric. Sci. (SEAS)* **2021**, *5*, 22–28. [CrossRef]
11. Singh, B.K.; Pal, A.K.; Verma, A.; Singh, A.K.; Yadav, K.S.; Tiwari, A. Impact of Integrated Nutrient Management on Physico-Chemical Attributes in Strawberry (*Fragaria x ananassa* Duch.) cv Chandler. *Environ. Ecol.* **2017**, *35*, 363–367.
12. Khunte, S.D.; Kumar, A.; Ansari, N.; Saravanan, S. Influence of PGRs and Poultry Manure on Physico-Chemical Parameters of Strawberry (*Fragaria x ananassa* Duch.) cv. Chandler. *Int. J. Curr. Microbiol. Appl. Sci.* **2019**, *8*, 108–117. [CrossRef]
13. Gamba-Santos, J.; Vasco, M.F.; Campañnone, L. Diffusional analysis and textural properities of coated strawberries during osmotic dehydration treatment. *J. Berry Res.* **2021**, *11*, 151–169. [CrossRef]
14. Wójcik, D.; Markiewicz, M.; Matysiak, B.; Sowik, I. effect of LED light irradiation on morphology, chlorophyll content and photosynthetic activity of strawberry (*Fragaria x ananasa* Duch.) cuttings. *Sci. J. Inst. Hortic.* **2021**, *29*, 59–70.
15. Kaczmarska, E.; Dobrowolska, A.M.; Hortyński, J.A. The influence of pollen viability on seed set and fruit mass in strawberry (*Fragaria x ananassa* Duch). *Acta Agrobot.* **2008**, *61*, 79–84. [CrossRef]
16. Kalisz, S.; Marszałek, K.; Mitek, M. Research into the impact of high methoxyl pectin preparations on qualitative parameters of strawberry nectars. *Food Sci. Technol. Qual.* **2009**, *6*, 129–139.
17. Dziadczyk, E.; Domaciuk, M.; Nowak, M.; Szczuka, E.; Bednara, J. The development of the female gametophyte in *Fragaria x ananasa* Duch. cv. Selva. *Acta Biol. Cracoviensia Ser. Bot.* **2011**, *53*, 104–112. [CrossRef]
18. Wójcik- Seliga, J.; Studnicki, M.; Wójcik-Gront, E. Evaluating economic value of 23 strawberry cultivars in the climatic conditions of central Europe. *Acta Sci. Pol. Hortorum Cultus* **2017**, *16*, 11–19.
19. FAOSTAT. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 4 January 2024).
20. GUS. *Statistical Yearbook of Agriculture*; Statistics Poland: Warsaw, Poland, 2023.
21. GUS. *Production of Agriculutral and Horitcultural Crops in 2023*; Statistics Poland: Warsaw, Poland, 2024.
22. GUS. *Production of Agricultural and Horticultural Crops in 2020*; Statistics Poland: Warsaw, Poland, 2021.
23. Dobry Start dla Produkcji Sadowniczej. Available online: http://piorin.gov.pl/gi-aktualnosci/dobry-start-dla-produkcji-sadowniczej,574.html (accessed on 20 July 2024).
24. EUROSTAT. Organic Crop Area by Agricutural Production Methods and Crops; Organic Crop Production by Crops. Available online: https://ec.europa.eu/eurostat/databrowser/view/ORG_CROPPRO$DEFAULTVIEW/default/table (accessed on 26 January 2023).
25. Staniek, H.; Krejpcio, Z. Evaluation of Cd and Pb content in selected organic and conventional products. *Probl. Hig. Epidemiol.* **2013**, *94*, 857–861.
26. Zydlik, P.; Zydlik, Z. Horticultural ecological crops in Poland—The dynamics of changes and perspectives for development. *Nauka Przyr. Technol.* **2016**, *10*, 25. [CrossRef]
27. Feledyn-Szewczyk, B.; Nakielska, M.; Jończyk, K.; Berbeć, A.K.; Kopiński, J. Assessment of the Suitability of 10 Winter Triticale Cultivars (x *Triticosecale* Wittm. ex A. Camus) for Organic Agriculture: Polish Case Study. *Agronomy* **2020**, *10*, 1144. [CrossRef]
28. Nachtman, G. Organic farming in Poland and activities undertaken for its development. *Pol. Stat.* **2021**, *66*, 24–43. [CrossRef]
29. Staniak, S. Characteristics of food produced in organic farming. *Pol. J. Agron.* **2014**, *19*, 25–35. [CrossRef]
30. Szymona, J. Problem of chemical plant protection products' residues in organic raw material. *J. Res. Appl. Agric. Eng.* **2010**, *55*, 146–149.
31. Regulation (EU) 2018/848 of The European Parliament and of the Council of 30 May 2018 on Organic Production and Labelling of Organic Products and Repealing Council Regulation (EC) No 834/2007. OJ L 150, 14 June 2018, p. 1. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02018R0848-20220101 (accessed on 4 January 2024).
32. Ondrasek, G.; Horvatinec, J.; Kovačić, M.B.; Reljić, M.; Vinceković, M.; Rathod, S.; Bandumula, N.; Dharavath, R.; Rashid, M.I.; Panfilova, O.; et al. Land Resources in Organic Agriculture: Trends and Challenges in the Twenty-First Century from Global to Croatian Contexts. *Agronomy* **2023**, *13*, 1544. [CrossRef]
33. Akanmu, A.O.; Olowe, O.M.; Phiri, A.T.; Nirere, D.; Odebode, A.J.; Karemera Umuhoza, N.J.; Asemoloye, M.D.; Babalola, O.O. Bioresources in Organic Farming: Implications for Sustainable Agricultural Systems. *Horticulturae* **2023**, *9*, 659. [CrossRef]
34. Łuczka, W.; Kalinowski, S.; Shmygol, N. Organic Farming Support Policy in a Sustainable Development Context: A Polish Case Study. *Energies* **2021**, *14*, 4208. [CrossRef]
35. Carbonaro, M.; Mattera, M.; Nicoli, S.; Bergamo, P.; Cappelloni, M. Modulation of antioxidant compounds in organic vs conventional fruit (peach, *Prunus persica* L., and pear, *Pyrus communis* L.). *J. Agric. Food Chem.* **2002**, *50*, 5458–5462. [CrossRef]
36. Lester, G.E.; Manthey, J.A.; Buslig, B.S. Organic vs conventionally grown rio red whole grapefruit and juice: Comparison of production inputs, market quality, consumer acceptance, and human health-bioactive compounds. *J. Agric. Food Chem.* **2007**, *55*, 4474–4480. [CrossRef] [PubMed]
37. Duarte, A.M.; Caixeirinho, D.; Miguel, M.G.; Sustelo, V.; Nunes, C.; Fernandes, M.M.; Marreiros, A. Organic Acids Concentration In Citrus Juice From Conventional *versus* Organic Farming. *Acta Hortic.* **2012**, *933*, 601–606. [CrossRef]
38. Grzyb, A.; Waraczewska, Z.; Niewiadomska, A.; Wolna-Marówka, A. What are biopreparations and what is their use. *Nauka Przyr. Technol.* **2019**, *13*, 65–76.

39. Pylak, M.; Oszust, K.; Frąc, M. Review report on the role of bioproducts, biopreparations, biostimulants and microbial inoculants in organic production of fruit. *Rev. Environ. Sci. Biotechnol.* **2019**, *18*, 597–616. [CrossRef]
40. Derkowska, E.; Sas Paszt, L.; Harbuzov, A.; Sumorok, B. Root Growth, Mycorrhizal Frequency and Soil Microorganisms in Strawberry as Affected by Biopreparations. *Adv. Microbiol.* **2015**, *5*, 65–73. [CrossRef]
41. Aisakulova, K. Organic fertilizer's role in the improvement of soil microflora and biometric values in fruit crops. *Sabrao J. Breed. Genet.* **2023**, *55*, 1719–1728. [CrossRef]
42. Krutiakova, V. Biological method as the basis of sustainable development of domestic agriculture. *Visnyk Agrar. Nauk.* **2020**, *98*, 5–14. [CrossRef]
43. Kosicka, D.; Wolna-Marówka, A.; Trzeciak, M. The influences of microbial inoculates on morphological traits in plants). *KOSMOS Probl. Biol. Sci. Pol. Copernic. Soc. Nat.* **2015**, *64*, 327–335.
44. Sas-Paszt, L.; Sumorok, B.; Derkowska, E.; Trzciński, P.; Lisek, A.; Grzyb, Z.S.; Sitarek, M.; Przybył, M.; Frąc, M. Effect of microbiologically enriched fertilizers on the vegetative growth of strawberry plants under field conditions in the first year of plantation. *J. Res. Appl. Agric. Eng.* **2019**, *64*, 29–37.
45. Sas-Paszt, L.; Sumorok, B.; Derkowska, E.; Trzciński, P.; Lisek, A.; Grzyb, Z.S.; Sitarek, M.; Przybył, M.; Frąc, M. Effect of microbiologically enriched fertilizers on the vegetative growth of strawberry plants in container-based cultivation at different levels of irrigation. *J. Res. Appl. Agric. Eng.* **2019**, *64*, 38–46.
46. El-Bialy, S.M.; El-Mahrouk, M.E.; Elesawy, T.; El-Dein Omara, A.; Elbehiry, F.; El-Ramady, H.; Aron, B.; Prokisch, J.; Brevik, E.C.; Solberg, S.Ø. Biological Nanofertilizers to Enhance Growth Potential of Strawberry Seedlings by Boosting Photosynthetic Pigments, Plant Enzymatic Antioxidants, and Nutritional Status. *Plants* **2023**, *12*, 276. [CrossRef]
47. Bayat, M.; Pakina, E.; Astarkhanova, T.; Sediqi, A.N.; Zargar, M.; Vvedenskiy, V. Review on agro-nanotechnology for ameliorating strawberry cultivation. *Res. Crops* **2019**, *20*, 731–736. [CrossRef]
48. Hindersach, R.; Purba, P.S.J.; Cahyaningrum, D.N.; Nurbaity, A.; Kamaluddin, N.N.; Akutsu, M. Evaluation of Strawberry Seedling Growth in Various Planting Media Amended with Biofertilizer. First Asian PGPR Indonesian Chapter International e-Conference 2021. *KnE Life Sci.* **2022**, 358–367. [CrossRef]
49. Tarafdar, M.; Mishra, S.; Singh, R.K.; Kumar, A.; Ekka, S.K. Effect on Vegetative Growth and Development of Strawberry (*Fragaria ananassa*) in Potting Mixture System under Shade Net Conditions cv. Winter Dawn. *Int. J. Environ. Clim. Chang.* **2023**, *13*, 799–808. [CrossRef]
50. Singh, M.; Jamwal, M.; Sharma, N.; Kumar, R.; Wali, V.K. Response of iron and zinc on vegetative and reproductive growth of strawberry (*Fragaria x ananassa* Duch.) cv Chandler. *Bangladesh J. Bot.* **2015**, *44*, 337–340. [CrossRef]
51. Kopeć, M.; Gondek, K.; Mierzwa-Hersztek, M.; Zaleski, T.; Bogdał, S.; Bienisz, M.; Błaszczyk, J.; Kaczmarczyk, E.; Knaga, J.; Łapczyńska-Kordon, B.; et al. The effect of stimulating biomass growth of everbearing strawberry cultivar San Andreas® by the foliage application of a product containing zinc. *Prog. Plant Prot.* **2019**, *59*, 126–132. [CrossRef]
52. Filipczak, J.; Sas-Paszt, L.; Sitarek, M. The influence of silica preparations on growth and yielding of strawberry plants. *Sci. J. Inst. Hortic.* **2019**, *27*, 17–24.
53. Filipczak, J.; Żurawicz, E.; Sas Paszt, L. Influence of selected biostimulants on the growth and yielding of 'Elkat' strawberry plants. *Sci. J. Inst. Hortic.* **2016**, *24*, 43–58.
54. Pertot, I.; Zasso, R.; Amsalem, L.; Baldessari, M.; Angeli, G.; Eldad, Y. Use of biocontrol agents against powdery mildew in integrated strategies for reducing pesticide residues on strawberry: Evaluation of efficacy and side effects. *IOBC/WPRS Bull.* **2004**, *27*, 109–113.
55. Pertot, I.; Zasso, R.; Amsalem, L.; Baldessari, M.; Angeli, G.; Elad, Y. Integrating biocontrol agents in strawberry powdery mildew control strategies in high tunnel growing systems. *Crop Prot.* **2008**, *27*, 622–631. [CrossRef]
56. Mariańska-Cichoń, B.; Sapiecha-Waszkiewicz, A.; Miętkowski, R. Effectiveness of biofungicydes Bioczos S and Poliversum used to soak strawberry cuttings in verticillum wilt disease control. *J. Plant Prot. Res.* **2009**, *49*, 395–398. [CrossRef]
57. Grata, K.; Rombel-Bryzek, A.; Ziembik, Z. *Bacillus subtilis* BS-2 and pepermint oil as biocontrol agents against *Botrytis cinerea*. *Ecol. Chem. Eng. S* **2019**, *26*, 597–607. [CrossRef]
58. Demir, S.; Durak, E.D.; Güneş, H.; Boyno, G.; Mulet, J.M.; Denesh, Y.R.; and Porcel, R. Biological Control of Three Fungal Diseases in Strawberry (*Fragaria x ananassa*) with Arbuscular Mycorrhizal Fungi. *Agronomy* **2023**, *13*, 2439. [CrossRef]
59. Trzciński, P.; Frąc, M.; Lisek, A.; Przybył, M.; Frąc, M.; Sas-Paszt, L. Growth promotion of raspberry and strawberry plants by bacterial inoculants. *Acta Sci. Pol. Hortorum Cultus* **2021**, *20*, 71–82. [CrossRef]
60. Kowalska, J.; Kowalska, H.; Marzec, A.; Brzeziński, T.; Samborska, K.; Lenart, A. Dried strawberries as a high nutritional value fruit snack. *Food Sci. Biotechnol.* **2018**, *27*, 799–807. [CrossRef] [PubMed]
61. Daugaard, H.; Lindhard, H. Strawberry Cultivars for organic production. *Gartenbauwissenschalft* **2000**, *65*, 213–217.
62. Weissinger, H.; Spornberger, A.; Steffek, R.; Jezik, K.; Stich, K. Evaluation of New Strawberry Cultivars for their Potential Use in Organic Farming and *Verticillum-infested* Soils. *Eur. J. Hort. Sci.* **2009**, *74*, 30–34.
63. Şener, S.; Türemiş, N.F. Effect of Genotype and Fertilization on Fruit Quality in Several Harvesting Periods of Organic Strawberry Plantation. *Int. J. Agric. Innov. Res.* **2016**, *5*, 252–256.
64. Feledyn-Szewczyk, B.; Cacak-Pietrzak, G.; Lenc, L.; Stalenga, J. Rating of Spring Weat Cultivars (*Triticum aestivum* L.) According to Their Suitability for Organic Agriculture. *Agronomy* **2020**, *10*, 1900. [CrossRef]

65. Drobek, M.; Cybulska, J.; Frąc, M.; Pieczywek, P.; Pertile, G.; Chibrikov, V.; Nosalewicz, A.; Feledyn-Szewczyk, B.; Sas-Paszt, L.; Zdunek, A. Microbial biostimulants affect the development of pathogenic microorganisms and the quality of fresh strawberries (*Fragaria ananassa* Duch.). *Sci. Hortic.* **2024**, *327*, 112793. [CrossRef]
66. Kuś, J. *Wpływ Preparatów Biologicznych (ProBioEmów) na Plonowanie Pszenicy Ozimej i Jarej oraz Ziemniaków w Uprawie Ekologicznej i Konwencjonalnej. pp. 275–286. W: Wyniki Badań z Zakresu Rolnictwa Ekologicznego Realizowanych w 2012 Roku*; Ministerstwo Rolnictwa i Rozwoju Wsi: Warszawa, Poland, 2013; ISBN 978-83-62416-51-6. (In Polish)
67. Mikiciuk, G.; Sas-Paszt, L.; Mikiciuk, M.; Derkowska, E.; Trzciński, P.; Głuszek, S.; Lisek, A.; Wera-Bryl, S.; Rudnicka, J. Mycorrhizal frequency, physiological parameters, and yield of strawberry plants inoculated with endomycorrhizal fungi and rizosphere bacteria. *Mycorrhiza* **2019**, *29*, 489–501. [CrossRef]
68. Mohamed, M.H.M.; Petropolus, S.A.; Ali, M.M.E. The Application of Nitrogen Fertilization and Foliar Spraying with Calcium and Boron Affects Growth Aspects, Chemical Composition, Productivity and Fruit Quality of Strawberry Plants. *Horticulturae* **2021**, *7*, 257. [CrossRef]
69. Ahmed, R.; Karim, M.R.; Quddus, M.A.; Ahmed, S.; Siddiky, M.A. Response of strawberry to NPKS on yield in terrace soil. *Bangladesh J. Agril. Res.* **2018**, *43*, 89–97. [CrossRef]
70. Feledyn-Szewczyk, B.; Jończyk, K.; Stalenga, J. The Effect of Crop Production Systems and Cultivars on Spring Wheat (*Triticum aestivum* L.) Yield in a Long-Term Experiment. *Agriculture* **2024**, *14*, 625. [CrossRef]
71. You, Z.J.; Xing, Y.; Guan, W.; Ma, H.P.; Liu, Z.M. Evaluation of the soil ecological measure for overcoming replant disorder of strawberry. *Eur. J. Hort. Sci.* **2015**, *80*, 128–133. [CrossRef]
72. Şener, S.; Türemiş, N.F. Influence of Mulch Types on Yield and Quality of Organically Grown Strawberry Cultivars. *Süleyman Demirel Üniversitesi Ziraat Fakültesi Derg.* **2017**, *12*, 66–72.
73. Kalnina, I.; Sterne, D.; Strautina, S. Strawberry (*Fragaria ananassa*) cultivar 'Rumba' assessment under the northern climatic conditions. *Acta Hortic.* **2016**, *1139*, 259–264. [CrossRef]
74. Kilic, N.; Turemis, N.F.; Dasgan, H.Y. The effect of fertilizers on crop yield, fruit quality and plant nutrition of organically grown strawberry (*Fragaria x ananassa* Duch.). *Appl. Ecol. Environ. Res.* **2021**, *19*, 2201–2211. [CrossRef]
75. Develi, E.A.; Yavuz, A.; Erdoğan, Ü. The Effects of Vermicompost Applications on the Yield and Quality of San Andreas (*Fragaria Ananassa* Duch.) Strawberry Cultivar[#]. *Turk. J. Agric.-Food Sci. Technol.* **2021**, *9*, 2641–2648. [CrossRef]
76. Sharma, R.R.; Singh, R. Gibberellic acid influences the production of malformed and button berries, and fruit yield and quality in strawberry (*Fragaria x ananassa* Duch.). *Sci. Hortic.* **2009**, *119*, 430–433. [CrossRef]
77. Saima, Z.; Sharma, A.; Umar, I.; Wali, V.K. Effect of plant bio-regulators on vegetative growth, yield and quality of strawberry cv. Chandler. *Afr. J. Agric. Res.* **2014**, *9*, 1694–1699. [CrossRef]
78. Stachowiak, B.; Ratajczyk, H. The application possibility of *Bacillus circulans* strains in plant protection against grey mould and *fusarium* spp. *Agric. Advis.* **2021**, *3*, 30–44.
79. Morkeliūnė, A.; Rasiukevičiūtė, N.; Valiuškaitė, A. Meteorological conditions in a temperate climate for *Colletotrichum acutatum*, strawberry pathogen distribution and susceptibility of different cultivars to anthracnose. *Agriculture* **2021**, *11*, 80. [CrossRef]
80. Morkeliūnė, A.; Rasiukevičiūtė, N.; Valiuškaitė, A. Pathogenicity of *Colletotrichum acutatum* to different strawberry cultivars and anthracnose control with essential oils. *Zemdirb.-Agric.* **2021**, *108*, 173–180. [CrossRef]
81. Keldibekova, M. Genes and loci controlling the resistance of strawberry (*F. ananassa* Duch.) to pathogens. *Indian J. Agric. Res.* **2023**, *57*, 709–716. [CrossRef]
82. Gannett, M.; Pritts, M.P.; Lehmann, J. Soil amendments affect soil health indicators and crop yield in perennial strawberry. *Horttechnology* **2019**, *29*, 179–188. [CrossRef]
83. Song, Z.; Yan, D.; Fang, W.; Zhang, D.; Jin, X.; Li, Y.; Wang, Q.; Wang, G.; Li, Q.; Cao, A. Response of strawberry fruit yield, soil chemical and microbial properties to anaerobic soil disinfestation with biochar and rice bran. *Agriculture* **2023**, *13*, 1466. [CrossRef]
84. Ziedan, E.S.H. A review of the efficacy of biofumigation agents in the control of soil-borne plant diseases. *J. Plant Prot. Res.* **2022**, *62*, 1–11. [CrossRef]
85. Tournas, V.H.; Katsoudas, E. Mould and yeast flora in fresh berries, grapes and citrus fruits. *Int. J. Food Microbiol.* **2005**, *105*, 11–17. [CrossRef]
86. Kordowska-Wiater, M. Yeasts as biological control agents for plants. *Post Mikrobiol.* **2011**, *50*, 17–119.
87. Kowalska, J. Effects of *Trichoderma asperellum* [T1] ON *Botrytis cinerea* [PERS.: FR.], growth and yield of organic strawberry. *Acta Sci. Pol. Hortorum Cultus* **2011**, *10*, 107–114.
88. Meszka, B.; Bielenin, A. Activity of laminarin in control of strawberry diseases. *Phytopathologia* **2011**, *62*, 15–23.
89. Wachowska, U.; Borowska, J.; Kwiatkowska, E.; Kowalska, E. Biological, bio-technological and chemical possibilities in reducing of grey mould (*Botrytis cinerea*) severity on strawberries. *Prog. Plant Prot.* **2015**, *55*, 275–279. [CrossRef]
90. Oliveira Filho, J.G.; Cruz Silva, G.; Aguiar, A.C.; Cipriano, L.; Azeredo, H.M.C.; Junior, S.B.; Ferreira, M.D. Chemical composition and antifungal activty of essential oils and their combinations against *Botrytis cinerea* in strawberries. *J. Food Meas. Charact.* **2021**, *15*, 1815–1825. [CrossRef]
91. Gebel, M.P.; Magurno, F. Assessment of the antifungal potential of the essential oil from *Thymus vulgaris* against *Botrytis cinerea* causative agent of postharvest grey mould on strawberry fruits. *Columella-J. Agric. Environ. Sci.* **2014**, *1*, 17–23. [CrossRef]

92. Rhouma, A.; Hajji-Hedfi, L.; Ben Othmen, S.; Shah, K.K.; Matrood, A.A.A.; Okon, O.G.; Pant, D. Strawberry grey mould, a devastating disease caused by the airborne fungal pathogen *Botrytis cinerea*. *Egypt. J. Phytopathol.* **2022**, *50*, 44–50. [CrossRef]
93. Jia, S.; Wang, Y.; Zhang, G.; Yan, Z.; Cai, Q. Strawberry FaWRKY25 transcription factor negatively regulated the resistance of strawberry fruits to *Botrytis cinerea*. *Genes* **2021**, *12*, 56. [CrossRef] [PubMed]
94. Caproni, C.M.; Rodrigues, F.A.; Rezende, R.A.L.S.; Pomella, A.W.V.; Pasqual, M. Application of biological products in strawberry cultivars to control *Botrytis cinerea*. *Res. Soc. Dev.* **2021**, *10*, e8710514655. [CrossRef]
95. Nielsen, K.A.G.; Skårn, M.N.; Strømeng, G.M.; Brurberg, M.B.; Stensvand, A. Pervasive fungicide resistance in *Botrytis* from strawberry in Norway: Identification of the grey mould pathogen and mutations. *Plant Pathol.* **2022**, *71*, 1392–1403. [CrossRef]
96. Leroch, M.; Plesken, C.; Weber, R.W.S.; Kauff, F.; Scalliet, G.; Hahn, M. Gray mold populations in German strawberry fields are resistant to multiple fungicides and dominated by a novel clade closely related to *Botrytis cinerea*. *Appl. Environ. Microbiol.* **2013**, *79*, 159–167. [CrossRef] [PubMed]
97. Aguilar-Gonzàlez, A.E.; Palou, E.; López-Malo, A. Antifungal activity of essential oils of clove (*Syzygium aromaticum*) and/or mustard (*Brassica nigra*) in vapor phase against gray mold (*Botrytis cinerea*)in strawberries. *Innov. Food Sci. Emerg. Technol.* **2015**, *32*, 181–185. [CrossRef]
98. Garrido, C.; Carbú, M.; Fernández-Acero, F.J.; Budge, G.; Vallejo, I.; Colyer, A.; Cantoral, J.M. Isolation and pathogenicity of *Colletotrichum* Spp. causing anthracnose of strawberry in south west Spain. *Eur. J. Plant Pathol.* **2008**, *120*, 409–415. [CrossRef]
99. Freeman, S.; Horowitz, S.; Sharon, A. Pathogenic and nonpathogenic lifestyles in *Colletotrichum acutatum* from strawberry and other plants. *Phytopathology* **2001**, *91*, 986–992. [CrossRef]
100. Sreenivasaprasad, S.; Talhinhas, P. Genotypic and phenotypic diversity in *Colletotrichum acutatum*, a cosmopolitan pathogen causing anthracnose on a wide range of hosts. *Mol. Plant Pathol.* **2005**, *6*, 361–378. [CrossRef] [PubMed]
101. Miller- Butler, M.A.; Smith, B.J.; Kreiser, B.R.; Blythe, E.K. Composition of Anthracnose Resistance with the Presence of Two SCAR Markers Associated with the *Rca*2 Gene in Strawberry. *Hort. Sci.* **2019**, *54*, 793–798. [CrossRef]
102. Haack, S.E.; Ivors, K.L.; Holmes, G.J.; Förster, H.; Adaskaveg, J.E. Natamycin, a new biofungicide for managing crown rot of strawberry caused by QoI-resistant Colletotrichum acutatum. *Plant Dis.* **2018**, *102*, 1687–1695. [CrossRef]
103. Harp, T.; Kuhn, P.; Roberts, P.; Pernezny, K. Management and cross-infectivity potential of *Colletotrichum acutatum* causing anthracnose on bell pepper in florida. *Phytoparasitica* **2013**, *42*, 31–39. [CrossRef]
104. Lima, N.B.; de A. Batista, M.V.; De Morais, M.A., Jr.; Barbosa, M.A.G.; Michereff, S.J.; Hyde, K.D.; Câmara, M.P.S. Five *Colletotrichum* species are responsible for mango anthracnose in northeastern Brazil. *Fungal Divers.* **2013**, *61*, 75–88. [CrossRef]
105. Moreira, R.R.; Nesi, C.N.; May De Mio, L.L. *Bacillus* spp. and *Pseudomonas putida* as inhibitors of the *Colletotrichum acutatum* group and potential to control Glomerella leaf spot. *Biol. Control* **2014**, *72*, 30–37. [CrossRef]
106. Marian, M.; Ohno, T.; Suzuki, H.; Kitamura, H.; Kuroda, K.; Shimizu, M. A novel strain of endophytic *Streptomyces* for the biocontrol of strawberry anthracnose caused by *Glomerella cingulata*. *Microbiol. Res.* **2020**, *234*, 126428. [CrossRef]
107. Alijani, Z.; Amini, J.; Ashengroph, M.; Bahramnejad, B. Isolation of strawberry endophytic bacteria and investigation of their antifungal effects on *Colletotrichum nymphaeae*, the casual agent of strawberry anthracnose. *Biocontrol Plant Prot.* **2020**, *8*, 29–46.
108. Nellist, C.F.; Vickerstaff, R.J.; Sobczyk, M.K.; Marina-Montes, C.; Wilson, F.M.; Simpson, D.W.; Whitehouse, A.B.; Harrison, R.J. Quantitative trait loci controlling *Phytophthora cactorum* resistance in the cultivated octoploid strawberry (*Fragaria* × *ananassa*). *Hortic. Res.* **2019**, *6*, 60. [CrossRef]
109. Bhat, R.G.; Browne, G.T. Specific detection of *Phytophthora cactorum* in diseased strawberry plants using nested polymerase chain reaction. *Plant Pathol.* **2010**, *59*, 121–129. [CrossRef]
110. Poimala, A.; Parikka, P.; Hantula, J.; Vainio, E.J. Viral diversity in *Phytophthora cactorum* population infecting strawberry. *Environ. Microbiol.* **2021**, *23*, 5200–5221. [CrossRef]
111. Lu, X.; Xu, H.; Song, W.; Yang, Z.; Yu, J.; Tian, Y.; Jiang, M.; Shen, D.; Dou, D. Rapid and simple detection of *Phytophthora cactorum* in strawberry using a coupled recombinase polymerase amplification–lateral flow strip assay. *Phytopathol. Res.* **2021**, *3*, 12. [CrossRef]
112. Ali, A.; Kumar, R.; Mazáková, J.; Maňasová, M.; Zouhar, M.; Pánek, M. Evaluation of the ability of seven active ingredients of fungicides to suppress *Phytophthora cactorum* at diverse life stages, and variability in resistance found among isolates. *J. Fungi* **2022**, *8*, 1039. [CrossRef] [PubMed]
113. Sharma, S.; Marín, M.V.; Lee, M.B.; Baggio, J.S.; Peres, N.A.; Lee, S. Genomic approaches for improving resistance to Phytophthora crown rot caused by *P. cactorum* in strawberry (*Fragaria* × *ananassa*). *Front. Agron.* **2022**, *4*, 941111. [CrossRef]
114. Pánek, M.; Hanáček, A.; Wenzlová, J.; Maňasowá, M.; Zouhar, M. A Comparision of the Ability of Some Commercially Produced Biological Control Agents to Protect Strawberry Plants against the Plant Pathogen *Phytophthora cactorum*. *Agriculture* **2021**, *11*, 1086. [CrossRef]
115. Meszka, B.; Michalecka, M. Identification of *Phytophtora* spp. isolated from plants and soil samples on strawberry plantations in Poland. *J. Plant Dis. Prot.* **2016**, *123*, 29–36. [CrossRef]
116. Sas-Paszt, L.; Sumorok, B.; Górnik, K.; Grzyb, Z.S.; Lisek, A.; Głuszek, S.; Trzciński, P.; Derkowska, E.; Frąc, M.; Treder, W.; et al. Influence of beneficial soil microorganisms and mineral fertilizers enriched with them on the flowering, fruiting, and physical and chemical parameters of the fruit of three-year-old strawberry plants in field cultivation. *Hortic. Sci.* **2023**, *50*, 112–126. [CrossRef]

117. Rahman, M.; As Sabir, A.; Mukta, J.A.; Khan, M.A.; Mohi-Ud-Din, M.; Miah, G.; Rahman, M.; Islam, T. Plant probiotic bacteria *Bacillus* and *Paraburkholderia* improve growth, yield and content of antioxidants in strawberry fruit. *Sci. Rep.* **2018**, *8*, 2504. [CrossRef]
118. Todeschini, V.; AitLahmidi, N.; Mazzucco, E.; Marsano, F.; Gosetti, F.; Robotti, E.; Bona, E.; Massa, N.; Bonneau, L.; Marengo, E.; et al. Impact of beneficial microorganisms on strawberry growth, fruit production, nutritional quality, and volatilome. *Front. Plant Sci.* **2018**, *9*, 1611. [CrossRef] [PubMed]
119. Palencia, P.; Martínez, F.; Pestana, M.; Oliveira, J.; Correia, P. Effect of *Bacillus velezensis* and *Glomus intraradices* on fruit quality and growth parameters in strawberry soilless growing system. *Hortic. J.* **2015**, *84*, 122–130. [CrossRef]
120. Hong, S.; Kim, T.Y.; Won, S.-J.; Moon, J.-H.; Ajuna, H.B.; Kim, K.Y.; Ahn, Y.S. Control of fungal diseases and fruit yield improvement of strawberry using *Bacillus velezensis* CE 100. *Microorganisms* **2022**, *10*, 365. [CrossRef] [PubMed]
121. Koilybayeva, M.; Shynykul, Z.; Ustenova, G.; Abzaliyeva, S.; Alimzhanova, M.; Amirkhanova, A.; Turgumbayeva, A.; Mustafina, K.; Yeleken, G.; Raganina, K.; et al. Molecular characterization of some *Bacillus* species from vegetables and evaluation of their antimicrobial and antibiotic potency. *Molecules* **2023**, *28*, 3210. [CrossRef] [PubMed]
122. Sas-Paszt, L.; Smolińska, U.; Kowalska, B.; Szczech, M.; Lisek, A.; Trzciński, P.; Głuszek, S.; Górnik, K.; Derkowska, E.; Sumorok, B. Influence of microbiologically enriched mineral fertilizers on selected groups of microorganisms in the rhizosphere of strawberry plants. *J. Hortic. Res.* **2021**, *29*, 35–46. [CrossRef]
123. Pastrana, A.M.; Basallote-Ureba, M.J.; Aguado, A.; Akdi, K.; Capote, N. Biological control of strawberry soil-borne pathogens *Macrophomina phaseolina* and *Fusarium solani*, using *Trichoderma asperellum* and *Bacillus* spp. *Phytopathol. Mediterr.* **2016**, *55*, 109–120. [CrossRef]
124. Jamiołkowska, A.; Thanoon, A.H.; Skwaryło-Bednarz, B.; Patkowska, E.; Mielniczuk, E. Mycorrhizal inoculation as an alternative in the ecological production of tomato (*Lycopersicon esculentum* Mill.). *Int. Agrophys.* **2020**, *34*, 253–264. [CrossRef] [PubMed]
125. Makała, H. Organic food and factors of its choice by consumers. *Res. Bull. Leis. Tour.* **2019**, *1*, 151–166.
126. Góralczyk, K. Czy żywność ekologiczna rzeczywiście jest najlepsza? *Stud. Ecol. Et Bioethicae* **2018**, *16*, 51–56. [CrossRef]
127. Bieniek–Majka, M. Konsumpcja owoców i warzyw w Unii Europejskiej oraz jej potencjalne środowiskowe i zdrowotne konsekwencje. *Issues Agric. Advis. Serv.* **2022**, *1*, 22–41.
128. Migdał, W.; Migdał, Ł. Od Pola do Stołu-wymagania konsumentów w stosunku do rolników. *Food Sci. Technol. Qual.* **2021**, *28*, 24–46. [CrossRef]
129. Lipa, J.J.; Pruszyński, S. Scale of use of biological methods in plant protection in Poland and in the world. *Prog. Plant Prot.* **2010**, *50*, 1033–1043.
130. Jamiołkowska, A.; Hetman, B. The mechanism of action of biological preparations used in plant protection against pathogens). *Ann. UMCS Sect. E Agric.* **2016**, *LXXI*, 13–29.
131. Klepacka, A.M. Selected assumptions of the European Green Deal and possibilities of development of a conventional and organic farm. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2023**, *XXV*, 108–123. [CrossRef]

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Microbial Fertilizing Products Impact on Productivity and Profitability of Organic Strawberry Cultivars

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Abstract: Poland is a major producer of various fruits, including strawberries. As growing consumer awareness of food quality, health, and wellbeing is increasing, farmers are receiving a new market opportunity for organic products of good quality. The integration of microbial solutions into agricultural practices can foster the transition of agricultural farms towards more resilient and sustainable production of quality food. The objective of this study was to assess the influence of novel microbial biopreparations (microbial fertilizing products) containing *Bacillus* sp., humic acids, and other organic compounds on the economic viability of three strawberry cultivars ('Honeoye', 'Vibrant', and 'Rumba') under organic farming conditions. This study was conducted in 2021 as a field experiment. Irrigated and non-irrigated strawberries were treated with five microbial fertilizing products (K2–K6). The single plot area was 16 m^2, with a total of 144 plots. The adopted planting density of strawberries was 30,052 per hectare. K3 treatment was found to be the most universal microbial treatment in terms of positive impact on yields, with significant yield increase on both the non-irrigated (yield increase of 3.76 $t \cdot ha^{-1}$) and irrigated experiments (yield increase of 5.78 $t \cdot ha^{-1}$). The K4 treatment on the non-irrigated strawberries resulted in a yield increase of 4.96 $t \cdot ha^{-1}$, which at the same time had no effect on the yield of the irrigated experiment. On average, application of the K2–K6 combinations on the non-irrigated strawberries resulted in a yield increase from 13.4% (K2) to 33.5% (K4). The irrigated strawberries showed a yield increase from 3.9% (K4—non-significant yield increase) to as much as 36.1% (K3). The highest direct surplus for the non-irrigated strawberries was recorded for the K4 treatment (38,603 $PLN \cdot ha^{-1}$) and for K3 for the irrigated experiment (42,945 $PLN \cdot ha^{-1}$). The direct surplus for 'Rumba' and 'Vibrant' was higher than for 'Honeoye' on both the irrigated (22% and 53%, respectively) and non-irrigated (19% and 18%, respectively) experiments. The average profitability index for all tested non-irrigated and irrigated varieties improved when treated with microbial fertilizer products, with profitability indexes of 143.3–168.8% on the non-irrigated plantation and 129.2–169.7% on the irrigated plantation. The tested microbial fertilizing products proved to be valuable products to improve the productivity and economic effectiveness of organic strawberry production. At the same time, their use needs to be adapted to local plantation conditions.

Keywords: direct surplus; economic efficiency; microbial fertilizers; *Bacillus* sp.; humic acids

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1. Introduction

Organic farming, an environmentally friendly agricultural farming system, is one of the EU's integral strategies to create a sustainable and resilient agricultural future. Environmental sustainability, consumer health and safety, animal welfare, sustainable rural development, and satisfying market demands are ambitious targets for organic farming, which are also reflected in the EU's Green Deal [1] and Farm-to-Fork [2] strategies. One of the goals of the current EU strategy is to have 25% of its agricultural land under organic farming principles.

According to Parlińska et al. [3], the European Green Deal strategy is almost entirely directly or indirectly related to agriculture. It mostly deals with crop production and processing, but also with the use of ecosystem services, climate change, and carbon sequestration, as well as efficient food management. Organic farming can support the objectives of the European Green Deal. The development of this farming system is influenced by increasing demand and interest in healthy food of improved quality [4]. The aim of organic farming is to produce high-quality food and protect the natural environment [5]. Nachtman [6] defines organic farming as "a system of agricultural production that ensures the production of food under environmentally sound conditions". Greenhouse gas emissions, as well as air-polluting chemical emissions from organic farming are low; thereby this system counteracts the negative effects of climate change and helps to maintain water and soil quality [7]. According to Brzozowski and Zmarlicki [8], the development of organic production is largely determined by consumer preferences, as their willingness to pay higher prices for organic products is the main driving force behind the development of the organic market.

According to Zmarlicki and Brzozowski [9], the main source of income for the European organic food sector is organic fruits and vegetables. One of the challenges for organic farming is to meet consumer demands regarding food quality without the use of chemical plant protection products. According to Rahmann et al. [10], organic farming should be supported by multidisciplinary research to find solutions to the technical and socio-economic challenges. Meeting these objectives requires the development of new, non-chemical methods of production, including the use of biopreparations (microbial fertilizing products).

The current and future development of organic farming is closely linked to its profitability and competitiveness with other farming systems. Currently, EU agriculture is influenced by new strategies such as the European Green Deal, the Farm-to-Fork Strategy, the European Biodiversity Strategy for 2030, and the Adaptation Strategy: Climate Resilient EU, which commit countries to a significant shift towards more sustainable farming and an increase in organic areas (up to 25% of agricultural land by 2030) [1,11,12]. The increase in both the number of certified organic farms and the area under certified organic cultivation in Poland is related to the growing demand for organic food and also by the support instruments for organic farming under the Common Agricultural Policy (CAP—Table 1) of the European Union [13,14].

Table 1. Index of abbreviations used in the text.

Abbreviation	Expansion of the Abbreviation
CAP	Common Agricultural Policy
CFU	Colony-forming unit
K1	Control
K2	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier consisting of dry humic acids, mustard, rapeseed oil, and clove oil on micorized dolomite (10^9 CFU/plant)
K3	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier consisting of dry humic acids, mustard, rapeseed oil, and clove oil on micorized dolomite (10^9 CFU/plant), and *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD on a carrier consisting of plant extracts (nettle, horsetail, and calendula) and humic acids in micorized dolomite (10^5 CFU/cm^2)
K4	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier consisting of dry humic acids, mustard, rapeseed oil, and clove oil on micorized dolomite (10^9 CFU/plant), and *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, humic acids, and yeast culture effluent in micorized dolomite (10^5 CFU/cm^2)

Table 1. *Cont.*

Abbreviation	Expansion of the Abbreviation
K5	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier consisting of dry humic acids, mustard, rapeseed oil, and clove oil on micorized dolomite (10^9 CFU/plant) and *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD on a carrier consisting of plant extracts (nettle, horsetail, and calendula) and humic acids in micorized dolomite (10^5 CFU/cm^2), and *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, humic acids, and yeast culture effluent in micorized dolomite (10^5 CFU/cm^2)
K6	Preparation containing *Bacillus subtilis* AF75AB2 and *Bacillus sp.* Sp115AD on a carrier consisting of plant extracts (nettle, horsetail, and calendula), and humic acids in micorized dolomite (10^5 CFU/cm^2), and *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, humic acids, and yeast culture effluent in micorized dolomite (10^5 CFU/cm^2)

Source: Drobek et al. [15] and Nakielska et al. [16], modified.

Poland has a relatively large agricultural economic potential, as well as favorable soil and climatic conditions, to be an important and competitive exporter of dessert and industrial strawberries to the European and world markets [17]. According to Paszko et al. [18], the market competitiveness of farms specialized in berry production is mainly based on the continuous improvement of productivity and quality by implementing new technologies. Currently, Poland is among the largest European and global producers of berries. It is the second largest European producer of strawberries [19,20], and it ranks fifth worldwide [20]. The quantity and quality of strawberry yields can be influenced by natural (mostly climatic and soil) conditions, as well as the age of the plantation, field location, and cultivar and agricultural management strategies [20], with irrigation, fertilization, and crop protection as the main influencing forces [19]. Strawberry yields can also be under the strong influence of genotype and planting season characteristics [21].

One of the main challenges of European agriculture, reflected in the European Green Deal strategy, emphasizes the need for development of sustainable agricultural practices to mitigate climate change and biodiversity loss. The integration of microbial solutions into agricultural practices represents a potential avenue for fostering a transition towards a more resilient and sustainable food system. This approach aligns with the objectives of the Green Deal and offers a means of addressing the pressing challenges of climate change and food security. The development of new microbial products has the potential to address the existing research gaps of microbial consortia's impact on plant health and productivity, which remains an under-explored area [22,23]. Research initiatives funded under Horizon Europe have the potential to drive innovation in this area, with a particular focus on the development of microbial products that enhance crop yield and quality while minimizing environmental impacts [24,25].

The aim of this study was to compare the productivity and economic profitability of cultivation of three strawberry cultivars ('Honeoye', 'Vibrant', and 'Rumba') in an organic farming system with the use of newly developed microbial enriched biopreparations (microbial fertilizing products) under irrigated and non-irrigated plantation conditions.

2. Materials and Methods

2.1. Strawberry Productivity Assessment

2.1.1. Experimental Site

The research was conducted in 2021 on a strawberry plantation established in 2019 as a certified organic strawberry field at the Agricultural Experimental Station of IUNG-PIB (Institute of Soil Science and Plant Cultivation State Research Institute) in Grabów nad Wisłą (Mazowieckie region). The area of the plantation was 23 a, and it was divided into two objects: non-irrigated (11.5 a) and irrigated (11.5 a). The experiment was established in a system of equivalent blocks on a loessive soil made up of strong loamy sands on light loam. The pre-crop for the strawberry was red clover (tilled in 2019).

2.1.2. Factors of Experiments

The experimental factors on both irrigated and non-irrigated experiments were:

I. Microbial biopreparations (microbial fertilizing products) based on beneficial microorganisms and plant extracts, including *Bacillus* sp., humic acids, yeast culture effluent, micronized dolomite, mustard, and rapeseed oil (the tested products were newly developed and first tested in field conditions in the present study). Six levels of this factor were studied: 1—water treated K1 (control object), 2—preparation K2 (trade name: BacilRoots), 3—preparation K3 (trade names: BacilRoots + BacilExtra), 4—preparation K4 (trade names: BacilRoots + BacilHumus), 5—preparation K5 (trade names: BacilRoots + BacilExtra + BacilHumus), and 6—preparation K6 (trade names: BacilExtra + BacilHumus).

II. Strawberry cultivars. Three levels of this factor were studied: 'Honeoye', 'Vibrant' and 'Rumba'.

The study had a design with four replications, which included 72 plots per both irrigated and non-irrigated fields (6 preparation combinations × 3 cultivars × 4 replicates = 72 plots per irrigated/non-irrigated experiments). The biopreparations were developed under the EcoFruits project (NCBiR, BIOSTRATEG3/344433/16/NCBR/2018). The experiment was set up using black agrotextile as soil cover (sheet) at a plant density of 30,000 plants ha^{-1} (48 plants per plot, each with an area of 16 m^2). Biopreparations were applied by spraying three times during the growing season (13, 21, and 28 May 2021) at a rate of 35 $kg \cdot ha^{-1}$ dissolved in 400 L of water per hectare. The control site was sprayed with water alone at the same rate (400 L water per 1 ha).

The site was drip irrigated three times during the growing season: 14th of May, 25th of May, and 11th of June at a rate of 7000 $L \cdot ha^{-1}$ (7 mm of rainfall equivalent).

2.1.3. Weather Conditions

The weather during the key months of strawberry growth, broken down by decade of the month, is given in Table 2.

Table 2. Weather conditions during the 2021 growing season.

Month	1st Decade	2nd Decade	3rd Decade	Total	Multi-Year Average
			Precipitation (mm)		
April	4.3	42.9	4.0	51.2	42.0
May	14.3	15.0	20.6	49.9	53.0
June	0.8	2.0	67.6 [1]	70.4 [1]	110.0
July	30.0 [1]	21.6 [1]	10.1 [1]	61.7 [1]	105.0
			Temperature (°C)		
April	5.6	7.2	7.0	6.6	7.5
May	10.0	14.5	12.9	12.5	12.4
June	17.3	19.4	21.7	19.5	16.7
July	21.2	22.7	21.5	21.8	17.8

[1] The amount of precipitation in the third decade of June and July may deviate from the actual amount due to the failure of the measuring system at the meteorological station.

2.1.4. Agricultural Management and Fruit Harvest

The experimental field was managed according to certified organic farming principles with the use of certified organic fertilizers and plant protection products.

The details of treatments are given in Table 3. The strawberry fruit yield was determined cumulatively over successive harvests from 2 to 24 June 2021 (seven harvests in total). Fruits were harvested by hand on each of the 144 plots. Eight plants of each plot were randomly selected, from which fruits were harvested, counted, and weighed. At the end of the season, the total weight of fruit harvested from each plot was summed and converted to average single plant yield (in g/plant) and average 1 hectare yield (in $t \cdot h^{-1}$). To do so, the average weight from a single plant was multiplied by 30,052 plants per hectare (planting density), and the resulting weight was converted to tonnes. The final result included the density reduction factor (percentage of plants that were missing from the plot).

Table 3. Agricultural treatments (fertilization and plant protection) on experimental site in 2021.

Treatment Type	Product and/or Formulation	Manufacturer	Dose per Hectare	Number of Treatments
Fertilization	Redarom Activstart	Biodevas Laboratoires ZA de l' L'Épine, Savigné-l'Évêque, France,	1.5 L	2
	Olibio	Biodevas Laboratoires ZA de l' L'Épine, Savigné-l'Évêque, France	2 L	2
	Aminosol (N)	AZELIS POLAND Sp. z o.o., Poznań, Poland	3 L	2
	Potassium sulfate Patent Kali	K+S Polska Sp. z o.o., Poznań, Poland	250 kg	1
	Potassium salt	K+S Minerals and Agriculture GmbH, Kassel, Germany	60 kg	1
	Carbonate lime Polcalc	Polcalc Nawozy Wapniowe Sp. z o.o., Przemysłowa, Poland	500 kg	1
Biopreparations (microbial fertilizing products)	K2 (BacilRoots)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K3 (BacilRoots + BacilExtra)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K4 (BacilRoots + BacilHumus)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K5 (BacilRoots + BacilExtra + BacilHumus)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K6 (BacilExtra + BacilHumus)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3

2.2. Economic Efficiency of Organic Strawberry Production

2.2.1. Methodology of Economic Assessment

The primary source of data for the economic analyses was the technology sheets of the experiment for 2021. They included the characteristics of the individual agrotechnical treatments, the amount of input of production inputs, and the production volume (yield). The economic evaluation of the strawberry production was carried out according to the methodology of IERiGŻ—PIB (Institute of Agricultural and Food Economics—National Research Institute), taking into account the first income category—direct surplus [26,27].

In the analysis, two indicators were calculated: a standard direct surplus and a profitability index. The direct surplus was the difference between the value of the yield (income from the sale of strawberries) and the direct costs (seedling consumption, fertilizers, and plant protection products) and the selected indirect costs (fuel used for the application of biopreparations) according to the following formula: *VALUE OF PRODUCTION — DIRECT COSTS — INDIRECT COSTS = DIRECT SURPLUS*. The value of production was assessed on the basis of the weight of the harvested strawberry fruits (Section 2.1.4) and strawberry fruit prices (Section 2.2.2).

In order to compare the different variants in terms of production profitability, a profitability index was also calculated. The Productivity Index is a measure that evaluates the efficiency with which resources are used in the production of agricultural goods. It was expressed as a percentage and calculated by comparing the value of the production to the value of the costs (value of resources used in production), as follows:

$$productivity\ index = \left(\frac{value\ of\ production}{value\ of\ costs}\right) \cdot 100\%$$

2.2.2. Strawberry Fruit Prices and Direct Costs Evaluation

To calculate the production value, the average purchase price of strawberries intended for direct consumption from the area of Mazowieckie Voivodeship (region where the study was carried out) for 2021 (4.80 PLN·kg^{-1}) was adopted.

In the evaluated technologies of plant production, the following were classified as (annual) direct costs: the cost of hired labor, seedling costs (1/4 of the purchase costs as strawberry plantations should last 4 years), the cost of applied fertilizers and plant protection products certified for use in organic farming, and the cost of applied biopreparations (microbiologically enriched fertilizers) in the form of foliar spraying of plants.

The labor and tractor-hour inputs were assessed according to the documentation sheet of the experiment. Fertilizer and plant protection product costs were calculated based on the consumption and purchase prices in Q1 2021 included in the experiment documentation sheet. The cost of biopreparations was the same for each combination and amounted to 400 PLN·ha^{-1} per 1 treatment.

The cost of fuel consumption for the Ursus 4512 tractor (44.5 kW) was assumed to be 31.87 PLN per 1 h, according to the methodology described by Harasim [28], assuming an average diesel price for the period 1–10 2021 of 5.30 PLN^{-1}. The water price of 3.66 PLN·m^{-3} was adopted on the basis of the 2021 ordinance of the municipality of Przyłęk.

To calculate the labor costs, the cost of one man-hour of 11.01 PLN·h^{-1} was adopted, calculated on the basis of the minimum net wage in 2021 converted into the annual working hours of a full-time person working in agriculture (2120 h per year according to IERiGŻ-PIB).

The economic calculation did not include the cost of the machinery and tractors. However, 1/8 of the cost of the irrigation system was taken into account (as installation is expected to be functional for at least 8 years), which in the case of the experiment in Grabów amounted to approximately 40,000 PLN per ha (total cost of the drip irrigation system).

2.2.3. Statistical Analysis

The data on strawberry yields were analyzed using STATISTICA software (Statistica v. 10, Statsoft Inc., Tulsa, OK, USA). The data were analyzed using a two-way analysis of variance (ANOVA) followed by a post hoc Fisher's test. The significance of differences was determined at $p < 0.05$.

Descriptive statistics were used to characterize the economic efficiency of the strawberry production. The economic results were not subjected to a statistical analysis of the significance of the differences, as economic efficiency results are directly linked to yields. For the statistical analysis, the irrigated and non-irrigated plantations were treated as two separate experiments.

3. Results and Discussion

3.1. Strawberry Yields

The biopreparations (microbial fertilizing products) and cultivars had a significant impact on yield (Table 4). The average fruit yield from the irrigated experiment was 18.74 t·ha^{-1}, while the average fruit yield from the non-irrigated plantation was more than a tonne lower (7%) (17.51 t·ha^{-1}).

In the non-irrigated experiment, the K4 combination had the highest yields for all three tested cultivars (19.75 t·ha^{-1}). Interestingly, the non-irrigated 'Vibrant' had a yield level similar to most of the tested treatments, including the control (K1, K2, K4, K5), with yields significantly lower from the K6 treatment (15.13 t·ha^{-1}). 'Vibrant' treated with K3 was the highest yielder in the non-irrigated part of the experiment (20.69 t·ha^{-1}) (Table 4).

Table 4. Yield of strawberries (t·ha^{-1}) in the organic system on an irrigated and non-irrigated site depending on the cultivar and biopreparations used.

Specification	Treatment						
	K1	K2	K3	K4	K5	K6	Average
			Non-irrigated				
'Honeoye'	11.09 a	15.61 ab	17.69 ab	19.85 b	14.93 ab	17.75 ab	16.61
'Rumba'	13.34 a	17.39 ab	17.28 ab	19.87 b	16.83 ab	18.10 ab	17.48
'Vibrant'	19.93 ab	17.32 ab	20.69 b	19.53 ab	18.70 ab	15.13 a	18.42
Average	14.79	16.77	18.55	19.75	16.82	16.99	17.51
			Irrigated				
'Honeoye'	16.53 a	18.96 a	22.64 a	15.88 a	16.74 a	16.57 a	18.01
'Rumba'	14.37 a	19.80 ab	21.37 b	17.94 ab	22.07 b	17.41 ab	19.23
'Vibrant'	17.18 a	18.31 a	21.41 a	16.12 a	21.72 a	18.14 a	18.96
Average	16.03	19.03	21.81	16.65	20.18	17.37	18.74

Lowercase letters indicate significant differences between tested biopreparations (microbial fertilizing products).

In the irrigated experiment, the K3 and K5 treatments had the best positive effect on strawberry yields (21.81 and 20.18 t·ha^{-1}, respectively). There was no statistically significant impact of the tested treatments on the 'Honeoye' and 'Vibrant' cultivars. The yields of 'Rumba' were positively affected by the K3 and K5 treatments with a yield increase of more than 7 t·ha^{-1} (21.37 and 22.07 t·ha^{-1}, respectively) compared to the control object K1 (14.37 t·ha^{-1}) (Table 4).

On average, in all combinations in both the irrigated and non-irrigated experiments, all three cultivars yielded similar levels. The average yields of the irrigated experiment (18.74 t·ha^{-1}) were 7% higher compared to the non-irrigated one (17.51 t·ha^{-1}) (Table 4). The spread of results between the lowest yielding and highest yielding objects was large in both the non-irrigated and irrigated experiments and was 9.6 t·ha^{-1} (11.09 t·ha^{-1} to 20.69 t·ha^{-1}) for the non-irrigated experiment and 8.27 t·ha^{-1} (14.37 t·ha^{-1} to 22.64 t·ha^{-1}) for the irrigated experiment (Table 4).

In a study conducted by Brzozowski and Zmarlicki [29], organic strawberries yielded an average of about 8 tonnes per hectare, which was 15% (1.2 t·ha^{-1}) lower than the yields of conventional strawberries. This was considerably lower than in the present study, where yields ranged from 11.09 t·ha^{-1} for 'Honeoye' in the non-irrigated experiment (control plot with no microbial fertilizing products added) to as much as 22.64 t·ha^{-1} for the same variety in the plot where the K3 combination was used on the irrigated part. Yields similar to those reported in the present study were recorded by Pawlak et al. [20], who found yields of organic strawberries to be higher than those of conventional strawberries. The authors found organic strawberry yields of 17.24 t·ha^{-1} (ranging from 15.42 t·ha^{-1} to 18.41 t·ha^{-1} and yields of conventional strawberries of 15.87 t·ha^{-1} (ranging from 13.37 t·ha^{-1} to 18.79 t·ha^{-1}). The authors found yields of organic 'Honeoye' higher by 0.94 t·ha^{-1} to 1.94 t·ha^{-1} than conventional strawberries, depending on the year of the study. Paszko [17] reported yields of strawberries at a lower level of 8.2 t·ha^{-1} for conventional strawberries and 12.7 t·ha^{-1} for dessert strawberries in his 2001–2007 study. Seufert et al. [30], on the basis of a meta-analysis of organic and conventional farming, concluded that yields obtained in an organic farming system match the yield from conventional farming if the organic farm is managed properly with the best agricultural practices and crop types selected for the organic farming system and local conditions.

The use of K3 showed a consistent positive effect on yields, which was probably due to the composition of this combination of preparations. The K3 formulation consisted of (1) *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier consisting of dry humic acids, mustard, rapeseed oil, and clove oil on micorized dolomite (109 CFU/plant)), and (2) *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD on a carrier consisting of plant extracts (nettle, horsetail, and calendula) and humic acids in micorized dolomite (105 CFU/cm^2). It is likely that the beneficial effect was due to the high concentration of *Bacillus subtilis* in this specific combination, the addition of both *Bacillus* sp. AF75BC and *Bacillus* sp. Sp115AD, and the effect of the addition of plant extracts (nettle, horsetail, and calendula) to this particular combination of microorganisms. K3 showed the most consistent positive effect in both the irrigated and non-irrigated experiments. The positive effect of beneficial soil organisms, including *Bacillus* sp., has been confirmed by Sas-Paszt et al. [31], Drobek et al. [32], and Mikiciuk et al. [33].

3.2. Economic Efficiency

3.2.1. Direct Costs

Labor inputs and machinery working time were lower for the non-irrigated system than for the irrigated system. This was due to the nature of the irrigation system used, which required the preparation and transport of water from the farm to the field in order to work (there was no on-field water source). The difference between the two systems was about 50 h in man-hours and about 10.5 h in tractor-hours (Table 5). In both systems, the control object had lower labor inputs than the objects on which the tested biopreparations were used. The difference of about five man-hours and 3.6 tractor-hours was due to the need to prepare, transport, and use the biopreparations.

Table 5. Man-hour and tractor-hour inputs for irrigated and non-irrigated experiments.

Specification	Treatment					
	K1	**K2**	**K3**	**K4**	**K5**	**K6**
			Non-irrigated			
Man-hours	3375.9	3380.4	3380.4	3380.4	3380.4	3380.4
Tractor-hours	2.6	6.2	6.2	6.2	6.2	6.2
			Irrigated			
Man-hours	3422.1	3426.6	3426.6	3426.6	3426.6	3426.6
Tractor-hours	13.1	16.7	16.7	16.7	16.7	16.7

Most of the labor was related to the harvesting process of the strawberries. Detailed worksheets were not kept for each plot (each combination); harvest time was recorded for the whole experiment (Table 5). For the purpose of the preliminary study, it was assumed that the labor time required for harvesting was equal for each plot (total harvesting time the same regardless of the yield from the test plot).

Strawberry field production, whether in an irrigated or a non-irrigated system, requires high inputs of manual work (labor input), mainly during the harvest and maintenance work on the plantations of strawberries. The implementation of efficient irrigation practices is crucial for enhancing productivity and reducing labor costs in irrigated strawberry production. Water application and automation technologies can optimize irrigation process, limit water use, and reduce the labor costs of cultivation [34]. This indicates that advanced irrigation technologies can streamline the irrigation process, potentially reducing the labor requirement for manual irrigation management. In the present study, as the irrigation system was manually operated, and water had to be transported to the field plantation (no source of water on plantation), the labor needed on the irrigated plantation (treated with the tested biopreparations) was slightly higher (by approx. 46.2 h and 1%) in terms of man-hours and approx. 2.7 times higher in terms of tractor-hours (by approx. 10.5 h). Ariza et al. [35] discussed the influence of different irrigation regimes on the yield and fruit quality of strawberry cultivars, highlighting the importance of water-saving strategies, such as using low water-consuming cultivars or implementing deficit irrigation strategies, to increase water productivity [35].

In non-irrigated strawberry production, labor inputs may increase substantially if additional irrigation is needed during dry periods for saving not only the strawberry harvest but also the plantation itself from drought damage. Studies have shown that irrigation of strawberries during transplant establishment and frost protection can be crucial also for non-irrigated systems [36]. This suggests that labor inputs in non-irrigated systems may include tasks related to monitoring weather conditions and providing supplemental irrigation when needed to support plant growth and prevent plantations from critical damage. In the present study, the non-irrigated plantation had an irrigation system installed, but it was never used. The system was installed as a risk management measure in case of catastrophic drought and the risk of strawberry plants drying out. In the present study, irrigation of the plantation was set to start when soil moisture dropped below a field water capacity of 75%. The field was irrigated to reach field water capacity. This was far from an optimal water irrigation technique; however, due to technical limitations (the need to transport water to the plantation), this strategy was chosen and implemented on the irrigated field. Even such a technique showed positive effects on both the yield and economic efficiency of strawberry production (Table 6).

Table 6. Yield value and direct surplus of the different cultivars of strawberry treated with different biopreparations.

Specification	Treatment						
	K1	K2	K3	K4	K5	K6	Average
Non-irrigated							
Direct costs (PLN)	54,783	56,098	56,098	56,098	56,098	56,098	55,878.8
Yield (average, t·ha^{-1})	14.79	16.77	18.55	19.75	16.82	16.99	17.28
Yield value (PLN)							
'Honeoye'	53,177	74,850	84,824	95,181	71,589	85,111	77,455.3
'Rumba'	63,965	83,385	82,858	95,277	80,700	86,790	82,162.5
'Vibrant'	95,564	83,049	99,209	93,646	89,667	72,548	88,947.2
Average	70,918	80,412	88,947	94,701	80,652	81,467	82,849.5
Direct surplus (PLN)							
'Honeoye'	−1606	18,752	28,726	39,083	15,492	29,013	21,576.7
'Rumba'	9182	27,287	26,760	39,179	24,602	30,692	26,283.7
'Vibrant'	40,781	26,952	43,111	37,549	33,569	16,451	33,068.8
Average	16,135	24,314	32,849	38,603	24,554	25,369	26,970.7
Average direct surplus with subsidies	19,010	27,189	35,724	41,478	27,429	28,244	29,845.7
Irrigated							
Direct costs (PLN)	60,271	61,586	61,586	61,586	61,586	61,586	61,366.8
Yield (average, t·ha^{-1})	16.03	19.03	21.81	16.65	20.18	17.37	18.51
Yield value (PLN)							
'Honeoye'	79,118	91,105	108,367	76,241	80,077	79,597	85,750.8
'Rumba'	69,048	94,941	102,613	85,831	105,970	83,433	90,306.0
'Vibrant'	82,474	87,749	102,613	77,200	104,052	86,790	90,146.3
Medium	76,720	91,105	104,531	79,597	96,859	83,433	88,707.5
Direct surplus (PLN)							
'Honeoye'	18,846	29,519	46,781	14,654	18,490	18,011	24,383.5
'Rumba'	8777	33,355	41,027	24,244	44,383	21,847	28,938.8
'Vibrant'	22,203	26,162	41,027	15,613	42,465	25,203	28,778.8
Average	16,449	29,519	42,945	18,011	35,273	21,847	27,340.7
Average direct surplus with subsidies	19,323	32,394	45,820	20,886	38,148	24,722	30,215.5

Source: own calculations.

The type of soil on which strawberries are cultivated also affects the needed labor inputs. Depardieu et al. [37] discussed the use of sawdust and bark-based matter as substrates for soilless strawberry production, highlighting the importance of managing irrigation to ensure water use efficiency and crop quality. Irrigated strawberry plantations need proper timing of irrigation, which can be determined, for instance, on the basis of tensiometer irrigation scheduling [38]. The quality of water used for irrigation can also influence labor inputs. Use of water of poor quality (e.g., wastewater) can have a negative impact on strawberry productivity and fruit quality [39,40]. Labor inputs related with water management of production fields may include additional tasks related to water treatment, monitoring water quality parameters, and ensuring compliance with safety regulations to protect crop health and productivity. In the present study, these aspects of strawberry production were not assessed. Both plantations were covered in black agrotextile to reduce the inputs needed for weed control, and tap water was used to reduce the risk of contamination of the irrigated field with microbes from, e.g., farms, ponds, or other water sources.

Direct costs were lower for the non-irrigated system compared to the irrigated system (Table 7). This was due to the cost of the water itself but also the cost of preparing and transporting the water. The direct costs in the case of the irrigated plantation were 61,586 PLN per hectare, and 67.4% of these costs were the cost of hired labor. This was followed by fertilizers accounting for about 2.7% of the costs, biopreparations for 1.9%, fuel for 3.1%, and water for 0.2% of the costs. In the case of the control object, lower direct costs resulted from the non-application of biopreparations (lower costs of preparations and labor necessary for their application) (Table 7).

Table 7. Direct costs and their structure depending on the combination of formulations and irrigation used.

Specification	Treatment					
	K1	**K2**	**K3**	**K4**	**K5**	**K6**
			Non-irrigated			
Direct costs (PLN)	54,783	56,098	56,098	56,098	56,098	56,098
			Cost structure (%)			
Materials total:	21.6	23.2	23.2	23.2	23.2	23.2
Seedlings	8.2	8.0	8.0	8.0	8.0	8.0
Fertilizers	3.1	3.0	3.0	3.0	3.0	3.0
Biopreparations	0.0	2.1	2.1	2.1	2.1	2.1
Water	0.0	0.0	0.0	0.0	0.0	0.0
Other	10.3	10.1	10.1	10.1	10.1	10.1
Fuel	2.7	2.8	2.8	2.8	2.8	2.8
Labor (hired)	75.7	73.9	73.9	73.9	73.9	73.9
			Irrigated			
Direct costs (PLN)	60,271	61,586	61,586	61,586	61,586	61,586
			Cost structure (%)			
Material total	28.2	29.5	29.5	29.5	29.5	29.5
Seedlings	7.5	7.3	7.3	7.3	7.3	7.3
Fertilizers	2.8	2.7	2.7	2.7	2.7	2.7
Biopreparations	0.0	1.9	1.9	1.9	1.9	1.9
Water	0.3	0.2	0.2	0.2	0.2	0.2
Other	17.7	17.3	17.3	17.3	17.3	17.3
Fuel	3.0	3.1	3.1	3.1	3.1	3.1
Labor (hired)	68.8	67.4	67.4	67.4	67.4	67.4

In the system without irrigation, direct costs in the combinations with biopreparations were lower by 5488 PLN than in the irrigated system. Here too, labor accounted for the majority of costs (73.9%), followed by fertilizers (3.0%), biopreparations (2.1%), and fuel (2.8%) (Table 7).

Manual labor in strawberry cultivation is often the most important element of the cost structure. This is linked to the nature of the crop, where mechanization of crucial management practices (particularly harvesting and plantation maintenance) is low. Most of the labor is related to planting, weeding, pruning, harvesting, and general field maintenance. Achieving a high economic efficiency of the production of strawberries in Poland can be supported by its local natural, climatic, and soil conditions [20]. One of the limiting factors affecting strawberries is pathogens. Strawberry plants can be negatively affected by fungi such as *Botritis cinerea*, *Colletotrichum acutatum*, *Phytophtora cactorum*, *Fusarium oxysporum*, and *Verticillium dahlia*. Disease and pest prevention and control measures, including biological measures, are essential for keeping crop productivity [41,42]. In the present study, the tested biopreparations included different organic compounds, including *Bacillus* sp., humic acids, yeast culture effluent, micronized dolomite, mustard, and rapeseed oil, which provided some nutrients but could also be beneficial in terms of supporting biological pest control. The direct costs of the use of the tested biopreparations were the same for each tested combination, as the cost for each of the newly developed biopreparations was the same (the doses per hectare were also the same). However, the potential for yield promotion of the tested treatments was different and strongly influenced yield quantity (Table 4). Adequate plant nutrition is a factor that often determines the yield. In the case of strawberries, as with many other plants, nitrogen supply is crucial. Calcium and micro-nutrients are also important to support the quality of strawberries [43]. Nutrient management based on growth stages can help promote yield and quality, potentially offsetting indirect costs associated with suboptimal nutrient management practices [44].

The direct costs of organic strawberry production in the research conducted by Brzozowski and Zmarlicki [29] were 14,280 PLN·ha^{-1}, with direct costs lower by 1550 PLN·ha^{-1} in conventional farms. The difference was due to higher expenditures on manual work in organic farming systems. The authors found that fruit harvesting (labor) was the most expensive cost of strawberry production. Labor costs were assessed at 43.2% in conventional cultivation and at 57.5% of the total direct costs, while in the present study, those costs were higher, reaching about 67.4% in the irrigated experiment compared to 73.9% in the non-irrigated experiment. On the other hand, Brzozowski and Zmarlicki [8], on the basis of their research, found that for the profitability of organic strawberry production, human labor costs were the most important factor, accounting for more than 90% of the determined direct costs, which is very similar to findings of the present study. According to Brzozowski and Zmarlicki [8] organic strawberry labor productivity can be increased (reduced labor costs) by utilizing equipment and machinery to remove runners and weeds. In the present study, both runners and weeds were removed manually. Brzozowski and Zmarlicki [8] also found the costs of strawberry production with organic methods to be about 9% higher than conventional production when only the surface of the plantation is taken into consideration and about 30% higher for 1 kg of fruits.

In Paszko's [45] study of strawberry harvesting costs, depending on the direction of production, harvesting dessert fruit was on average twice as expensive as fruit for processing. Picking costs accounted for between 46.0 and 53.9% of total strawberry harvesting costs. According to Paszko [45], strawberry cultivation is characterized by high labor intensity, of which fruit harvesting is the most expensive. According to Gołębiewska and Sobczak [46], the level of profitability of strawberry production depends on the intensity and destination of production (direct consumption or processing), the yield, and the selling prices. The profitability of strawberry production can be increased by extending the harvesting period, but this requires the selection of suitable cultivars and the use of modern technologies [47] Moreover, Paszko et al. [19] found a possibility of increasing the productivity of strawberry plantations by the introduction of new, more productive cultivars or the use of modern production technologies.

3.2.2. Yield Value and Direct Surplus

Yields are a critical determinant of both economic efficiency and direct surplus. Higher yields lead to greater efficiency and surpluses. In the present study, for the non-irrigated system, a high direct surplus was observed for the application of the K4 formulation combination (for all cultivars), which reached about 38.6 thousand PLN·ha^{-1} (Table 6). Higher values of direct surplus for this system were observed for 'Vibrant' in the case of the application of K3 (43.1 thousand PLN·ha^{-1}) and, surprisingly, in the case of no application of preparations (40.8 thousand PLN·ha^{-1}).

In the irrigated system, the best economic effect expressed in terms of direct surplus was found for the combination of K3 (direct surplus from 41.0 thousand PLN to 46.8 thousand PLN·ha^{-1} depending on the cultivar) (Table 6). A similar direct surplus was recorded for the combination of K5 for the 'Rumba' and 'Vibrant' cultivars (approximately

PLN 44.4–42.5 thousand ha^{-1}). However, at the same time, one of the worst economic efficiencies was observed for this formulation for the cultivar 'Honeoye' (18.5 thousand PLN·ha^{-1}).

The lowest direct surplus values in the irrigated system were found for the control (without biopreparations) and the biopreparation combination K4 (16.4 and 18.0 thousand PLN·ha^{-1}, respectively) (Table 6).

The lowest values of direct surpluses in the non-irrigated system were recorded for the control (16.1 thousand PLN·ha^{-1}) and, among the sites with biopreparation applications, for K2 and K5 (about 24.3 and 24.6 thousand PLN·ha^{-1}) (Table 6). Brzozowski and Zmarlicki [29], on the basis of their research on the economics of organic apple, cherry, and strawberry production found that strawberry production in the organic system was more profitable than conventional strawberry production. Similarly, Pawlak et al. [20] reported higher or comparable economic efficiency for organic crops compared to conventional crops, which was also due to 17–23% higher fruit selling prices and higher yields in the organic farming system. In the present study, the profitability of production of three strawberry cultivars did not receive an organic "price premium" (higher price for organic fruits), as there is basically no large purchaser of organic strawberries in the area. In the present study, no organic price premium was adopted to calculate the economic efficiency of strawberry production. Prices for conventional strawberry were used, as most probably it would be difficult to sell organic strawberries at higher prices on the local market. Other authors, like Sredojević et al. [48], on the basis of a survey study, found organic strawberry production more profitable than conventional cultivation. According to Paszko et al. [49], in countries where berries are produced mainly for the fresh (dessert) market, the stability of farmgate prices is higher. This shows that the profitability of organic and conventional production is dependent on (local) market conditions.

An important element for the profitability of agricultural production is the effectiveness of the pest management used [50]. A study by Vultaggio et al. [51] investigated the combined effect of *Trichoderma atroviride* and a plant-derived protein hydrolysate in forest strawberry production. The results showed that the application of microbial and non-microbial biostimulants significantly improved the yields, fruit quality, and economic profitability of strawberry cultivation. Moreover, the integration of microbial communities into plant nutritional regimes can influence post-harvest characteristics and economic aspects of strawberry production. The application of different classes of biostimulants on strawberry plants has been shown to enhance growth, yield, and fruit quality under nutrient limitation conditions, as demonstrated by Soppelsa et al. [52]. Furthermore, Soltaniband et al. [53] found that various biostimulants can promote plant development, crop productivity, and fruit quality in protected strawberries, ultimately impacting the economic efficiency of cultivation.

Valentinuzzi et al. [54] studied the epiphytic microbial community and post-harvest characteristics of strawberry fruit under a plant nutrition regime supplemented with silicon. The study identified the presence of probiotic bacteria, such as *Bacillus breve*, in the microbial community associated with strawberries. These probiotic bacteria were found to offer technological benefits and potentially increase the economic efficiency of strawberry cultivation by improving fruit quality and post-harvest characteristics [54].

According to Seufert et al. [30], organic systems are often nutrient-limited, and, for this reason, probably have a weaker response to irrigation than a conventional system. This was partially confirmed by the present study, where the yields of non-irrigated strawberries were at the level of 93% of the irrigated strawberries.

According to Zmarlicki and Brzozowski [9], in economic terms, apples and strawberries are the two most important orchard species in Poland. The price relationship between organic and conventional fruit could convince many Polish fruit growers to switch from conventional to organic production [9]. According to the Institute of Agricultural and Food Economics—PIB in Warsaw, the parity payment rate for the labor input of a farmer and his family members is estimated at PLN 21.39 per hour [55].

The direct surplus per hour worked in the non-irrigated experiment was the highest for the K4 treatment and reached 11.42 PLN·h^{-1} on average without subsidies and 12.27 PLN·h^{-1}. The direct surplus per hour worked reached 12.75 PLN h^{-1} for 'Vibrant' treated with K3. Interestingly, 'Vibrant' treated with water (control—K1) showed a direct surplus at a very high level of 12.08 PLN·ha^{-1}. The direct surpluses in the irrigated experiment were generally higher than those in the non-irrigated experiment. However, treatment K4 showed rather poor performance in terms of direct surplus per hour worked, reaching on average 5.26 and 6.10 PLN·h^{-1} without and with subsidies, respectively. A direct surplus of 12.53 and 13.37 PLN·h^{-1} without and with subsidies was found for the K3 treatment (average for three cultivars) (Table 8).

Table 8. Direct surplus (PLN per working hour) according to the combination of preparations used, irrigation, and strawberry cultivars.

Specification	Treatment					
	K1	K2	K3	K4	K5	K6
Non-irrigated						
'Honeoye'	−0.48	5.55	8.50	11.56	4.58	8.58
'Rumba'	2.72	8.07	7.92	11.59	7.28	9.08
'Vibrant'	12.08	7.97	12.75	11.11	9.93	4.87
Average	4.78	7.19	9.72	11.42	7.26	7.50
Average with subsidies	5.63	8.04	10.57	12.27	8.11	8.36
Irrigated						
'Honeoye'	5.51	8.61	13.65	4.28	5.40	5.26
'Rumba'	2.56	9.73	11.97	7.08	12.95	6.38
'Vibrant'	6.49	7.64	11.97	4.56	12.39	7.36
Average	4.81	8.61	12.53	5.26	10.29	6.38
Average with subsidies	5.65	9.45	13.37	6.10	11.13	7.21

On average, for all combinations, the 'Vibrant' cultivar reached a direct surplus of 33,068.8 PLN per hectare in the non-irrigated part, while 'Rumba' reached 28,938.8 PLN per hectare in the irrigated one. The non-irrigated 'Rumba' and 'Vibrant' showed direct surpluses higher than that of 'Honeoye' by 21.8% and 53.3%, respectively. In the irrigated experiment, those differences were 18.7% for 'Rumba' and 18% for 'Vibrant'.

3.2.3. Profitability Index

The profitability index in strawberry cultivation is a measure of the profitability of growing strawberries, calculated by comparing the costs incurred in cultivation to the returns generated from the sale of the strawberries. In the present study, only the cultivation of the non-irrigated 'Honeoye' with no biopreparation added was unprofitable (profitability index of 97.1%) (Table 9). The highest profitability index for the non-irrigated plantation was found, on average, for the K3 (158.6%) and K4 treatments (168.8%), with 'Vibrant' treated with K3 as the most profitable unirrigated cultivar. The non-irrigated 'Vibrant' with no microbial treatment had one of the highest profitability indexes at 174.4%. The yield offsetting the direct costs for tested treatments on the non-irrigated plantation was 11.7 t, while the untreated plantation needed 11.4 t to offset the direct costs of production.

The irrigated strawberry plantation showed a profitability index above 100% for all tested treatments and also for the control object. The K3 and K5 treatments were, on average, the most profitable ones, with profitability indices of 169.7% and 157.3%, respectively. The object with no biopreparation treatment was least profitable on the irrigated strawberry plantation, followed by the K4 object (127.3% and 129.2, respectively). The yield offsetting the direct costs on the irrigated plantation was higher than on the non-irrigated plantation and reached 12.8 t, while the untreated plantation needed 12.6 t to offset the direct costs of production. Chaulagain et al. [56] highlighted that growing strawberries is a profitable enterprise, as the returns are greater than the costs incurred. This indicates that the profitability index in strawberry cultivation can be positive, making it a financially viable agricultural activity. The profitability of production can also be influenced by the yield stability over time and quality of the strawberries produced [57]. Those two factors were not taken into account in the present study; however, only fruits with no visible pathogen infestation were harvested. The yields achieved in organic farming are often at a lower level than in conventional farming. At the same time, organic strawberries are perceived as a wholesome, high-quality product, and therefore the price of the crop is often higher. Economic analyses have shown that differences in organic and conventional yield can be offset by the higher retail price of organic strawberries, leading to superior profitability of organic production [58]. The share of yield classified as commercial produce is also important for the profitability of strawberry cultivation [59].

Table 9. Profitability index (%) and yield offsetting direct costs depending on the combination of preparations used, irrigation, and strawberry cultivars.

Specification	Treatment					
	K1	K2	K3	K4	K5	K6
		Non-irrigated				
'Honeoye'	97.1	133.4	151.2	169.7	127.6	151.7
'Rumba'	116.8	148.6	147.7	169.8	143.9	154.7
'Vibrant'	174.4	148.0	176.8	166.9	159.8	129.3
Average	129.5	143.3	158.6	168.8	143.8	145.2
Yield offsetting direct costs (t)	11.4	11.7	11.7	11.7	11.7	11.7
		Irrigated				
'Honeoye'	131.3	147.9	176.0	123.8	130.0	129.2
'Rumba'	114.6	154.2	166.6	139.4	172.1	135.5
'Vibrant'	136.8	142.5	166.6	125.4	169.0	140.9
Average	127.3	147.9	169.7	129.2	157.3	135.5
Yield offsetting direct costs (t)	12.6	12.8	12.8	12.8	12.8	12.8

Source: own calculations.

4. Summary and Conclusions

The irrigated strawberries yielded a similar (18.74 t·ha^{-1}) level as the non-irrigated objects (17.51 t·ha^{-1}). Some of the tested cultivars in both the irrigated and non-irrigated experiments showed statistically higher yields when treated with tested microbial fertilizing products; for the others, this was not proven statistically. Direct costs per hectare in the present experiments were lower in the non-irrigated system (ranging from 54,783 PLN to 56,089 PLN) compared to the irrigated system (ranging from 60,271 PLN to 61,586). This was to a large extent due to the water costs and also the limitations of the experimental site, where water had to be transported in tanks to the experiment.

The average profitability index for all tested non-irrigated and irrigated cultivars (average) with no microbial fertilizers added was 129.5% and 127.3%, respectively. The addition of tested microbial fertilizing products improved the profitability index to 143.3–168.8% on the non-irrigated site and to 129.2–169.7% on the irrigated plantation.

Of the biopreparations tested, the economic effects of the K3 combination were satisfying for the broad growing conditions, i.e., its use gave a relatively good economic result for all cultivars, both in the irrigated and non-irrigated systems. The K4 treatment in the non-irrigated experiment also showed a very positive economic effect and can be recommended for strawberry cultivation without irrigation. Of the biopreparations tested, the economic effects of the K6 combination were unsatisfying for broad cultivation conditions (i.e., it produced a relatively small increase in direct surplus for all cultivars, both in the irrigated and non-irrigated systems), although for some cultivars, the effectiveness of the K6 treatment was at a moderate level.

This study showed that different cultivars respond differently to microbial fertilizers. Also, its effectiveness can be affected by management practices (irrigated vs. non-irrigated fields). Future studies should include different cultivars, such as 'Elsanta', 'Senga Sengana', 'Polka', 'Roxana', 'Marmolada', 'Pegasus', 'Kent', 'Florence', or 'Albion' to check the response of different cultivars to microbial products and to search for recommendations of different products for the specific cultivars (and cultivation conditions). It would also be interesting to test the performance of the tested formulations in integrated and conventional plantations, as tested treatments can be used alongside other conventional treatments. Longer studies (e.g., over four consecutive growing seasons), including other soft fruit species (e.g., raspberries) could result in a cumulative effect of microbial community establishment in soil over time. The rested microbial fertilizing products showed that they can be valuable products to improve the productivity and economic effectiveness of organic strawberry production. At the same time, their use has to be adapted to plantation conditions (e.g., cultivar and/or irrigation practices).

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References

1. European Commission. *Communication from the Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee and The Committee of the Regions, The European Green Deal*; European Commission: Brussels, Belgium, 2019.
2. EUR-Lex, European Union. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:ea0f9f73-9ab2-11ea-9d2d-01aa75ed71a1.0015.02/DOC_1&format=PDF (accessed on 18 September 2024).
3. Parlińska, M.; Jaśkiewicz, J.; Rackiewicz, I. Challenges for Agriculture under the European Green Deal Development Strategy During the COVID-19 Pandemic Period. *Sci. J. Wars. Univ. Life Sci. Probl. World Agric.* **2020**, *20*, 22–36. [CrossRef]
4. Golik, D.; Żmija, D. Organic Farming and the Prospects for Its Development in Poland in the Light of the European Union's Experience. *Krakow Rev. Econ. Manag.* **2017**, *1*, 117–129. [CrossRef]
5. The European Parliament and The Council of the European Union. Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on organic production and labelling of organic products and repealing Council Regulation (EC) No 834/2007. *Off. J. Eur. Union* **2018**, L 150/1–L 150/92.
6. Nachtman, G. Organic farming in Poland and activities undertaken for its development. *Pol. Stat.* **2021**, *66*, 24–43. [CrossRef]
7. Klepacka, A.M. Selected assumptions of the European Green Deal and possibilities of development of a conventional and organic farm. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2023**, *25*, 108–123. [CrossRef]
8. Brzozowski, P.; Zmarlicki, K. The changes of unicosts of strawberry organic production in the years 2009–2013. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2015**, *17*, 9–13.
9. Zmarlicki, K.; Brzozowski, P. Comparison of wholesale prices of fruits from organic and conventional production. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2013**, *15*, 386–390.
10. Rahmann, G.; Ardakani, M.R.; Bàrberi, P.; Boehm, H.; Canali, S.; Chander, M.; David, W.; Dengel, L.; Erisman, J.W.; Galvis-Martinez, A.C.; et al. Organic Agriculture 3.0 is innovation with research. *Org. Agric.* **2017**, *7*, 169–197. [CrossRef]
11. European Commission. *Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions, EU Biodiversity Strategy for 2030, Bringing Nature Back into Our Lives*; European Commission: Brussels, Belgium, 2020. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0380 (accessed on 12 June 2023).

12. European Commission. *Communication from the Commission to the European Parliament, The European Council, The Council, The European Economic and Social Committee and The Committee of the Regions, A New Circular Economy Action Plan for a Cleaner and More Competitive Europe*; Forging a Climate-Resilient Europe—The New EU Strategy on Adaptation to Climate Change; European Commission: Brussels, Belgium, 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN (accessed on 27 December 2023).
13. Kociszewski, K.; Śliczna, M. Development of organic food distribution system in Poland at the background of situation in the Europenan Union. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2010**, *12*, 183–189.
14. Pawlak, J.; Paszko, D.; Wróblewska, W. Prospects to the sale of organic fruit and vegetables in Lublin in the opinion of retailers. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2016**, *18*, 202–206.
15. Drobek, M.; Cybulska, J.; Frąc, M.; Pieczywek, P.; Pertile, G.; Chibrikov, V.; Nosalewicz, A.; Feledyn-Szewczyk, B.; Sas-Paszt, L.; Zdunek, A. Microbial biostimulants affect the development of pathogenic microorganisms and the quality of fresh strawberries (*Fragaria ananassa* Duch.). *Sci. Hortic.* **2024**, *327*, 112793. [CrossRef]
16. Nakielska, M.; Feledyn-Szewczyk, B.; Berbeć, A.K.; Frąc, M. Microbial biopreparations and their impact on organic strawberry (*Fragaria x ananassa* Duch.) yields and fungal infestation. *Sustainability* **2024**, *16*, 7559. [CrossRef]
17. Paszko, D. Profitability of fresh and industrial strawberry production in Poland. *Sci. J. Inst. Pomol. Floric. Szczepan Pieniążek* **2009**, *17*, 67–78.
18. Paszko, D.; Krawiec, P.; Pawlak, J.; Wróblewska, W. Assess the cost and profitability of raspberry production under cover in the context of building competitive advantage on example of selected farm. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2017**, *19*, 218–223. [CrossRef]
19. Paszko, D.; Pawlak, J.; Wróblewska, W. Yield of two strawberry cultivars depending on the cropping method on the example of a commercial plantation in a specialized horticultural farm. *Acta Sci. Pol. Hortorum Cultus* **2014**, *13*, 149–159.
20. Pawlak, J.; Wróblewska, W.; Paszko, D. Production and economic efficiency in the cultivation of strawberry (*Fragaria* × *ananassa* Duch.) depending on the method of production—Case study. *Agron. Sci.* **2022**, *78*, 15–26. [CrossRef]
21. Diel, M.I.; Pinheiro, M.V.M.; Cocco, C.; Caron, B.O.; Fontana, D.C.; Meira, D.; Thiesen, L.A.; Schmidt, D. Yield and Quality Performance of Italian and American Strawberry Genotypes in Brazil. *J. Agric. Sci.* **2018**, *10*, 139–147. [CrossRef]
22. Helepciuc, F.-E.; Todor, A. EU microbial pest control: A revolution in waiting. *Pest Manag. Sci.* **2022**, *78*, 1314–1325. [CrossRef]
23. Prandecki, K.; Wrzaszcz, W.; Zieliński, M. Environmental and climate challenges to agriculture in Poland in the context of objectives adopted in the European Green Deal Strategy. *Sustainability* **2021**, *13*, 10318. [CrossRef]
24. Wolf, S.; Teitge, J.; Mielke, J.; Schütze, F.; Jaeger, C. The European Green Deal—More than climate neutrality. *Intereconomics* **2021**, *2*, 99–107. [CrossRef]
25. Liobikienė, G.; Miceikienė, A. Contribution of the European Bioeconomy Strategy to the Green Deal Policy: Challenges and opportunities in implementing these policies. *Sustainability* **2023**, *15*, 7139. [CrossRef]
26. Skarżyńska, A.; Abramczuk, Ł.; Czułowska, M. *Wyniki Ekonomiczne Produktów Rolniczych w 2016 Roku*; IERiGŻ-PIB: Warszawa, Poland, 2016; p. 112.
27. Żekało, M. *Produkcja, Koszty i Dochody Wybranych Produktów Rolniczych w Latach 2014–2015*; IERiGŻ-PIB: Warszawa, Poland, 2016; 89p.
28. Harasim, A. *Przewodnik Ekonomiczno-Rolniczy w Zarysie*; IUNG-PIB: Puławy, Poland, 2006.
29. Brzozowski, P.; Zmarlicki, K. Economics of the 2009–2012 organic apple, strawberry, and sour cherry production in Poland. *J. Fruit Ornam. Plant Res.* **2012**, *20*, 63–70. [CrossRef]
30. Seufert, V.; Ramankutty, N.; Foley, J.A. Comparing the yields of organic and conventional agriculture. *Nature* **2012**, *485*, 229–232. [CrossRef] [PubMed]
31. Sas-Paszt, L.; Sumorok, B.; Górnik, K.; Grzyb, Z.S.; Lisek, A.; Głuszek, S.; Trzciński, P.; Derkowska, E.; Frąc, M.; Treder, W.; et al. Influence of beneficial soil microorganisms and mineral fertilizers enriched with them on the flowering, fruiting, and physical and chemical parameters of the fruit of three-year-old strawberry plants in field cultivation. *Hortic. Sci.* **2023**, *50*, 112–126. [CrossRef]
32. Drobek, M.; Cybulska, J.; Gałązka, A.; Feledyn-Szewczyk, B.; Marzec-Grządziel, A.; Sas-Paszt, L.; Gryta, A.; Trzciński, P.; Zdunek, A.; Frąc, M. The use of interactions between microorganisms in strawberry cultivation (*Fragaria* × *ananassa* Duch.). *Front. Plant Sci.* **2021**, *12*, 780099. [CrossRef]
33. Mikiciuk, G.; Sas-Paszt, L.; Mikiciuk, M.; Derkowska, E.; Trzciński, P.; Głuszek, S.; Lise, A.; Wera-Bryl, S.; Rudnicka, J. Mycorrhizal frequency, physiological parameters, and yield of strawberry plants inoculated with endomycorrhizal fungi and rhizosphere bacteria. *Mycorrhiza* **2019**, *29*, 489–501. [CrossRef]
34. Gendron, L.; Létourneau, G.; Cormier, J.; Depardieu, C.; Boily, C.; Levallois, R.; Caron, J. Using pulsed water applications and automation technology to improve irrigation practices in strawberry production. *HortTechnology* **2018**, *28*, 642–650. [CrossRef]
35. Ariza, M.T.; Miranda, L.; Gómez-Mora, J.A.; Medina, J.J.; Lozano, D.; Gavilán, P.; Soria, C.; Martínez-Ferri, E. Yield and Fruit Quality of Strawberry Cultivars under Different Irrigation Regimes. *Agronomy* **2021**, *11*, 261. [CrossRef]
36. Santos, B.M.; Salame-Donoso, T.P.; Whidden, A.J. Reducing sprinkler irrigation volumes for strawberry transplant establishment in Florida. *HortTechnology* **2012**, *22*, 224–227. [CrossRef]
37. Depardieu, C.; Prémont, V.; Boily, C.; Caron, J. Sawdust and Bark-Based Substrates for Soilless Strawberry Production: Irrigation and Electrical Conductivity Management. *PLoS ONE* **2016**, *11*, e0154104. [CrossRef]
38. Cormier, J.; Depardieu, C.; Letourneau, G.; Boily, C.; Gallichand, J.; Caron, J. Tensiometer-based irrigation scheduling and water use efficiency of field-grown strawberries. *Agron. J.* **2020**, *112*, 2581–2597. [CrossRef]

39. Christou, A.; Maratheftis, G.; Elia, M.; Hapeshi, E.; Michael, C.; Fatta-Kassinos, D. Effects of wastewater applied with discrete irrigation techniques on strawberry plants' productivity and the safety, quality characteristics and antioxidant capacity of fruits. *Agric. Water Manag.* **2016**, *173*, 48–54. [CrossRef]
40. Renai, L.; Tozzi, F.; Scordo, C.V.A.; Giordani, E.; Bruzzoniti, M.C.; Fibbi, D.; Mandi, L.; Ouazzani, N.; Bubba, M. Productivity and nutritional and nutraceutical value of strawberry fruits (*Fragaria* × *ananassa* Duch.) cultivated under irrigation with treated wastewaters. *J. Sci. Food Agric.* **2021**, *101*, 1239–1246. [CrossRef] [PubMed]
41. Meszka, B.; Michalecka, M. Identification of *Phytophthora* spp. isolated from plants and soil samples on strawberry plantations in Poland. *J. Plant Dis. Prot.* **2016**, *123*, 29–36. [CrossRef]
42. Łabanowska, B.H.; Tartanus, M.; Gruchała, M.; Masny, A. Efficacy of *Beauveria Bassiana* and Abamectin in the control of strawberry mite-*Phytonemus pallidus* (Banks) (Acari: Tarsonemidae) and the susceptibility of cultivars to pest infestation. *J. Berry Res.* **2015**, *5*, 1–7. [CrossRef]
43. Gupta, S.; Anusree, T.; Harini, K.; Kumar, D.; Kumar, V.; Kulshreshtha, S.K.; Maurya, D.K.; Sonkar, S. Effect of Nitrogen, Calcium and Nano Fertilizers on Growth Yield and Quality of Strawberry (*Fragaria* × *ananassa* Duch.): A Review. *Int. J. Environ. Clim. Change* **2023**, *13*, 2299–2307. [CrossRef]
44. Yu, W.; Zheng, J.; Wang, Y.; Ji, F.; Zhu, B. Adjusting the nutrient solution formula based on growth stages to promote the yield and quality of strawberry in greenhouse. *Int. J. Agric. Biol. Eng.* **2023**, *16*, 57–64. [CrossRef]
45. Paszko, D. Costs of strawberries picking depending of production type. *Ann. Pol. Assoc. Agric. Agribus. Econ.* **2010**, *12*, 245–250.
46. Gołębiewska, B.; Sobczak, N. Directions of use and profitability of strawberry production. The Use and Profitability of Strawberries. *Sci. J. Wars. Univ. Life Sci. Econ. Organ. Agri-Food Sect.* **2012**, *98*, 109–121.
47. Masny, A.; Żurawicz, E. Season extension possibilities in two Polish june-bearing strawberry cultivars. *Acta Sci. Pol. Hortorum Cultus* **2015**, *14*, 115–127.
48. Sredojević, Z.; Vlahović, B.; Maksimović, A. Economic indicators of different ways of strawberry production on family farms. *Agroekonomika* **2015**, *44*, 114–124.
49. Paszko, D.; Pawlak, J.; Wróblewska, W. Seasonal Fluctuations in Berries Production in Poland and in the World. *Sci. J. Wars. Univ. Life Sci. Probl. World Agric.* **2016**, *16*, 301–312.
50. Kruk, K.; Dzięgielewska, M. The influence of acetamiprid and chlorpyrifos on the biological activity entomopathogenic nematodes (Steinernematidae, Heterorhabditidae). *Prog. Plant Prot.* **2020**, *60*, 179–185. [CrossRef]
51. Vultaggio, L.; Allevato, E.; Consentino, B.B.; Bellitto, P.; Napoli, S.; Cannata, C.; Ntatsi, G.; Vasto, S.; Baldassano, S.; La Bella, S.; et al. Joint Action of *Trichoderma atroviride* and a Vegetal Derived-Protein Hydrolysate Improves Yield, Fruit Quality and Economic Profitability of Two Woodland Strawberry Cultivars Grown under Greenhouse. *Preprints* **2024**. [CrossRef]
52. Soppelsa, S.; Kelderer, M.; Casera, C.; Bassi, M.; Robatscher, P.; Matteazzi, A.; Andreotti, C. Foliar Applications of Biostimulants Promote Growth, Yield and Fruit Quality of Strawberry Plants Grown under Nutrient Limitation. *Agronomy* **2019**, *9*, 483. [CrossRef]
53. Soltaniband, V.; Brégard, A.; Gaudreau, L.; Dorais, M. Biostimulants Promote Plant Development, Crop Productivity, and Fruit Quality of Protected Strawberries. *Agronomy* **2022**, *12*, 1684. [CrossRef]
54. Valentinuzzi, F.; Pii, Y.; Borruso, L.; Mimmo, T.; Puglisi, E.; Trevisan, M.; Cesco, S. Epiphytic Microbial Community and Post-Harvest Characteristics of Strawberry Fruits as Affected by Plant Nutritional Regime with Silicon. *Agronomy* **2021**, *11*, 2407. [CrossRef]
55. Augustyńska, I. *Production, Costs and Income of Selected Agricultural Products in 2021–2022*; IERiGŻ-PIB: Warsaw, Poland, 2023; p. 120.
56. Chaulagain, M.; Dhakal, A.; Adhikari, A.; Oli, D. Value chain analysis of strawberry in Nuwakot district. *Rev. Food Agric.* **2022**, *3*, 1–5. [CrossRef]
57. Lapshin, V.; Yakovenko, V.; Shcheglov, S. Analysis of yield stability of strawberry cultivars and hybrids. *BIO Web Conf.* **2020**, *25*, 02014. [CrossRef]
58. Rhainds, M.; Kovach, J.; English-Loeb, G. Impact of strawberry cultivar and incidence of pests on yield and profitability of strawberries under conventional and organic management systems. *Biol. Agric. Hortic.* **2002**, *19*, 333–353. [CrossRef]
59. Zanin, D.S.; Fagherazzi, A.F.; Santos, A.M.; Martins, R.; Kretzschmar, A.A.; Rufato, L. Agronomic performance of cultivars and advanced selections of strawberry in the South Plateau of Santa Catarina State. *Rev. Ceres Viçosa* **2019**, *66*, 159–167. [CrossRef]

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The Effect of Newly Developed Microbial Biopreparations on the Chemical Composition of Strawberry (*Fragaria* × *ananassa* Duch.) Fruit Grown in an Organic Farming System

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Abstract: Non-chemical methods of fertilisation and protection have been gaining importance in recent years. This trend is closely linked to current European Union (EU) agricultural policy and the growing consumer awareness of the impact of nutrition on health. Newly developed biopreparations have to be tested for their agricultural efficiency alongside a quality assessment of the resulting food. The aim of this study was to determine whether the use of newly developed microbially enriched fertilisers in organic strawberry cultivation had an effect on fruit chemical composition and heavy metal accumulation. In the research, five biopreparations (K2–K6 combinations) containing selected *Bacillus* strains and plant extracts were tested in 2021 and 2022 on three strawberry cultivars: 'Honeoye', 'Rumba', and 'Vibrant'. After the vegetation period, the collected fruit samples were frozen, freeze-dried, and subjected to chemical analyses to determine the total carbon and nitrogen content, as well as the concentration of microelements (Mn, Fe), macroelements (Na, Mg, K, Ca, P) and heavy metals (Cd, Pb, Cu, and Zn). The application of the tested biopreparations did not significantly impact the total carbon content of strawberry fruit. For most of the tested traits, cultivars reacted differently to the tested preparations. A higher total nitrogen content was found for treatments treated with biopreparations, especially for the 'Vibrant' cultivar—ranging from 15.2 g·kg^{-1} K2 (BacilRoots) to 16.3 g·kg^{-1} K3 (BacilRoots + BacilExtra) and K5 (BacilRoots + BacilExtra + BacilHumus)—being about 10–18% higher than on the control object (K1). The content of sodium, phosphorus, calcium, and magnesium did not change significantly under the influence of biopreparations. The use of the K3 and K5 treatment resulted in significantly lower iron contents when compared to those of the control (strawberries sprayed with water with no biopreparations added)—respectively, by 16.1% and 17.9%. 'Vibrant' treated with water (control treatment) showed the highest contents of iron, copper, and zinc when compared to those treated with biopreparations. No exceedances of the permissible heavy metal content were found in the samples tested.

Keywords: macroelements; microelements; organic system; non-chemical plant protection; microbial fertilising products

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1. Introduction

A review of the international literature reveals an increasing awareness among farmers of the necessity to reduce the use of chemical inputs in plant cultivation and to introduce organic products instead [1]. This fact facilitates the development of biological alternatives based on, among others, beneficial microorganisms that can protect plants from diseases, stimulate their growth and development, provide the necessary mineral nutrients, and improve soil quality [2].

The negative effects of excessive chemical input have led to a necessity for the replacement of these inputs with organic alternatives that do not pose a risk to human health and the environment [1]. One method of reducing the utilisation of fertilisers is to enhance their efficacy through the incorporation of beneficial microorganisms, which may encompass filamentous and arbuscular fungi (AMF), in addition to bacteria that facilitate the growth and physiological condition of plants. These microorganisms can also contribute to soil quality improvement and to the protection of plants from diseases and pests [1]. The limited availability of manure, as the majority of both conventional and organic farms do not keep livestock, is often a significant challenge, especially for organic farming. This is why organic farmers are searching for alternatives that can effectively fulfil the role of mineral fertilisers [2]. Şener and Cantemur [3] found that the consumer interest in premium foodstuffs being produced in an environmentally conscious manner can be attributed to a heightened environmental awareness and also a decline in consumer confidence in the quality and safety of mass-produced foodstuffs, which are often contaminated with dioxins, bacterial pathogens, and heavy metals.

A diet based on food from conventional, intensive agriculture can be contaminated with plant protection product (PPP) residues. This can translate into an increased incidence of cancer and chronic diseases among consumers. Therefore, it is important to provide farmers with solutions, including safe formulations for fertilisation and plant health improvement, that will promote yield quantity and food quality and are safe for consumers.

Strawberry fruits, derived from *Fragaria chiloensis* and *Fragaria virginiana*, date back to the 18th century. Currently, these are of great interest to consumers, mainly for their tastiness, but especially for their numerous health-promoting properties and high content of bioactive compounds [4–6].

The high content of phenolic compounds in strawberries, including anthocyanins, flavonols, and derivatives of hydroxycinnamic acid and ellagic acid, contributes to their antioxidant activity [7]. Additionally, strawberries are rich in amino acids, which provide health benefits such as antimutagenicity, a reduction in blood sugar, and a decrease in coronary heart diseases [8,9]. They are a source of minerals (iron, potassium, calcium, phosphorus) and vitamins A and C [10–14]. They also contain pectin, fibre, carotenoids [10,12,15–17], and glutathione [10].

Camargo et al. [18] found that organic strawberries had a higher anthocyanin content than that of conventional ones. Organic products are often considered safer as they contain lower levels or are completely free of pesticide residues, making them a preferred choice for consumers concerned about food safety and health [19–21]. On the other hand, some authors showed that organic crops are more likely to be contaminated by mycotoxins [22,23], while Brodal et al. [24], on the basis of a literature study, concluded that a farming system itself does not increase the risk of mycotoxin contamination. Organic products were also chosen by consumers as they had better sensory attributes, such as taste, texture, and aroma [25,26]. Consumer perception and willingness to pay also play a significant role in the preference for organic fruits. Some consumers are willing to pay a premium for organic fruits due to their perceived environmental benefits, such as reduced chemical input and support for sustainable agricultural practices [27,28].

According to Jamiołkowska and Hetman [29], increasing consumer demands for the quality of food consumed as well as a growing interest in environmental issues are the main causes of the increasing share of alternative, sustainable production methods in agriculture. Currently, the safety of plant protection products and promotion of biological and other non-chemical methods to improve plant health are of great interest both to agricultural scientists and farmers [29,30].

As a safer alternative, it is recommended to use PGPR—plant-growth-promoting rhizobacteria—which positively affect plant health and growth by suppressing pathogenic organisms and accelerating nutrient availability and assimilation [31]. In contrast, Mynett et al. [32] emphasise the importance of PGPMs (plant-growth-promoting microorganisms), which stimulate the growth of young plants, enhance root system development, and improve their resistance to abiotic and biotic stresses. PGPMs include, among others, *Trichoderma harzianum*, *Bacillus amyloliquefaciens*, *Serenolipita indica*, and *Gliocladium virens*, which are used in bioprotection against numerous fungal diseases.

According to Schönbichler et al. [33], the intensive use of chemical plant protection products has led to substantial environmental pollution, which poses a significant threat to human and animal health. This is mostly due to the translocation of pesticides' active substances through food chains, which can ultimately risk the health of people. As an alternative, synthetic crop protection products could be replaced by rhizobacteria, which naturally stimulate the growth and health of certain groups of plants [33]. Grzegorczyk et al. [34] highlighted two main advantages of biological plant protection: the increased nutritional value of crops and possibility to utilise pathogen antagonists to degrade mycotoxins. Such activities are in line with the Sustainable Development Goals of soil and food conservation, as well as the implementation of the Farm-to-Table Strategy and thus the European Green Deal.

According to these principles, accelerating the EU's transformation to a sustainable food system involves the production of healthy and quality food products. Thus, the heavy metal content of strawberries can be a serious concern due to the potential health risks associated with their consumption. Heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) can accumulate in strawberry fruit, posing a risk to human health. Moreover, heavy metals accumulated in food can be toxic even in low concentrations [3,35] due to their direct absorption through the gastrointestinal tract. The chosen farm management strategy as well as the choice of the production method can affect the chemical composition of fruit. An organic farming system might have some advantages here, as it does not rely strongly on industrial inputs, which conventional farming does. A study by Şener [3] highlighted that strawberries grown in a conventional system had higher concentrations of heavy metals compared to those grown organically, suggesting that farming practices have a significant impact on strawberry fruit safety and quality.

In view of the increasing number of newly discovered microorganisms and their potential different co-interaction, it is necessary to continue research that will enable the development of effective biopreparations. Their performance will be thoroughly and succinctly tested by scientific bodies, and then, after passing this stage, they will be put on the market [36].

A review of the existing literature reveals a deficit in the research findings exploring the impact of biopreparations on the quality of plant products, including their macro- and micronutrient composition, which is related to their direct nutritional value. Therefore, the aim of this study was to investigate the potential influence of newly developed biopreparations enriched with beneficial microbes and plant extracts on strawberry chemical composition, with the aim of enhancing fruit quality.

2. Materials and Methods

2.1. Experimental Study

The field experiment was set up at the Agricultural Experimental Station of the Institute of Soil Science and Plant Cultivation, State Research Institute in Puławy, located in Grabów nad Wisłą (Mazowieckie region, Poland: 51°21′18.7″ N 21°39′22.2″ E) in May 2019 on a certified organic field on Luvisolstype soil on a grey-brown podzolic soil created from strong loamy sands on light loam. The frigo strawberry seedlings were delivered by the Agronom Plants (Zienki 14, 21-230 Sosnowica, Poland) company. The experimental site had an area of 11.5a and was divided into 72 plots, each with an area of 16 m^2 and with 48 plants cultivated. The pre-crop for the strawberry was red clover. In the first year (2019), the flowers from the strawberry plants were removed in order to strengthen the aboveground parts and roots of the strawberry for the coming seasons. The experimental site was divided into six strips: control (K1) and five strips where the preparations were applied (K2–K6). The formulations tested were developed from locally sourced microbial strains and tested as part of wider study. Furthermore, the microbial products tested in this research are currently undergoing the patenting process and are slated for market introduction as microbial fertilising products. The detailed composition and trade names of the newly developed preparations patented by Bacto-tech Sp. z o.o. are detailed in Table 1.

Table 1. Details of tested biopreparations.

Abbreviation	Trade Name	Details
K1	-	Control object
K2	BacilRoots	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier that consists of dry humic acids, mustard, rapeseed oil, and clove oil in micronised dolomite (10^9 CFU/plant)
K3	BacilRoots + BacilExtra	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier that consists of dry humic acids, mustard, rapeseed oil, and clove oil in micronised dolomite (10^9 CFU/plant), and *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD on a carrier that consists of plant extracts (nettle, horsetail, calendula) and humic acids in micronised dolomite (10^5 CFU/cm^2)
K4	BacilRoots + BacilHumus	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier that consists of dry humic acids, mustard, rapeseed oil, and clove oil in micronised dolomite (10^9 CFU/plant), as well as *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, humic acids, and yeast culture effluent in micronised dolomite (10^5 CFU/cm^2)
K5	BacilRoots + BacilExtra + BacilHumus	Preparation containing *Bacillus* sp. AF75BC and *Bacillus subtilis* AF75AB2 on a carrier that consists of dry humic acids, mustard, rapeseed oil, and clove oil in micronised dolomite (10^9 CFU/plant), and *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD on a carrier that consists of plant extracts (nettle, horsetail, calendula) and humic acids in micronised dolomite (10^5 CFU/cm^2), as well as *Bacillus* sp. Sp116AC*, *Bacillus* sp. Sp115AD, humic acids, and yeast culture effluent in micronised dolomite (10^5 CFU/cm^2)
K6	BacilExtra + BacilHumus	Preparation containing *Bacillus subtilis* AF75AB2 and *Bacillus* sp. Sp115AD on a carrier that consists of plant extracts (nettle, horsetail, calendula) and humic acids in micronised dolomite (10^5 CFU/cm^2), as well as *Bacillus* sp. Sp116AC*, Bacillus sp. Sp115AD, humic acids, and yeast culture effluent in micronised dolomite (10^5 CFU/cm^2)

Source: Nakielska et al. [37], modified.

According to current Polish marketing criteria, the preparations that were used were classified as microbial fertilising products. This implies they have not been registered as biostimulators; however, their composition suggests effects beyond plant health promotion. Additionally, other fertilisers and products approved for organic farming were used to keep the nutrient content of soil at an optimal level (Table 2).

Table 2. Applied bioformulations and fertilisers during 2021 and 2022 seasons.

Treatment Type	Product and/or Formulation	Manufacturer	Dose per Hectare	Number of Treatments
Fertilisation	Redarom Activstart	Biodevas Laboratoires Savigné-1' Évêque, France	1.5 L	2
	Olibio	Biodevas Laboratoires Savigné-1' Évêque, France	2 L	2
	Aminosol (N)	AZELIS POLAND Sp. z o. o., Poznań, Poland	3 L	2
Fertilisation	Potassium sulphate Patentkali®	K+S Polska Sp. z o.o., Poznań, Poland	250 kg	1
	Potassium salt	K+S Minerals and Agriculture GmbH, Kassel, Germany	60 kg	1
	Carbonate lime Polcalc	Polcalc Nawozy Wapniowe Sp. z o.o., Warsaw Poland	500 kg	1
Biopreparations (microbial fertilising products)	K2 (BacilRoots)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K3 (BacilRoots + BacilExtra)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K4 (BacilRoots + BacilHumus)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K5 (BacilRoots + BacilExtra + BacilHumus)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3
	K6 (BacilExtra + BacilHumus)	Bacto-Tech Sp. z o.o., Toruń, Poland	50 kg	3

Source: Nakielska et al. [37].

The experimental factors of the experiments were as follows: (1) the recently developed K2–K6 preparations and (2) three strawberry varieties ('Honeoye' (Figure 1), 'Rumba' (Figure 2), and 'Vibrant' (Figure 3)). These are early varieties recommended for organic cultivation. 'Rumba' shows fairly good resistance to leathery rot and verticilliosis, as well as the powdery mildew of strawberries. It is considered one of the most popular early varieties due to its high resistance to most diseases, frost resistance, as well as good fruit quality and flavour. [38]. 'Vibrant' is a dessert variety with large fruits. It is valued for its flavour, high yielding potential, and long post-harvest shelf life. The variety is moderately resistant to powdery mildew, leathery fruit rot, and strawberry crown rot. An additional advantage is easy and fast harvesting due to the plant height and large fruits [39]. 'Honeoye' is a variety showing good resistance to grey mould and leaf diseases, but it is quite sensitive to verticilliosis and has low frost resistance. It is prized for its juicy and very sweet fruits, which are recommended for processing [40]. The plantation under investigation was not irrigated.

The formulations were applied three times throughout the growing season via a Fragaria boom sprayer (Figure 4). The dose per treatment was 50 kg·ha^{-1} of formulation, dissolved in 700 L of water. The formulation used was a prototype; the target formulations for the market are 10 times more concentrated. The results presented herein are for the 2021 and 2022 harvest seasons, which represent the second and third years of plantation fruiting, respectively. The strawberry fruits were harvested at intervals of 2–3 days. Chemical analyses were conducted on the fruit harvested on 14 June 2021 and 13 June 2022. The fruits were harvested from the same eight plants on each harvest date. Following harvesting, the fruits were frozen and then freeze-dried (lyophilised). The chemical analysis with an ICP-MS spectrometer (for metal content analysis) and a TOC/TN analyser (vario Macro cube CN elementary analyser (Elementar Analysensysteme GmbH; Langenselbold, Germany)) (for carbon and nitrogen content analysis) was used. The analysis of metal concentration was conducted using inductively coupled plasma mass spectrometry (Agilent quadrupole 7500CE ICP-MS; Santa Clara, CA, USA). The extracts were prepared in concentrated nitric acid by microwave digestion. A blank sample and certified reference material (NIST1400 and CRM028-050) were included in the analyses for quality control of the entire analytical process. The basic validation of the parameters included the recognition of recovery, ranging from 90 to 97% for the analysed metals, and precision, defined as a relative standard deviation < 3%. The limit of detection (LOD) ranged from 0.007 mg/kg to 0.099 mg/kg.

Figure 1. Plant of the 'Honeoye' variety.

Figure 2. Plant of the 'Rumba' variety.

Figure 3. Plant of the 'Vibrant' variety.

Figure 4. Application using a Fragaria boom sprayer.

2.2. Meteorological Conditions

Both the years of the study, with the exception of April, were quite dry and warm compared to the multi-year average (Table 3). In particular, May and June 2022 had significantly lower rainfall than the multi-year average for these months.

Table 3. Weather conditions during the 2021 and 2022 growing seasons.

Month	Precipitation [mm]			Temperature [°C]		
	2021	2022	Multi-Annual Average	2021	2022	Multi-Annual Average
April	51.2	42.4	42.0	6.4	6.5	7.5
May	49.9	23.3	53.0	12.5	14.4	12.4
June	70.1 *	31.5	110.0	19.5	19.5	16.7
July	61.7 *	80.6	105.0	21.8	19.1	17.8

* The rainfall values may deviate from the actual ones due to hail damage to the rain gauge.

2.3. Statistical Analysis

Basic statistical analyses were performed to reject random and coarse errors and to create a database of analysed variables. The data were analysed using two-way analysis of variance (ANOVA) followed by a post hoc Fisher's test. The significant differences between the groups of variables were determined at $p < 0.05$. As there were no significant differences between years or interactions of years × biopreparation combinations, the results for the individual traits are presented as an average of 2021–2022. In order to classify the varieties and treatments based on the element content in the strawberry fruits, Principal Component Analysis (PCA) was used to perform ordination. The data were analysed using STATISTICA software (Statistica v. 10, Statsoft Inc., Tulsa, OK, USA).

3. Results and Discussion

The tested biopreparations developed under the EcoFruits project were created in response to the needs of organic strawberry and raspberry farmers. A positive effect of the selected preparation combinations on the strawberry fruit yield was observed on the same experimental site as in the present study (paper by Nakielska et al. [37]). The tested products contained bacteria of the genus *Bacillus*, which when used as biocontrol agents have a positive effect on plants by improving nitrogen fixation; solubilising soil phosphorus; and producing numerous secondary metabolites, such as antioxidants and cell wall-degrading enzymes, which directly support plant resistance against pathogens [33]. Previous research indicates that tested microbial biostimulants affect the development of pathogenic microorganisms and the quality of fresh strawberries that have beneficial influences on fruits. Although the presence of bacteria and fungi in strawberries fruit was observed, the phytopathogens were not present, which may have been a consequence of the application of the tested carriers and microbial preparations [41].

The tested microbial preparations also contained humic acids, which, according to Mynett et al. [32], can change plant metabolism and increase the permeability of cell membranes, which results in the faster transport of mineral compounds in the plant, which in turn increases the intensity of cell respiration and enhances cell division processes.

Sas-Paszt et al. [1] and Mynett et al. [32] found that intensive mineral fertilisation does not always have a positive effect on plant growth. On the other hand, the use of microbial preparations containing the strains *Bacillus* sp. and *Bacillus amyloliquefaciens*, *Paenibacillus* can significantly reduce the use of mineral fertilisers [1,32]. The introduction of natural plant breeding technologies and the use of biofertilisers is an ideal alternative to intensive mineral fertilisation, which increases production costs and negatively impacts the environment [1].

Ayaz et al. [42] emphasise that an integrated approach combining breeding with biological control agents is crucial to maintain biodiversity and ecosystem health from further depletion and to maintain sustainable agricultural practices. The authors note the need for further research on, inter alia, the development of potential biological conservation agents and the use of biotechnology and 'omics' techniques to improve biological control measures [42]. In contrast, Grzegorczyk et al. [34] emphasise that an important direction of research is the search for other positive mechanisms involved in biological plant protection.

Macro- and micronutrients are essential for human health. Ca, P, Mg, S, and F are the building materials of the human body. Na, K, Ca, and Mg are important for the maintenance of osmotic pressure and acid–base balance; Fe and Zn are part of compounds that are crucial for metabolic processes, while Mg and Ca are important for maintaining normal muscle contractility. Strawberry plants are able to easily uptake minerals from the soil, resulting in relatively a high content of minerals in fruits [43].

According to Bojarska et al. [43], strawberry plants readily take up minerals from the soil, so their fruit contains a fairly high amount of these elements.

One of the basic parameters for assessing the quality of an agricultural product, along with an assessment of the impact of the fertiliser product, is the dry weight. The dry matter content of the strawberry fruit differed significantly between cultivars. On average, the highest dry matter content was found in 'Honeoye' (11.18%) and the lowest in 'Vibrant' (8.75%) (Table 4). The effect of biopreparations on the dry matter content was found only for the cultivar 'Honeoye' (higher dry matter content in fruit treated with K2 (11.58%) compared to the control with the lowest dry matter content of 10.64%). For the other two cultivars, a trend towards a positive effect of the biopreparations on the increase in the dry matter content of strawberry fruit was also found, to the greatest extent with the K4 combination, but this could not be confirmed statistically. Kilic [14], on the basis of her research on strawberry cultivars 'Monterey' and 'Albion', found that the application of fertilisers containing beneficial bacteria (including *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, *Bacillus mucilaginosus*) and mycorrhiza can result in increased yields, as well as a positive effect on fruit quality due to the improved uptake rate of nutrients from the soil [14]. The positive effect of the tested microbial biopreparation on the strawberry yield was also confirmed by our research conducted on the same experiment [37].

Table 4. Dry matter content of strawberry fruit [%].

Varieties	Biopreparations						
	K1	K2	K3	K4	K5	K6	Average
'Honeoye'	10.64 a * (±0.50)	11.58 b (±0.56)	11.06 ab (±0.92)	11.44 ab (±1.38)	10.95 ab (±0.77)	11.24 ab (±1.04)	11.18 C (±0.36)
'Rumba'	8.78 a (±0.42)	9.04 a (±0.61)	9.81 a (±0.62)	10.02 a (±0.78)	9.78 a (±1.03)	9.83 a (±1.05)	9.59 B (±0.32)
'Vibrant'	8.07 a (±0.46)	8.93 a (±0.45)	9.28 a (±0.47)	8.99 a (±0.81)	8.70 a (±0.75)	8.31 a (±0.51)	8.75 A (±0.24)
Average	9.17 a (±0.41)	9.85 a (±0.42)	10.05 a (±0.42)	10.15 a (±0.61)	9.81 a (±0.52)	9.79 a (±0.57)	9.84 (±0.20)

* The different lowercase letters in the rows indicate significant differences between biopreparations, and the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were also not statistically significant at $p < 0.05$.

Çakmakçi and Çakmakçi [44], based on review studies, pointed out that organic food has a higher content of nutrients and flavour compounds especially, including compounds such as sugars whose main component is carbon. Nevertheless, no statistically significant differences were found in the total carbon content of strawberries in the tested combinations (Table 5). Despite the lack of significant differences, fruit that was not treated with biopreparations had an average 2.3% lower carbon content (446.3 $g \cdot kg^{-1}$) compared to that of fruit treated with biopreparation K5 (456.5 $g \cdot kg^{-1}$), which may indicate the occurrence of a certain trend of difference. According to Dinç et al. [45], the variety of the crop could be the most important factor that determines its nutritional quality; however, in the conducted studies, this effect was not visible.

Table 5. Total carbon content of strawberry fruit [g·kg^{-1}].

Varieties	Biopreparations						
	K1	K2	K3	K4	K5	K6	Average
'Honeoye'	446.6 a * (±20.0)	455.1 a (±14.0)	452.6 a (±13.8)	458.0 a (±15.6)	459.3 a (±13.4)	436.9 a (±7.7)	451.7 A (±5.4)
'Rumba'	452.4 a (±19.5)	447.6 a (±16.3)	462.9 a (±15.7)	448.7 a (±12.2)	455.6 a (±18.0)	461.9 a (±18.5)	455.0 A (±6.4)
'Vibrant'	439.9 a (±9.2)	459.2 a (±17.5)	449.4 a (±15.5)	456.1 a (±14.9)	454.7 a (±13.7)	452.7 a (±15.6)	452.7 A (±5.8)
Average	446.3 a (±9.0)	454.0 a (±8.7)	454.9 a (±8.3)	454.3 a (±7.8)	456.5 a (±8.2)	450.5 a (±8.3)	453.1 (±3.4)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

The growing season and the region of origin of the plants have been found to have minimal influence on the average metal content of strawberries [43].

The results for nitrogen content were slightly different where no statistically significant differences were found for the total nitrogen content in 'Honeoye' and 'Rumba' treated with biopreparations, while 'Vibrant' exhibited lower total nitrogen content compared to that of other varieties. Significant differences in the total nitrogen content were also found between cultivars. 'Rumba' fruits had the highest (on average 18.8 g·kg^{-1}) and 'Vibrant' fruits the lowest (15.7 g·kg^{-1}) total nitrogen content (Table 6). The presence of nitrogen in the form of nitrates in the fruit of crops is a consequence of feeding plants with nitrogen, as well as the result of the natural circulation of nitrogen in the soil–plant trace. Nitrates are taken up by plants for protein synthesis. Their levels in plants are influenced by both the geochemical composition of the environment and ecological characteristics [46,47].

Table 6. Total nitrogen content in strawberry fruit [g·kg^{-1}].

Varieties	Biopreparations						
	K1	K2	K3	K4	K5	K6	Average
'Honeoye'	14.8 a * (±1.3)	16.7 a (±2.2)	18.3 a (±2.3)	18.2 a (±1.7)	17.1 a (±1.7)	16.9 a (±1.6)	17.1 B (±0.7)
'Rumba'	18.6 a (±2.4)	17.6 a (±2.1)	19.3 a (±1.2)	19.2 a (±2.1)	18.4 a (±1.5)	19.8 a (±2.4)	18.8 C (±0.7)
'Vibrant'	13.8 a (±0.7)	15.2 ab (±1.5)	16.3 b (±2.3)	16.0 b (±1.6)	16.3 b (±1.6)	16.2 b (±1.5)	15.7 A (±0.7)
Average	15.7 a (±1.1)	16.5 ab (±1.1)	18.0 b (±1.1)	17.8 ab (±1.0)	17.3 ab (±0.9)	17.7 ab (±1.1)	17.2 (±0.4)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

Kopeć et al. [48] listed fertilisation, soil pH, and meteorological conditions as well as water deficit during the growing season among the factors modifying the chemical composition of strawberries, in addition to the cultivar. This was supported by Shrestha et al. [49] who concluded that there are clear differences in the chemical properties of different strawberry varieties. Additionally, the build-up of trace elements in the soil can result in their accumulation in edible crops. Consumption of these crops by animals and humans can subsequently lead to the development of diseases such as cancer [50]. According to Şener and Cantemur [3], a significant amount of heavy metals that penetrate into living organisms with food through the skin or respiratory system and cannot be excreted through the lungs, skin, kidneys, liver, or intestines can accumulate in the bodies of humans and animals. Accumulation of these metals in organisms can lead to thyroid disease, infertility, neurological diseases, autism, and even death [3]. In our research, the heavy metal content in none of the samples exceeded the permissible content.

Cadmium toxicity causes molecular, and physiological changes in plants, affecting photosynthesis, gas exchange, plant growth, water balance, and also mineral uptake. High cadmium levels lead to plant DNA damage and rapid changes in gene expression in the nucleus and chloroplasts [51]. Cadmium antagonises the effects of Ca, K, Mn, Mg, and Fe as a result of disturbances in carbohydrate metabolism and mineral nutrition, as well as slowing plant growth [51]. Due to its good water solubility, cadmium easily penetrates plant tissues, leading to reduced photosynthesis and transpiration and reduced plant root growth [51].

The highest manganese content of 41.8 mg·kg^{-1} was found for 'Vibrant', 24.4% higher than 'Rumba' (33.6 mg·kg^{-1}). Significantly, the lowest manganese content was found for the 'Honeoye' cultivar (29.2 mg·kg^{-1}) (Table 7). The manganese content of the fruit ranged from 24.6 mg·kg^{-1} (preparation K5 cultivar 'Rumba') to 45.3 mg·kg^{-1} (preparation K6 cultivar 'Vibrant'). On average, lower fruit manganese contents (29.0 mg·kg^{-1}) were recorded for all cultivars after application of the K5 combination compared to those for strawberries from sites where K2 (37.5 mg·kg^{-1}), K4 (37.1 mg·kg^{-1}), and K6 (36.2 mg·kg^{-1}) were applied. Hattab et al. [50] found the manganese content at a level of 0.387 µg·g^{-1}, while in the present study the manganese content ranged from 26.3 mg·kg^{-1} for 'Honeoye' fruits treated with K5 to 45.3 mg·kg^{-1} for 'Vibrant' fruits treated with the K6 biopreparation. Moreover, in a study conducted by Hattab et al. [50], the content of selected microelements and heavy metals (Fe, Mg, Mn, K, Ca, Na, Zn, Cu, Ni, Cd) in 'Sabrina' strawberry fruits cultivated under organic and conventional farming systems were analysed, and the results demonstrated significantly higher concentrations of micronutrients in organically cultivated fruits in comparison to in their conventionally grown counterparts. In the case of heavy metals Cd, Cu, and Zn, no significant differences were identified in the content of these elements between organic and conventional fruits. A significantly higher concentration of copper was observed in conventional fruits (0.62 µg·g^{-1} dry weight) compared to in organic fruits (0.48 µg·g^{-1} dry weight) [50]. In the present study, the mean copper content in organic strawberries was 2.57 mg·kg^{-1} for the K2 treated object and 3.52 mg·kg^{-1} for the control (K1).

Table 7. Manganese content of strawberry fruit [mg·kg^{-1}].

Varieties	Biopreparations						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	28.7 a * (±3.2)	33.3 a (±4.3)	30.1 a (±2.9)	30.0 a (±3.4)	26.3 a (±2.9)	26.7 a (±2.3)	29.2 A (±1.3)
'Rumba'	34.6 b (±2.9)	34.0 b (±4.4)	34.9 b (±3.5)	37.3 b (±2.7)	24.6 a (±1.7)	36.5 b (±2.7)	33.6 B (±1.4)
'Vibrant'	40.8 a (±4.3)	45.2 a (±3.9)	38.9 a (±6.1)	44.0 a (±4.4)	36.2 a (±2.2)	45.3 a (±2.1)	41.8 C (±1.7)
Average	34.7 ab (±2.4)	37.5 b (±2.6)	34.7 ab (±2.5)	37.1 b (±2.4)	29.0 a (±1.8)	36.2 b (±2.3)	34.9 (±1.0)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

The iron content in strawberry fruit on average for the tested cultivars remained at similar levels, from 33.0 mg·kg^{-1} for 'Honeoye' to 35.8 mg·kg^{-1} for 'Vibrant', and it did not differ significantly (Table 8). Fruit sprayed with combinations of the K3 and K5 preparations had a significantly lower iron content than in the control. The iron content of strawberries in present study ranged from 30.4 mg·kg^{-1} for 'Honeoye' strawberries from treatment K5 to 46.4 mg·kg^{-1} for 'Vibrant' fruits from the control treatment (K1), while in the study of Hattab et al. [50] it was 43.26 µg·g^{-1}.

Table 8. Iron content of strawberry fruit [mg·kg^{-1}].

Varieties	Biopreparations						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	32.7 a * (±3.4)	34.1 a (±4.7)	31.3 a (±0.4)	34.6 a (±4.5)	30.4 a (±1.3)	34.7 a (±1.6)	33.0 A (±1.2)
'Rumba'	38.4 b (±5.6)	32.4 ab (±2.2)	36.6 ab (±4.6)	35.3 ab (±3.5)	30.6 a (±1.5)	37.2 ab (±1.5)	34.9 A (±1.3)
'Vibrant'	46.4 b (±11.1)	35.4 ab (±4.8)	30.5 a (±1.6)	35.7 ab (±2.4)	35.3 ab (±1.2)	34.9 ab (±2.4)	35.8 A (±1.7)
Average	39.1 b (±4.2)	33.9 ab (±2.2)	32.8 a (±1.7)	35.2 ab (±1.9)	32.1 a (±0.9)	35.6 ab (±1.1)	34.5 (±0.8)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

On average, for all cultivars, the significantly highest copper content was found in fruit from the K1 control (3.52 mg·kg^{-1}) and the significantly lowest in fruit sprayed with K2 (2.57 mg·kg^{-1}) (Figure 1). On average, there was significantly less copper in 'Rumba' fruits than in the 'Honeoye' and 'Vibrant' fruits. For the 'Vibrant' cultivar, as with iron, the copper content of the fruit from the control (K1) was compared to that of strawberries from sites where K3 and K2 were applied.

Similarly, as in the case of copper, the zinc content in 'Rumba' fruit was significantly lower (7.37 mg·kg^{-1}) than in 'Vibrant' (9.66 mg·kg^{-1}) (Figure 5). The control treatment of 'Vibrant' had a significantly higher zinc content than that of the K3 treatment (by 115.5%). 'Rumba' fruits from the K4 treatment were characterised by a significantly higher (by 55.8%) Zn content than for the K5 treatment. Hattab et al. [50] reported a zinc content of 0.98 mg·kg^{-1} for organic strawberries. However, the present study found a higher content of zinc, with levels ranging from 6.08 mg·kg^{-1} for the 'Rumba' K5 treatment to as high as 15.30 mg·kg^{-1} for the 'Vibrant' fruits from the control object (K1). In Hattab et al.'s [50] study, the sodium content in fruits ranged from 125.8 µg·g^{-1}, while in present study it varied a lot, with values ranging from 13.2 mg·kg^{-1} for the 'Honeoye' control object (K1) to 34.0 mg·kg^{-1} for the 'Rumba' K3 treatment.

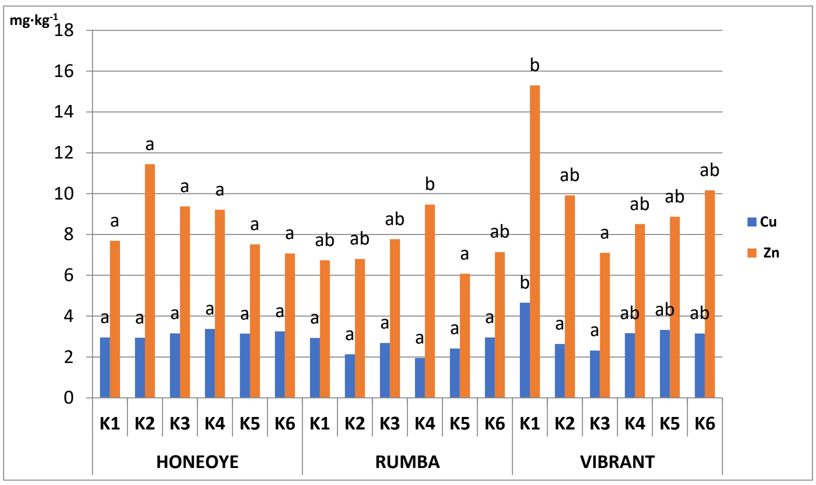

Figure 5. Zinc and copper content of strawberry fruit [mg·kg^{-1}]. The different small letters (a, b) in the rows mean significant differences between biopreparations.

Fresh strawberries contain about 90% water [52]. The limit values for cadmium (Commission Regulation (EU) 2023/915 of 25 April 2023) [53], which are 0.030 mg·kg^{-1}, are given for the content in fresh fruit mass. Given that in the tested study freeze-dried (lyophilised) fruits were used, the limit values were not exceeded in any sample (Figure 6). Fruits of the cultivars 'Honeoye' and 'Rumba' had a significantly lower cadmium content compared to that of 'Vibrant'. On average, for all cultivars, a significantly lower cadmium content (0.03 mg·kg^{-1}) was recorded at site K5 compared to at site K2 (0.06 mg·kg^{-1}).

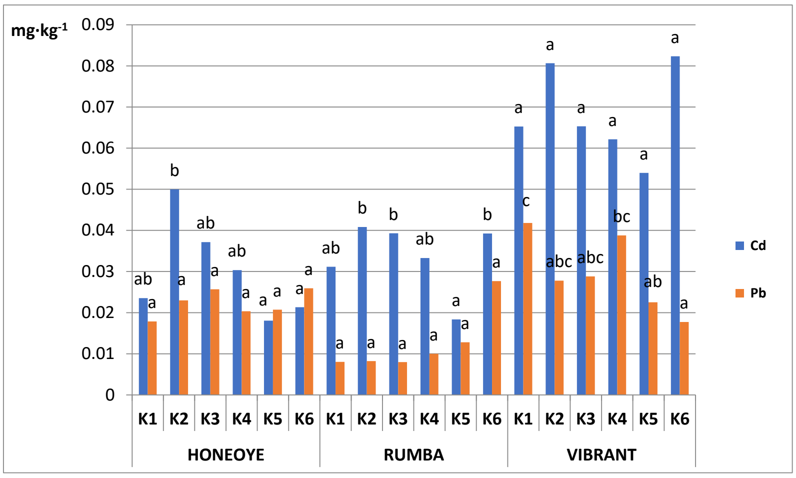

Figure 6. Cadmium and lead content of strawberry fruit [mg·kg^{-1}]. The different small letters (a, b, c) in the rows mean significant differences between biopreparations.

As in the case of cadmium, there were no exceedances of the permissible amounts of lead (0.10 mg·kg^{-1} fruit) in strawberry fruit for any of the combinations tested (Commission Regulation (EU) 2023/915 of 25 April 2023 [53] (Figure 6). As in the case of cadmium, fruit of the Rumba cultivar had a lower lead content (0.013 mg·kg^{-1}) than that of fruit of the 'Vibrant' cultivar (0.029 mg·kg^{-1}). In the control treatment K1 of the 'Vibrant' cultivar, fruits were characterised by a significantly higher lead content (0.42 mg·kg^{-1}) compared to that of treatments sprayed with the biopreparation K6 (0.018 mg·kg^{-1}) and K5 (0.023 mg·kg^{-1}).

The biopreparations used did not significantly differentiate the sodium content of the strawberry fruit (Table 9). Significant differences were only found between cultivars. 'Rumba' fruits had the highest sodium content (on average 28.5 mg·kg^{-1}), 'Vibrant' 15.1% less (24.2 mg·kg^{-1}), while 'Honeoye' showed 47% lower sodium content than that of 'Rumba' (15.1 mg·kg^{-1}). In a study by Bojarska et al. [43] conducted on 11 strawberry cultivars, the Na content of the fruit of the cultivar 'Honeoye' was 4.08 ± 0.11 mg·100 g^{-1} of the dry weight and was more than double that recorded in their own study for the same cultivar for each combination.

The use of biopreparations significantly differentiated the potassium content of 'Vibrant' fruit, with treatments with biopreparation K2 having a higher content (21,033 mg·kg^{-1}) compared to with K3 (17,493 mg·kg^{-1}) (Table 10). Similarly to the sodium and magnesium contents, 'Honeoye' fruit had significantly less potassium (17,640 mg·kg^{-1}) than that of the other two cultivars. 'Vibrant' fruit had 8.5% and 'Rumba' fruit had 14.3% higher potassium content than that of 'Honeoye' fruit. In the study conducted by Hattab et al. [50], the potassium content of the 'Sabrina' strawberries was found to be at a level of 15,415 µg·g^{-1}. In contrast, Bojarska et al. [43] found a potassium content of 1656 ± 37 mg·100 g^{-1} dry weight in the fruit of 'Honeoye'. In the present study, the potassium content was higher for most treatments (with the exception of K5 treatment). The results of our study indicated a higher concentration of potassium, with values ranging from 16,107 mg·kg^{-1} for K5 'Honeoye' to 21,953 mg·kg^{-1} for 'Rumba' fruits with K3 treatment.

The biopreparations used did not differentiate the calcium content of strawberry fruits for any of the varieties tested (Table 11). Statistically significant differences were only found between cultivars; 'Vibrant' fruit had on average a significantly higher calcium content (3582 mg·kg^{-1}), being 24.6% higher compared to that of 'Rumba' (2700 mg·kg^{-1}) and 21.4% higher compared to that of 'Honeoye' (2814 mg·kg^{-1}). Despite the lack of significant differences, a trend towards higher calcium content was found in the control treatment K1 (3261 mg·kg^{-1}) compared to in the treatments where biopreparations were applied (K3—2731 mg·kg^{-1}; K5—3198 mg·kg^{-1}) on average for all cultivars. The calcium content in the present study ranged from 2470 mg·kg^{-1} for 'Rumba' fruit from site K4 to 3905 mg·kg^{-1} for 'Vibrant' strawberries from site K6. In contrast, Hattab et al. [50] reported a significantly lower calcium content in the fruit, at a 1762 mg·kg^{-1} level. Similarly, in the study by Bojarska et al. [43], a lower Ca content of 207.3 ± 15.4 mg·100 g^{-1} of dry weight was recorded for the 'Honeoye' fruit than in the present study (2536–3176 mg·kg^{-1}).

Table 9. Sodium content of strawberry fruit [mg·kg^{-1}].

Varieties	Biopreparations						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	13.2 a * (±2.1)	14.2 a (±2.4)	13.2 a (±2.1)	18.5 a (±3.4)	16.0 a (±1.5)	14.9 a (±1.8)	15.1 A (±0.9)
'Rumba'	33.9 a (±4.1)	24.3 a (±2.1)	34.0 a (±7.4)	24.7 a (±6.2)	24.3 a (±2.8)	31.4 a (±5.9)	28.5 C (±2.1)
'Vibrant'	31.2 a (±10.0)	26.9 a (±4.7)	21.3 a (±2.8)	21.9 a (±1.8)	21.2 a (±2.5)	24.8 a (±4.2)	24.2 B (±1.7)
Average	26.1 a (±4.3)	21.8 a (±2.2)	22.9 a (±3.3)	21.7 a (±2.3)	20.5 a (±1.5)	23.7 a (±2.9)	22.6 (±1.1)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

Table 10. Potassium content of strawberry fruit [mg·kg^{-1}].

Varieties	Biopreparations						
	K1	**K2**	**K3**	**K4**	**K5**	**K6**	**Average**
'Honeoye'	18,381 a * (±1718)	18,828 a (±1568)	17,686 a (±1257)	18,322 a (±1464)	16,107 a (±631)	16,763 a (±795)	17,640 A (±503)
'Rumba'	19,609 a (±590)	20,326 a (±1252)	21,953 a (±2024)	19,974 a (±1770)	19,509 a (±917)	19,392 a (±689)	20,158 B (±546)
'Vibrant'	20,099 ab (±816)	21,033 b (±1531)	17,493 a (±1420)	17,757 ab (±923)	18,286 ab (±964)	20,469 ab (±1390)	19,136 B (±532)
Average	19,363 a (±639)	20,062 a (±821)	19,044 a (±1002)	18,684 a (±808)	17,968 a (±574)	18,874 a (±664)	18,978 (±319)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

As in the case of sodium and calcium, the biopreparations used did not significantly differentiate the magnesium content of strawberry fruit (Table 12). The magnesium content of strawberry fruits differed significantly among the cultivars tested. As in the case of the sodium content, 'Honeoye' fruit contained the least magnesium on average for all combinations (1436.0 mg·kg^{-1}). 'Vibrant' fruit had significantly higher magnesium content (1810.1 mg·kg^{-1}) than that of the other two cultivars. Despite the lack of significant differences, on average the control treatment had the highest magnesium content—1731.2 mg·kg^{-1}—while in the treatments where biopreparations were used, the magnesium content ranged from 1577.7 mg·kg^{-1} (preparation K3) to 1657.1 mg·kg^{-1} (preparation K6). Hattab et al. [50] recorded a magnesium content of 1531.52 µg·g^{-1}

in organic strawberries, while in the present study the content of this element ranged from 1387.6 mg·kg^{-1} for 'Honeoye' fruits treated with K6 to 1912.4 mg·kg^{-1} for the 'Vibrant' control (K1) treatment. In contrast, Bojarska et al. [43] found a Mg content of 122.7 ± 3.1 mg·100 g^{-1} of dry weight in the fruit of the cultivar 'Honeoye', which was lower than the Mg content found for the same cultivar in the present study.

Table 11. Calcium content of strawberry fruit [mg·kg^{-1}].

Varieties	Biopreparations						
	K1	K2	K3	K4	K5	K6	Average
'Honeoye'	2899 a * (±142)	2536 a (±264)	2575 a (±263)	3176 a (±106)	2935 a (±222)	2792 a (±381)	2814 A (±105)
'Rumba'	3092 a (±434)	2542 a (±182)	2604 a (±351)	2470 a (±261)	2796 a (±369)	2824 a (±109)	2700 A (±115)
'Vibrant'	3792 a (±406)	3507 a (±269)	3014 a (±166)	3487 a (±352)	3861 a (±381)	3905 a (±329)	3583 B (±132)
Average	3261 a (±217)	2862 a (±172)	2731 a (±155)	3045 a (±175)	3198 a (±213)	3174 a (±204)	3032 (±78)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

Table 12. Magnesium content of strawberry fruit [mg·kg^{-1}].

Varieties	Biopreparations						
	K1	K2	K3	K4	K5	K6	Average
'Honeoye'	1488 a * (±109)	1437 a (±97)	1432 a (±100)	1467 a (±81)	1422 a (±102)	1388 a (±104)	1436 A (±38)
'Rumba'	1793 a (±130)	1613 a (±125)	1720 a (±179)	1695 a (±135)	1573 a (±47)	1632 a (±64)	1664 B (±47)
'Vibrant'	1912 a (±113)	1798 a (±148)	1582 a (±104)	1794 a (±158)	1856 a (±105)	1951 a (±111)	1810 C (±52)
Average	1731 a (±82)	1616 a (±77)	1578 a (±77)	1652 a (±77)	1617 a (±65)	1657 a (±76)	1637 (±31)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

The application of biopreparations significantly differentiated the phosphorus content only in 'Vibrant' fruits (Table 13); the phosphorus content of fruit from treatment K6 (2518 mg·kg^{-1}) was significantly higher than that of K3 (1905 mg·kg^{-1}). Fruits of the 'Rumba' cultivar contained significantly more phosphorus (2552 mg·kg^{-1}) compared to that of the 'Honeoye' (2152 mg·kg^{-1}) and 'Vibrant' (2229 mg·kg^{-1}) cultivars. 'Honeoye' fruit had a 15.7% and 'Vibrant' a 12.7% lower phosphorus content compared to that of 'Rumba' fruit. In a study conducted by Bojarska et al. [43], the phosphorus content of the fruit of the cultivar 'Honeoye' was found to be 232.9 ± 11.0 mg·100 g^{-1} of the dry weight, a result that is comparable to that obtained in the present study for the K2 treatment. As reported by Kumar et al. [51], phosphorus is crucial in reducing the uptake and translocation of cadmium through processes related to the binding of cadmium to the plant cell wall and the formation of cadmium phosphate complexes. Zinc, boron, and iron play an important rol in growth, flowering, and fruiting, which affects the quality of strawberries grown in the field [48,54].

Bebek Markovinović et al. [55] assessed the microelement content of strawberries of the 'Albion' cultivar and the juice produced from them, as well as the by-products from strawberry juice production, and they ranged as follows: Cu 0.077–0.415 mg·kg^{-1}, Zn 0.988–3.12 mg·kg^{-1}, and Pb < 0.03–0.076 mg·kg^{-1}. In our study, the values for these elements ranged as follows: Cu from 1.95 mg·kg $^{-1}$ (K4, 'Rumba') to 4.66 mg·kg^{-1} (K1, 'Vibrant'), Zn from 6.08 mg·kg^{-1} (K5, 'Rumba') to 15.30 mg·kg^{-1} (K1, 'Vibrant'), and Pb from 0.008 mg·kg^{-1} (K1, K2, K3, 'Rumba') to 0.042 mg·kg^{-1} (K1, 'Vibrant').

Table 13. Phosphorus content of strawberry fruit [mg·kg^{-1}].

Varieties	Biopreparations						
	K1	K2	K3	K4	K5	K6	Average
'Honeoye'	2074 a * (±111)	2339 a (±340)	2112 a (±119)	2234 a (±221)	2122 a (±227)	2003 a (±123)	2152 A (±84)
'Rumba'	2310 a (±331)	2498 a (±244)	2579 a (±277)	2647 a (±331)	2741 a (±349)	2457 a (±281)	2552 B (±117)
'Vibrant'	2284 ab (±336)	2285 ab (±176)	1905 a (±164)	2150 ab (±193)	2252 ab (±264)	2518 b (±278)	2229 A (±94)
Average	2223 a (±150)	2374 a (±144)	2199 a (±127)	2343 a (±148)	2372 a (±167)	2326 a (±141)	2311 (±59)

* The different lowercase letters in the rows indicate significant differences between the biopreparations, while the different capital letters in the last column indicate significant differences between cultivars tested. The biopreparations × cultivar interactions were not statistically significant at $p < 0.05$.

In order to confirm the relationship between the macroelement and microelement content and the tested varieties and treatments, the ordination method of PCA (Principal Component Analysis) was used (Figures 7 and 8). The PCA analysis showed that the points corresponding to the tested varieties generally grouped together, indicating that the variety had a greater effect than that of the biopreparations on the chemical composition of the strawberry fruits. The points corresponding to the variety Honeoye are grouped together in the graph in Figure 8 at the position corresponding to the dry weight of the fruit in Figure 7. The points corresponding to the variety Rumba in Figure 8 are correlated with the contents of C, N, P, K, and Na in Figure 7. The highest content of micronutrients and heavy metals in the fruit is correlated with the position of the points corresponding to the variety Vibrant (Figure 8): Mg, Fe, Mn, Zn, Ca, Cd, Cu, and Pb (Figure 7).

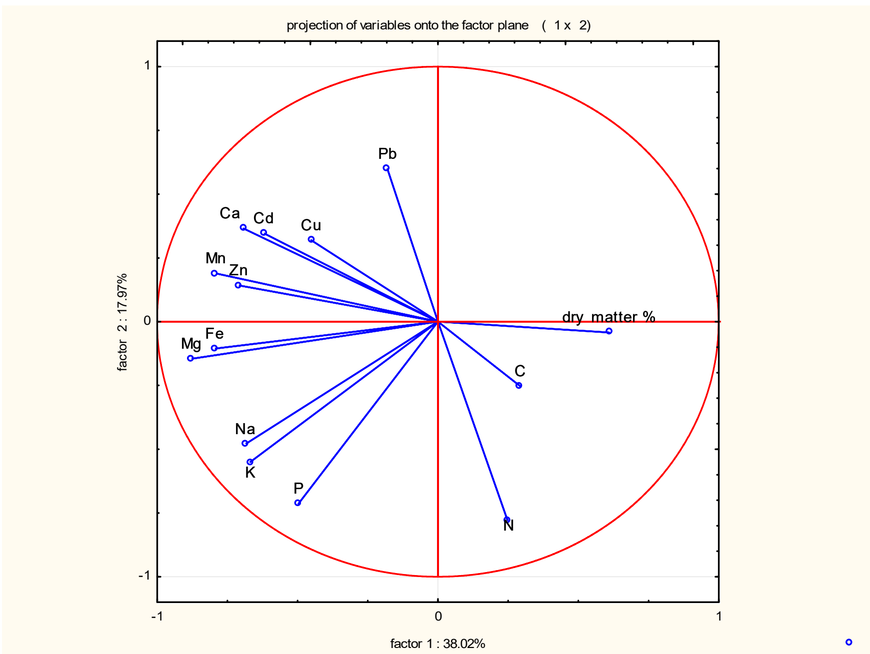

Figure 7. Ordination diagram of dry matter and element content in strawberry fruits in relation to first and second axes of PCA.

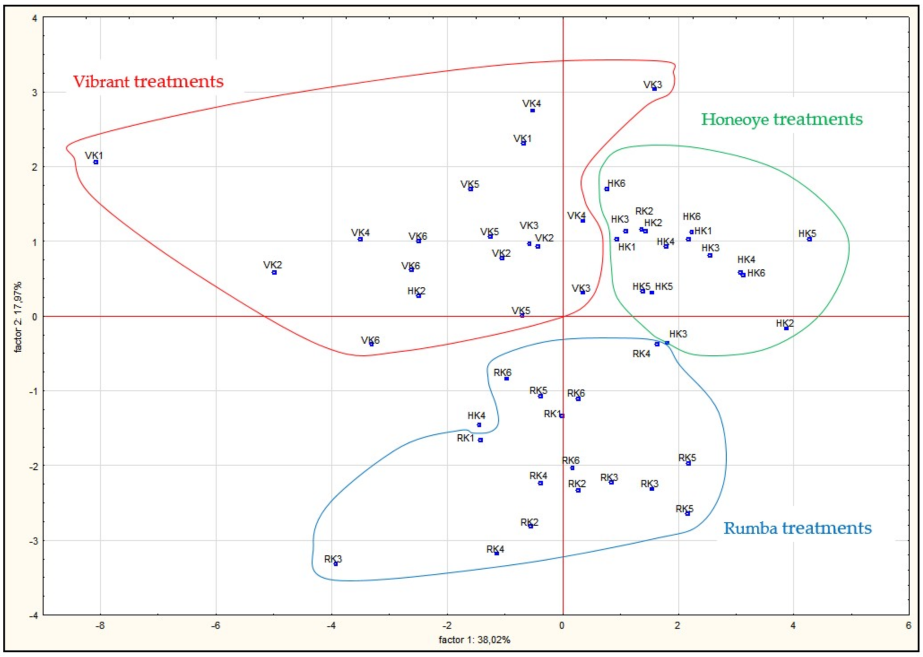

Figure 8. Ordination diagram of objects (varieties and biopreparation treatments) in relation to first and second axes of PCA (n = 3).

Research conducted by Bojarska et al. [43] on 11 strawberry cultivars confirms that the fruit of this species differs in terms of the macronutrient content depending on the cultivar. Of the 11 varieties tested, the fruit of the 'Honeoye' variety was the most abundant in magnesium, sodium, calcium, phosphorus, and potassium. In contrast, in the present study, the same cultivar had a lower content of Mn, Na, Mg, K, and P than that of the cultivars 'Vibrant' and 'Rumba'. The effectiveness of microorganisms in biopreparations and their effect on the growth, development, and yield of the cultivated plant are often determined by the method of inoculation. Foliar application increases the growth of the aboveground parts of the plant, while soil application stimulates growth mainly in the roots [1,56]. The efficacy of biopreparations is contingent upon the utilisation of organic matter by the constituent microorganisms as a source of energy, carbon, and electrolytes. This enables the microorganisms to proliferate and reproduce, while the organic matter is gradually biodegraded into innocuous end products. Biopreparations typically comprise bacteria, nutrients, a carrier, and, optionally, enzymes [36]. Babalola [31] mentions, among the advantages of the use of PGPR, the compensation of the decline in plant growth caused by heavy metals, weeds, drought, and salinity [31].

Excessive use of synthetic fertilisers contributes to the toxic accumulation of heavy metals, soil acidification, and the formation of soil crust, which lead to a decrease in soil organic matter and humus substance. In turn, soil acidification leads to an increase in the concentration of harmful ions in the soil, limits plant growth, and also reduces the uptake of phosphate by plants [57,58]. As disadvantages of the use of synthetic fertilisers, Babalola [31] lists the pollution of water bodies and the destruction of microorganisms and beneficial insects, which make crops more susceptible to diseases. In the long run, synthetic fertilisers can also reduce natural soil fertility, which leads to irreversible damage to the entire ecosystem.

The use of microbiological preparations may become a necessity to face current agronomic challenges. A crucial strategy for mitigating the negative effects of external factors, like climate change's negative impact, is plant biostimulation, which enhances plant resilience disturbances, accelerates physiological processes, and promotes the growth and development of plants. This approach is particularly effective when bacterial or bacterial–fungal consortia are incorporated into biopreparations [59].

Among such products are microbiological fertiliser preparations, exemplified by the K2–K6 formulations tested in the experiment described in this study. These preparations contained bacteria from the *Bacillus* genus. According to Furtak [60], products containing *Bacillus* species can positively influence seed germination, enhance root system development, improve plant resilience to prolonged stress conditions, and ultimately contribute to higher crop yields [60].

4. Summary and Conclusions

The present study investigated the effects of newly developed microbial biopreparations on the quality and chemical composition of strawberries grown under organic farming conditions. While there was a trend towards the increased total carbon content in strawberries from plots treated with biopreparations, this effect was not statistically significant. The biopreparations also did not result in significant differences in sodium, magnesium, and calcium levels. However, notable cultivar-specific responses to biopreparations were observed, especially in terms of the dry matter; total nitrogen; and several elements, including heavy metals.

Among the strawberry cultivars tested, significant differences were found for dry matter and the content of elements, such as nitrogen, manganese, copper, zinc, cadmium, lead, sodium, magnesium, potassium, calcium, and phosphorus. The 'Honeoye' cultivar showed the lowest levels of manganese, sodium, magnesium, potassium, and phosphorus, while 'Vibrant' had the highest manganese, zinc, lead, and magnesium content. 'Rumba' exhibited the lowest levels of heavy metals (copper, zinc, cadmium, and lead) and calcium, alongside the highest levels of total nitrogen, sodium, potassium, and phosphorus. The biopreparations notably influenced the dry matter content in 'Honeoye', total nitrogen in 'Vibrant', and several other elements across different cultivars.

Specific combinations of biopreparations had significant effects. For instance, application of the K2 preparation increased the dry matter in 'Honeoye', while K3–K6 enhanced the total nitrogen content in 'Vibrant'. The K5 preparation increased the iron content in Rumba, and K2–K3 reduced copper accumulation in 'Vibrant'. Furthermore, K6 and K5 reduced lead accumulation in 'Vibrant', indicating potential for selective nutrient management through biopreparation application.

These findings suggest that while microbial biopreparations can influence specific nutrient levels and quality parameters in strawberries, their effects are largely cultivar-dependent. This study showed that the effects of microbial biopreparations on the chemical composition of strawberry fruits varied widely among cultivars and treatments, with no clear or uniform pattern emerging across all the tested combinations. While certain trends were observed, such as the increased nitrogen content in 'Vibrant' fruits treated with K4, K5, and K6, or the reduced heavy metal content in specific treatments, these effects were not consistent across all cultivars or treatments. This shows the complex interactions between the biopreparations, plant genotype, and environmental conditions in organic farming systems. Further optimisation of biopreparation applications to specific cultivars and farming contexts can optimise their benefits. No clear pattern suggests that further research is needed to understand the mechanisms underlying these variable responses and to refine the use of microbial biopreparations in organic agriculture. This also includes further studies needed to test the effect of the preparations in other locations with soil conditions and on other varieties as well as to confirm the effectiveness of the tested biopreparations for different cultivation conditions. Future studies should expand to include a wider range of strawberry varieties commonly cultivated in Poland to assess the universality of these biopreparations. Additionally, testing across varied geographic locations and soil types would be valuable to determine how these factors influence the uptake and accumulation of nutrients, efficacy of biopreparations, and microbial survival in soil over time, thereby providing more targeted recommendations for organic strawberry production.

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References

1. Sas-Paszt, L.; Sumorok, B.; Grzyb, Z.S.; Głuszek, S.; Sitarek, M.; Lisek, A.; Derkowska, E.; Trzciński, P.; Przybył, M.; Frąc, M.; et al. Effect of microbiologically enriched fertilizers on the yielding of strawberry plants under field conditions in the second year of plantation. *J. Res. Appl. Agric. Eng.* **2020**, *65*, 31–38.
2. Derkowska, E.; Sas Paszt, L.; Trzciński, P.; Przybył, M.; Weszczak, K. Influence of biofertilizers on plant growth and rizosphere microbiology of greenhouse-grown strawberry cultivars. *Acta Sci. Pol. Hortorum Cultus* **2015**, *14*, 83–96.
3. Şener, S.; Cantemur, M.H. Comparison of fruit quality criteria and heavy metal contents of strawberries grown in organic and conventional agriculture. *Appl. Sci.* **2023**, *13*, 7919. [CrossRef]
4. Giampieri, F.; Forbes-Hernández, T.Y.; Gasparrini, M.; Álvarez-Suarez, J.M.; Afrin, S.; Bompadre, S.; Quiles, J.L.; Mezzetti, B.; Battino, M. Strawberry as a health promoter: An evidence based review. *Food Funct.* **2015**, *6*, 1386–1398. [CrossRef]
5. Basu, A.; Nguyen, A.; Betts, N.M.; Lyons, T.J. Strawberry as a functional food: An evidence-based review. *Crit. Rev. in Food Sci. and Nutr.* **2014**, *54*, 790–806. [CrossRef]
6. Kilic, N. Improvement in plant growth, yield and fruit quality with biostimulant treatment in organic strawberry cultivation. *HortScience* **2024**, *59*, 1165–1171. [CrossRef]
7. de la Peña Moreno, F.; Blanch, G.P.; Flores, G.; Ruiz del Castillo, M.L. Impact of postharvest methyl jasmonate treatment on the volatile composition and flavonol content of strawberries. *J. Sci. Food Agric.* **2010**, *90*, 989–994. [CrossRef]
8. Wang, X.; Wu, L.; Qui, J.; Qian, Y.; Wang, M. Comparative metabolomic analysis of the nutritional aspects from ten cultivars of the strawberry fruit. *Foods* **2023**, *12*, 1153. [CrossRef]
9. Shen, J.; Shao, W.; Li, J.; Lu, H. Integrated metabolomic and transcriptomic analysis reveals factors underlying differences in fruit quality between *Fragaria nilgerrensis* and *Fragaria pentaphylla*. *J. Sci. Food Agric.* **2022**, *102*, 3287–3296. [CrossRef]
10. Katel, S.; Mandal, H.R.; Kattel, S.; Yadav, S.P.S.; Lamshal, B.S. Impact of plant growth regulators in strawberry plant: A review. *Heliyon* **2022**, *8*, e11959. [CrossRef]
11. Khunte, S.D.; Kumar, A.; Ansari, N.; Saravanan, S. 2020. Effect of Different Levels of PGRs with Organic Manure on Growth Characters and Economics of Strawberry (*Fragaria* x *ananassa* Duch.) cv. Chandler in Northern region. *Int. J. Curr. Microbiol. App. Sci.* **2020**, *9*, 1633–1638. [CrossRef]

12. Sharma, K.; Negi, M. Effect of organic manures and inorganic fertilizers on plant growth of strawberry (*Fragaria* x *ananassa*) cv. Shimla delicious under mid-hill conditions of Uttarakhand. *J. Pharmacogn. Phytochem.* **2019**, *8*, 1440–1444.
13. Kumra, R.; Saravanan, R.S.; Bakshi, P.; Kumar, A.; Singh, M.; Kumar, V. Influence of plant growth regulators on strawberry: A review. *Int. J. Chem. Stud.* **2018**, *6*, 1236–1239.
14. Kilic, N. Synergistic effect of organic and biofertilizers on strawberry cultivation. *Sustainability* **2023**, *15*, 8206. [CrossRef]
15. Giamperi, F.; Tulipani, S.; Alvarez-Suarez, J.M.; Quiles, J.L.; Mezzetti, B.; Battino, M. The strawberry: Compositon, nutritional quality, and impact on human health. *Nutrition* **2012**, *28*, 9–19. [CrossRef]
16. Wójcik- Seliga, J.; Studnicki, M.; Wójcik-Gront, E. Evaluating economic value of 23 strawberry cultivars in the climatic conditions of central Europe. *Acta Sci. Pol. Hortorum Cultus* **2017**, *16*, 11–19.
17. Kobi, H.B.; Martins, M.C.; Silva, P.I.; Souza, J.L.; Carneiro, J.C.S.; Heleno, F.F.; Queiroz, M.E.L.R.; Costa, N.M.B. Organic and conventional strawberries: Nutritional quality, antioxidant characteristics and pesticide residues. *Fruits* **2018**, *73*, 39–47. [CrossRef]
18. Camargo, L.K.P.; Resende, J.T.V.; Tominaga, T.T.; Kurchaidt, S.M.; Camargo, C.K.; Figueiredo, A.S.T. Postharvest quality of strawberry fruits produced in organic and conventional systems. *Hortic. Bras.* **2011**, *29*, 577–583. [CrossRef]
19. Aninowski, M.; Kazimierczak, R.; Hallmann, E.; Rachtan-Janicka, J.; Fijoł-Adach, E.; Feledyn-Szewczyk, B.; Majak, I.; Leszczyńska, J. Evaluation of the potential allergenicity of strawberries in response to different farming practices. *Metabolites* **2020**, *10*, 102. [CrossRef]
20. Winter, C.K. Pesticide residues in imported, organic, and "suspect" fruits and vegetables. *J. Agric. Food Chem.* **2012**, *60*, 4425–4429. [CrossRef]
21. Alsanius, B.W.; Von Essen, E.; Hartmann, R.; Vagsholm, I.; Doyle, O.; Schmutz, U.; Stützel, H.; Fricke, A.; Dorais, M. The "one health"-concept and organic production of vegetables and fruits. *Acta Hortic.* **2019**, *1242*, 1–14. [CrossRef]
22. Ochmian, I.; Błaszak, M.; Lachowicz, S.; Piwowarczyk, R. The impact of cultivation systems on the nutritional and phytochemical content, and microbiological contamination of highbush blueberry. *Sci. Rep.* **2020**, *10*, 16696. [CrossRef]
23. Błajet-Kosicka, A.; Twarużek, M.; Kosicki, R.; Sibiorowska, E.; Grajewski, J. Co-occurrence and evaluation of mycotoxins in organic and conventional rye grain and products. *Food Control.* **2014**, *38*, 61–66. [CrossRef]
24. Brodal, G.; Hofgaard, I.S.; Eriksen, G.S.; Bernhoft, A.; Sundheim, L. Mycotoxins in organically versus conventionally produced cereal grains and some other crops in temperate regions. *World Mycotoxin J.* **2016**, *9*, 755–770. [CrossRef]
25. Lázaro, A.; de Lorenzo, C. Texture Analysis in Melon Landraces through Instrumental and Sensory Methods. *Int. J. Food Prop.* **2015**, *18*, 1575–1583. [CrossRef]
26. Altisent, R.; Jaeger, S.R.; Johnston, J.W.; Harker, F.R. Injection of flavor essences into fruit pieces: A new approach for exploring consumer preferences for novel flavors of apple fruit. *J. Sens. Stud.* **2013**, *28*, 405–413. [CrossRef]
27. Gao, Z.; Wong, S.S.; House, L.A.; Spreen, T.H. French consumer perception, preference of, and willingness to pay for fresh fruit based on country of origin. *Br. Food J.* **2014**, *116*, 805–820. [CrossRef]
28. Reganold, J.P.; Andrews, P.K.; Reeve, J.R.; Carpenter-Boggs, L.; Schadt, C.W.; Alldredge, J.R.; Ross, C.F.; Davies, N.M.; Zhou, J. Fruit and Soil Quality of Organic and Conventional Strawberry Agroecosystems. *PLoS ONE* **2010**, *5*, e12346. [CrossRef]
29. Jamiołkowska, A.; Hetman, B. The mechanism of action of biological preparations used in plant protection against pathogens. *Ann. UMCS Sect. E Agric.* **2016**, *71*, 13–29.
30. Lipa, J.J.; Pruszyński, S. Stan wykorzystania metod biologicznych w ochronie roślin w Polsce i na świecie. *Prog. Plant Prot.* **2010**, *50*, 1033–1043.
31. Babalola, O.O. Beneficial bacteria of agricultural importance. *Biotechnol. Lett.* **2010**, *32*, 1559–1570. [CrossRef]
32. Mynett, K.; Podwyszyńska, M.; Derkowska, E.; Górnik, K.; Sas-Paszt, L.; Wojtania, A. Effect of biologically active TotalHumus® and Bacterbase on the growth *ex vitro* of strawberry, blueberry and hip rose microcuttings. *Acta Sci. Pol. Hortorum Cultus* **2022**, *21*, 7–20. [CrossRef]
33. Schönbichler, A.; Diaz-Moreno, S.M.; Srivastava, V.; McKee, L.S. Exploring the potential for fungal antagonism and cell wall attack by Bacillus subtilis natto. *Frontin Microbiol.* **2020**, *11*, 521. [CrossRef]
34. Grzegorczyk, M.; Szalewicz, A.; Żarowska, B.; Połomska, X.; Wątorek, W.; Wójtowicz, M. Microorganisms in biological control of phytopathogenic fungi. *Acta Sci. Pol. Biotechnol.* **2015**, *14*, 19–42.
35. Rusin, M.; Domagalska, J.; Rogala, D.; Razzaghi, M.; Szymala, I. Concentration of cadmium and lead in vegetables and fruits. *Sci. Rep.* **2021**, *11*, 11913. [CrossRef]
36. Grzyb, A.; Waraczewska, Z.; Niewiadomska, A.; Wolna-Maruwka, A. What are biopreparations and what is their use? *Nauka Przyr. Technol.* **2019**, *13*, 65–76. [CrossRef]
37. Nakielska, M.; Berbeć, A.K.; Madej, A.; Feledyn-Szewczyk, B. Microbial fertilizing products impact on productivity and profitability of organic strawberry cultivars. *Horticulturae* **2024**, *10*, 1112. [CrossRef]
38. Available online: https://agronomplants.pl/truskawki/odmiany-wczesne/sadzonki-truskawek-rumba/ (accessed on 15 January 2025).

39. Available online: https://agronomplants.pl/truskawki/odmiany-wczesne/sadzonki-truskawek-vibrant/ (accessed on 15 January 2025).
40. Available online: https://agronomplants.pl/truskawki/odmiany-wczesne/sadzonki-truskawek-honeoye/ (accessed on 15 January 2025).
41. Drobek, M.; Cybulska, J.; Frąc, M.; Pieczywek, P.; Pertile, G.; Chibrikov, V.; Nosalewicz, A.; Feledyn-Szewczyk, B.; Sas-Paszt, L.; Zdunek, A. Microbial biostimulants affect the development of pathogenic microorganisms and the quality of fresh strawberries (*Fragaria ananassa* Duch.). *Sci. Hortic.* **2024**, *327*, 112793. [CrossRef]
42. Ayaz, M.; Li, C.-H.; Ali, Q.; Zhao, W.; Chi, Y.-K.; Shafiq, M.; Ali, F.; Yu, X.-Y.; Yu, Q.; Zhao, J.-T.; et al. Bacterial and fungal biocontrol agents for plant disease protection: Journey from lab to field, current status, challanges, and global perspectives. *Molecules* **2023**, *28*, 6735. [CrossRef]
43. Bojarska, J.E.; Zadernowski, R.; Tońska, E. Macroelements of strawberry fruits. *Bromat. Chem. Toksykol.* **2011**, *44*, 572–576.
44. Çakmakçi, S.; Çakmakçi, R. Quality and nutritional parameters of food in agri-food production systems. *Foods* **2023**, *12*, 351. [CrossRef]
45. Dinç, S.; Kara, M.; Takma, Ç.; Kara, Y.; Kolayli, S. Strawberries from Konya in the Central Anatolia Region of Türkiye: Phenolic profile, antioxidant potential and mineral composition. *Appl. Fruit Sci.* **2024**, *66*, 1229–1240. [CrossRef]
46. Santamaria, P. Nitrate in vegetables: Toxicity, content, intake, and EC regulation. *J. Sci. Food Agric.* **2006**, *86*, 10–17. [CrossRef]
47. Ahmed, M.; Rauf, M.; Mukhtar, Z.; Saeed, N.A. Excessive use of nitrogenous fertilizers: An unawareness causing serious threats to environment and human health. *Environ. Sci. Pollut. Res.* **2017**, *24*, 26983–26987. [CrossRef]
48. Kopeć, M.; Gondek, K.; Mierzwa-Hersztek, M.; Zaleski, T.; Bogdał, S.; Bienisz, M.; Błaszczyk, J.; Kaczmarczyk, E.; Knaga, J.; Łapczyńska-Kordon, B.; et al. The effect of stimulating biomass growth of everbearing strawberry variety San Andreas® by the foliage application of a product containing zinc. *Prog. Plant Prot.* **2019**, *59*, 126–132. [CrossRef]
49. Shrestha, B.; Tripathi, K.M.; Shrestha, A.K.; Gautam, R. Evaluation of chemical attributes of low chilling strawberry (*Fragaria ananassa*) varieties in Chitwan, Nepal. *Nepal. Hortic.* **2023**, *17*, 69–73. [CrossRef]
50. Hattab, S.; Bougattass, I.; Hassine, R.; Dridi-Al-Mohandes, B. Metals and micronutrients in some edible crops and their cultivation soils in estern-central region of Tunisia: A comparision between organic and conventional farming. *Food Chem.* **2019**, *270*, 293–298. [CrossRef]
51. Kumar, A.; Kumari, N.; Singh, A.; Kumar, D.; Kumar Yadav, D.; Varshney, A.; Sharma, N. The effect of cadmium tolerant Plant Growth Promoting Rhizobacteria on plant growth promotion and phytoremediation: A review. *Curr. Microbiol.* **2023**, *80*, 153. [CrossRef]
52. Recamales, A.F.; López Medina, J.; Hernanz, D. Physicochemical characteristics and mineral content of strawberries grown in soil and soilless system. *J. of Food Qual.* **2007**, *30*, 837–853. [CrossRef]
53. Commission Regulation (EU). 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. *Off. J. Eur. Union* **2023**, *119*, 103–157.
54. Verma, S.; Bairwa, R.K.; Rana, D.K.; Dimiri, T.; Dotaniya, C.K. Influence of different concentrations of zinc, boron and iron on yield characters of strawberry (*Fragaria* x *ananassa* Duch.) cv. Chandler under valley condition of Garhwal Himalaya. *Jof Pharmacogn. and Phytochem.* **2018**, *7*, 3881–3884.
55. Bebek Markovinović, A.; Putnik, P.; Duralija, B.; Krivohlavek, A.; Ivešić, M.; Mandić Andačić, I.; Palac Bešlić, I.; Pavlić, B.; Lorenzo, J.M.; Bursać Kovačević, D. Chemometric valorization of strawberry (*Fragaria* x *ananasa* Duch.) cv. 'Albion' for the production of functional juice: The impact of physiochemical, toxicological, sensory and bioactive value. *Foods* **2022**, *11*, 640. [CrossRef]
56. Şahin, M.; Eşitken, A.; Pirlak, L.; Altintaş, S.; Turan, M. Effect of DN1 bacterial strain applied by different methods on some morphological characteristics of strawberry cv. San Andreas (*Fragaria* × *ananassa* Duch.). *AGROFOR Int. J.* **2019**, *4*, 57–64. [CrossRef]
57. Alengebawy, A.; Abdelkhalek, S.T.; Quereshi, S.R.; Wang, M.-Q. Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risk and human health implications. *Toxics* **2021**, *9*, 42. [CrossRef] [PubMed]
58. Tsotetsi, T.; Nephali, L.; Malebe, M.; Tugizimana, F. *Bacillus* for plant growth promotion and stress resilience: What have we learned? *Plants* **2022**, *11*, 2482. [CrossRef]
59. Gałązka, A. Preparaty mikrobiologiczne potrzeby, szanse i znaczenie. In *Monografie i Rozprawy Naukowe: Preparaty Mikrobiologiczne w Rolnictwie i Ochronie Środowiska*, 2nd ed.; Gałązka, A., Podleśny, J., Eds.; Wydawnictwo IUNG-PIB: Puławy, Poland, 2024; Volume 66, pp. 9–27.
60. Furtak, K. Bakterie z rodzaju *Bacillus* jako składniki biopreparatów o szerokim spektrum zastosowania w rolnictwie. In *Monografie i Rozprawy Naukowe: Preparaty Mikrobiologiczne w Rolnictwie i Ochronie Środowiska*, 2nd ed.; Gałązka, A., Podleśny, J., Eds.; Wydawnictwo IUNG-PIB: Puławy, Poland, 2024; Volume 66, pp. 89–104.

14. Oświadczenie promotorów i autora rozprawy doktorskiej

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Oświadczam, że niniejsza rozprawa doktorska pt.: **„Wpływ biopreparatów na zdrowotność, wybrane cechy morfologiczne i plonowanie truskawki (*Fragaria x ananassa* Duchesne) uprawianej w systemie ekologicznym"** została przygotowana pod moim kierunkiem i stwierdzam, że spełnia ona warunki do przedstawienia jej w postępowaniu o nadanie stopnia naukowego doktora nauk rolniczych.

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Oświadczam, że niniejsza rozprawa doktorska pt.: **„Wpływ biopreparatów na zdrowotność, wybrane cechy morfologiczne i plonowanie truskawki (*Fragaria x ananassa* Duchesne) uprawianej w systemie ekologicznym"** została przygotowana z moim udziałem w procesie planowania badań, ich realizacji i analizy wyników oraz stwierdzam, że spełnia ona warunki do przedstawienia jej w postępowaniu o nadanie stopnia naukowego doktora nauk rolniczych.

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Świadoma odpowiedzialności prawnej oświadczam, że rozprawa doktorska pt.: **„Wpływ biopreparatów na zdrowotność, wybrane cechy morfologiczne i plonowanie truskawki (*Fragaria x ananassa* Duchesne) uprawianej w systemie ekologicznym”** przygotowana przeze mnie nie zawiera treści uzyskanych w sposób niezgodny z obowiązującymi przepisami.

Oświadczam również, że przedstawiona rozprawa nie była wcześniej przedmiotem procedur związanych z uzyskaniem stopnia naukowego w wyższej uczelni lub innej uprawnionej instytucji naukowej.

Oświadczam ponadto, że niniejsza wersja rozprawy jest identyczna z załączoną wersją elektroniczną.

Data 24.06.2025r. Małgorzata Nakielska
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