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

Małgorzata Nakielska *, Adam Kleofas Berbeć, Andrzej Madej and Beata Feledyn-Szewczyk

Department of Agroecology and Economics, Institute of Soil Science and Plant Cultivation, State Research Institute, Czartoryskich 8, 24-100 Puławy, Poland; aberbec@iung.pulawy.pl (A.K.B.); amjan@iung.pulawy.pl (A.M.); bszewczyk@iung.pulawy.pl (B.F.-S.)
* Correspondence: mnakielska@iung.pulawy.pl

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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