Interactive Effects of Mulching Materials and Biofertilizers on Growth, Root Biomass, and Leaf Chlorophyll of Greenhouse-Grown 'Albion' Strawberry

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Abstract

Strawberry (*Fragaria* × *ananassa* Duch.) is a valuable commercial crop whose shallow rooting structure makes it highly sensitive to root-zone variations. Although both soil mulching and biofertilization improve microenvironmental conditions and soil properties, thereby enhancing crop performance, their interactive effects in protected cropping systems have yet to be fully studied. This experiment aimed to investigate the effects of mulching techniques and biofertilizers on morpho-physiological properties and biomass of greenhouse-grown strawberries cv. 'Albion'. A factorial experiment was conducted under greenhouse conditions with two main factors: Mulching Factor (Un-Mulch, Black Polyethylene Mulch, and Organic Wheat Straw Mulch) and Biofertilizer Factor (No-Biofertilizer, BioHealth, Fulzyme, and BioHealth + Fulzyme combination). Parameters assessed included vegetative and biomass indices: leaf number leaves plant□¹, leaf area cm² plant^{-1}, fresh weight of the root system g plant□¹, and dry weight of the root system g plant□¹. Physiological parameter: chlorophyll content (SPAD index). Mulching and bio-fertilization had significant effects on plant growth and physiology compared to untreated treatments. The use of Black Polyethylene Mulch + BioHealth + Fulzyme showed a significant interaction in improving photosynthetic ability (SPAD). Using soil mulching along with PGPM inoculation is a sustainable method of managing roots. The combination of mulching along with the use of PGPM enhances the structure and, therefore, yield of 'Albion' strawberries grown under glasshouse conditions.

Keywords: *Fragaria* × *ananassa*, 'Albion', *Bacillus subtilis*, PGPM, biofertilizers, sustainability, root-zone management, non-biodegradable waste.

Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is an economically important fruit crop worldwide, valued for its distinct flavor and nutritional composition [1; 2]**.** It contains bioactive ingredients such as bioactive compounds, including anthocyanins, phenolics, carotenoids, vitamins, and minerals that provide antioxidant properties [3]. The global strawberry production amounted to nearly 9.56 million tons in 2022 and exceeded 10 million tons in 2023, according to FAO statistics. China, the USA, and Turkey are still major producers, with China being the leading country in strawberry production globally since 1994, while crop area expands to developing countries such as Iraq, where protected greenhouse systems are increasingly adopted to meet local demand [4]. In Iraq, strawberry cultivation is concentrated mainly in Baghdad, Diyala, and Salahuddin governorates, with climatic conditions

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generally compatible with the varieties currently grown. Strawberry productivity is limited by its shallow root system, which makes the crop highly sensitive to fluctuations in the root-zone environment, including moisture deficits, temperature extremes, nutrient scarcity, and weed competition [5]. These stresses impair vegetative growth, photosynthetic efficiency, and assimilate partitioning [6]. Management of the root-zone microclimate is therefore essential for improving yield while reducing environmental impact.

Soil mulching is a common practice used to regulate the root-zone environment. Black polyethylene mulch improves strawberry performance by conserving soil moisture, buffering temperature fluctuations, suppressing weeds, and enhancing nutrient-use efficiency [7], which supports vegetative growth, chlorophyll synthesis, and carbohydrate accumulation, resulting in larger fruit and higher yield [8]. However, the continuous use of plastic mulch leads to the accumulation of non-biodegradable waste, microplastic contamination, and disposal problems, raising sustainability concerns in commercial strawberry production and prompting interest in biodegradable alternatives [9].

Wheat straw mulch is a viable organic alternative. It reduces moisture loss and temperature fluctuation, suppresses weeds, and, through gradual decomposition, enriches soil organic matter and microbial activity [10]. Still, the physiological and qualitative response of greenhouse-grown strawberry to organic versus synthetic mulch remains insufficiently documented.

Biofertilizers offer an additional strategy for reducing dependence on synthetic fertilizers, whose overuse contributes to soil degradation, groundwater salinization, and higher production costs [11]**.** Plant growth-promoting microorganisms (PGPMs), including *Bacillus subtilis* and arbuscular mycorrhizal fungi (AMF), enhance nutrient availability through nitrogen fixation, phosphate and potassium solubilization, and phytohormone modulation [12], with Bacillus recognized as a spore-forming, saprophytic rhizosphere bacterium capable of long-term soil survival under harsh conditions. Commercial inoculants such as BioHealth and Fulzyme have improved root development and crop resilience in several horticultural species [13].

The combined effects of mulching and microbial inoculation influence the physiological and biochemical pathways governing plant growth. Leaf number and area, along with fresh and dry biomass, indicate structural development, while chlorophyll content reflects photosynthetic capacity. Carbon assimilation supports carbohydrate accumulation, which drives fruit development and determines fruit length, diameter, and weight. A multi-parametric evaluation of these traits is therefore necessary to characterize crop response to innovative management practices.

Although the individual effects of mulching and biofertilization on strawberries have been studied separately, their interactive effects remain poorly documented, particularly for the cultivar 'Albion' under protected cultivation. Combining specific mulch materials with targeted microbial inoculants may produce synergistic benefits for photosynthesis and biomass accumulation, while reducing synthetic inputs.

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Therefore, the present study evaluated the individual and interactive effects of black polyethylene mulch, wheat straw mulch, and biofertilizer formulations on the morpho-physiological, physical, and biochemical attributes of greenhouse-grown strawberry (*Fragaria* × *ananassa* Duch. cv. 'Albion'). Canopy development, chlorophyll, and biomass accumulation traits were assessed to identify an optimized and sustainable production strategy for high-quality strawberry cultivation.

Materials and Methods

Experimental Site

The experiment was conducted in one of the private fields in the Al-Azawiya area / Al-Musayyib district, located 40 km north of the city of Hilla in Babylon Governorate, longitude 44.5 east and latitude 32.7 north, during the 2024-2025 growing season, to study the effect of some soil covers and some biofertilizers on the growth and qualitative content of the strawberry plant *Fragaria* x *ananassa*.

Greenhouse Condition

The average temperature during the growing season was approximately 29.11 °C. The relative humidity was approximately 32 %. Plants were drip-irrigated 2-3 times a week.

Soil Analysis

Random soil samples were taken from different areas of the experimental field. This procedure was carried out before planting to randomly study some chemical and physical properties. The soil was collected at depths ranging from 0 to 30 cm, then air-dried, ground, and passed through a sieve with 2 mm openings. The soil analysis was performed at the Babylon Agriculture Laboratory (Table 1).

Table (1) Chemical and Physical Properties of Greenhouse Soil Before Planting.

Characteristic	Standard Unit	Values
EC	dS m^{-1}	2.6
pH	-	7.3
Organic matter	g kg^{1}	13.8
Nitrogen	mg kg^{1}	10.2
Potassium	mg kg^{1}	167
Phosphorus	mg kg^{1}	5.6
Bulk density	g cm^{3}	1.13
Sand	g kg^{1}	600
Silt	g kg^{1}	245
Clay	g kg^{1}	155
Soil texture	-	Sandy loam

Land Preparation and Experimental Design

The greenhouse was tilled, weeded, and arranged into raised beds for optimal access and crop maintenance. Drip irrigation was established and maintained for the duration of the experiment. The area was structured into three replicates, each consisting of one raised bed (1.5 m wide) containing 12 experimental units. Spacing parameters included 1 m between beds, 50 cm between experimental units (to isolate treatments), and 40 cm between individual plants. Weed density observations and photographs were recorded across all study variables both before planting and after applying soil mulches.

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Seedling Preparation and Transplanting

Healthy, uniform strawberry seedlings (*Fragaria* × *ananassa* cv. Albion) of Turkish origin were procured on October 28, 2024, via a commercial supplier from a nursery located in the Diyala Governorate. The seedlings were initially maintained in polystyrene (Styrofoam) trays to ensure vigorous development. On October 30, 2024, uniform plants were transplanted into the permanent greenhouse facility. Post-transplanting agronomic management included regular irrigation, weed control, foliar washing, and humidity maintenance throughout the establishment period.

Experimental Design and Statistical Analysis

The experiment was conducted as a 3×4 factorial trial arranged in a Randomized Complete Block Design (RCBD) with three replications per treatment. Treatment means were compared using the Least Significant Difference (LSD) test at a significance level of $p \leq 0.05$ [14]. Data organization and tabulation were performed using Microsoft Excel, while analysis of variance (ANOVA) was executed using GenStat statistical software (Version 14.2).

Experimental Treatments

The study comprised a two-factor experimental design involving soil mulching treatments and biofertilizer applications:

Factor A: Soil Mulching. (A_0Control (un-mulched). Black Polyethylene (A_1): Black polyethylene plastic mulch. Organic plant waste (A_2): Organic plant waste (wheat straw).

Factor B: Biofertilizers. Control (B_0): No biofertilizer applied. BioHealth (B_1): Applied at 25 mg L^{-1} (BS BioHealth WSG, Germany). Fulzyme (B_2): Applied at 25 mg L^{-1} (Karimina, Lebanon). Combination (B_3): Mixture of BioHealth + Fulzyme (25 mg L^{-1} each).

Treatment Application and Management

Raised beds were subjected to their respective mulching treatments (black polyethylene film, wheat straw mulch, or un-mulched treatment). Four-week-old strawberry seedlings were then transplanted immediately into the beds. Biofertilizer treatments were applied for 3 weeks post-transplanting according to the experimental layout. All morphological and yield parameters were evaluated at full fruit maturity.

The studied indicators

Vegetative characteristics:

Number of Leaves (leaves plant^{-1})

The number of leaves was counted for three randomly selected plants per experimental unit. The mean leaf count per plant was determined by dividing the total leaf count of these three plants by three, after which overall treatment means were calculated.

Leaf Area (cm^2 plant^{-1})

Random leaf samples were collected from three representative plants per experimental unit, scanned, and processed via ImageJ software. Individual leaf area measurements were multiplied by the plant's total leaf count to establish total leaf area per plant [15]. Mean values per treatment were subsequently computed.

Fresh weight of root system (g plant^{-1})

The fresh weight of the root system for each seedling within the experimental unit was calculated using a sensitive weight scale,

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after removing dust and other suspended particles.

Dry weight of root system (g plant^{-1})

Root dry matter percentage was evaluated at the conclusion of the experiment. Selected seedlings from each experimental unit were harvested, and the root system was detached from the shoot system at the root-crown junction. The roots were rinsed thoroughly with water, placed in perforated paper bags, and oven-dried at 70°C until reaching a constant weight [16]. The root dry weight percentage was calculated as follows:

$$\text{Root Dry Mass Percentage (\%)} = \left(\frac{\text{Root Dry Weight}}{\text{Root Fresh Weight}}\right) \times 100$$

Total Chlorophyll Content (SPAD Index)

Relative leaf chlorophyll content was determined non-destructively using a SPAD-502 chlorophyll meter (Konica Minolta, Japan). Measurements were recorded from three representative seedlings per experimental unit and averaged following the procedure described by [17].

Results

Number of Leaves (leaves plant^{-1})

The results shown in Table 2 indicate that the use of black polyethylene mulch had a significant effect on the average number of leaves per plant, achieving the highest average (16.17 leaves plant^{-1}), compared to the un-mulched treatment, which recorded (12.72 leaves plant^{-1}). The results in the table also indicate that the treatment with the biofertilizer Mix BioHealth and Fulzyme was the best, achieving a significantly higher average number of leaves (15.24 leaves plant^{-1}), while the non-biofertilizer treatment recorded the lowest mean leaf number (13.75 leaves plant^{-1}). Regarding the interaction between the experimental factors, the results in the same table showed the superiority of the combination of black polyethylene mulch and the biofertilizer Mix BioHealth and Fulzyme, achieving the highest average (17.06 leaves plant^{-1}), compared to the un-mulched, no-biofertilizer treatments, which recorded the lowest average (10.73 leaves plant^{-1}).

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Table 2. Effects of Mulching Materials and Biofertilizers on Leaf Number (leaves plant□¹) of Greenhouse Strawberry cv. 'Albion'.

Biofertilizer Factor	Mulching Factor			Biofertilizer Average
	Un-mulch	Black Polyethylene	Organic Wheat Straw	
No Biofertilizer	10.73	15.81	14.70	13.75
BioHealth	12.33	15.51	15.06	14.30
Fulzyme	13.85	16.29	13.96	14.70
BioHealth +Fulzyme	13.96	17.06	14.70	15.24
Mulching Average	12.72	16.17	14.61	
LSD 0.05	Mulching 0.519	Biofertilizer 0.620		Interaction 1.088

Leaf Area (cm^2 $plant^{-1}$)

The results shown in Table (3) indicate that using black polyethylene mulch had a significant effect on the average leaf area per cm², achieving the highest average of (83.74 cm^2 $plant^{-1}$), compared to the Un-mulched treatment, which recorded (58.55 cm^2 $plant^{-1}$). The results in the same table also indicate that the treatment with the biofertilizer BioHealth + Fulzyme was the best, achieving a significantly higher average leaf area of (75.80 cm^2 $plant^{-1}$), while the no-Biofertilizer treatment recorded the lowest mean leaf area (66.27 cm^2 $plant^{-1}$). Regarding the interaction between the experimental factors, the results in the same table showed the superiority of the combination of black polyethylene mulch and the biofertilizer BioHealth + Fulzyme, achieving a significantly higher leaf area of 87.56 cm^2 $plant^{-1}$ compared to the un-mulch, no Biofertilizer treatments, which recorded the lowest leaf area of 54.96 cm^2 $plant^{-1}$.

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Table 3. Effects of Mulching Materials and Biofertilizers on Leaf Area (cm^2 $plant^{-1}$ of Greenhouse Strawberry cv. 'Albion'.

Fresh weight of the root system (g $plant^{-1}$)

Biofertilizer Factor	Mulching Factor			Biofertilizer Average
	Un-mulch	Black Polyethylene	Organic Wheat Straw	
No Biofertilizer	54.96	78.52	65.34	66.27
BioHealth	56.67	84.06	69.60	70.11
Fulzyme	57.88	84.85	72.37	71.7
BioHealth +Fulzyme	64.70	87.56	75.16	75.80
Mulching Average	58.55	83.74	70.61	
LSD 0.05	Mulching 7.80	Biofertilizer 9.36		Interaction 16.37

The results shown in Table (4) indicate that the use of black polyethylene mulch has a significant effect on the fresh weight of the root system, achieving the highest average of (19.61 g $plant^{-1}$), compared to the un-mulched treatment, which recorded (16.86 g $plant^{-1}$). The results in the same table also indicate that the treatment with the biofertilizer BioHealth + Fulzyme is the best, achieving a significantly higher average fresh weight of the root system (19.62 g $plant^{-1}$), while the average of the no-biofertilizer treatment recorded the lowest mean root fresh weight (14.83 g $plant^{-1}$). Regarding the interaction between the experimental factors, the results in the same table show the superiority of the combination resulting from the use of black polyethylene mulch and the biofertilizer Fulzyme, achieving the highest average (21.03 g $plant^{-1}$), compared to the un-mulched, no-biofertilizer treatments, which recorded the lowest average (14.43 g $plant^{-1}$).

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Table 4. Effects of Mulching Materials and Biofertilizers on the Fresh Weight of Root System (g plant $^{-1}$) of Greenhouse Strawberry cv. 'Albion'.

Biofertilizer Factor	Mulching Factor			Biofertilizer Average
	Un-mulch	Black Polyethylene	Organic Wheat Straw	
No Biofertilizer	14.43	15.90	14.16	14.83
BioHealth	17.90	20.83	19.80	19.51
Fulzyme	17.13	21.03	17.43	18.53
BioHealth +Fulzyme	18.01	20.70	20.16	19.62
Mulching Average	16.86	19.61	17.88	
LSD 0.05	Mulching 0.3682	Biofertilizer 0.5660		Interaction 0.7625

Dry Weight of the Root System (g plant^{-1})

The results shown in Table (5) indicate that the use of black polyethylene mulch has a significant effect on the average dry weight of the root system, achieving the highest average of (8.230 g plant^{-1}), compared to the un-mulched treatment, which recorded (6.630 g plant^{-1}). The results in the same table also indicate that the treatment with the biofertilizer Mix BioHealth and Fulzyme was the best, achieving a significantly higher average dry weight of the root system (8.523 g plant^{-1}), while the biofertilizer treatment recorded the lowest mean root dry weight (6.644 g plant^{-1}). Regarding the interaction between the experimental factors, the results in the same table showed the superiority of the combination of black polyethylene mulch and the biofertilizer BioHealth + Fulzyme, achieving a significantly higher dry weight (9.993 g plant^{-1}), compared to the un-mulched, no-biofertilizer treatments, which recorded the lowest dry weight (5.840 g plant^{-1}).

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Table 5. Effects of Mulching Materials and Biofertilizers on Root System Dry Weight (g) of Greenhouse Strawberry cv. 'Albion'.

Biofertilizer Factor	Mulching Factor			Biofertilizer Average
	Un-mulch	Black Polyethylene	Organic Wheat Straw	
No Biofertilizer	5.840	6.913	7.180	6.644
BioHealth	6.697	7.800	7.653	7.383
Fulzyme	6.993	8.217	7.997	7.735
BioHealth +Fulzyme	6.993	9.993	8.583	8.523
Mulching Average	6.630	8.230	7.853	
LSD 0.05	Mulching 0.3626	Biofertilizer 0.4625		Interaction 0.6998

Total Chlorophyll Content (SPAD Index)

The results shown in Table (6) suggest a significant effect of the factors studied on leaf chlorophyll content. The treatment with black polyethylene significantly impacted chlorophyll content, registering an average of 49.22 SPAD, compared to the straw mulch treatment, which registered 45.85 SPAD. However, the treatment with the biofertilizer BioHealth + Fulzyme significantly outperformed the others, achieving the highest chlorophyll content (50.19 SPAD). In comparison, the biofertilizer treatment resulted in the lowest mean chlorophyll content (46.39 SPAD). The same table indicates that the interaction between the mulch type and the biofertilizer significantly affected leaf chlorophyll content. The combination of black polyethylene mulch and BioHealth + Fulzyme recorded the highest chlorophyll content (54.10 SPAD), whereas the combination of wheat straw mulch and BioHealth recorded the lowest value (45.33 SPAD).

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Table 6. Effects of Mulching Materials and Biofertilizers on Chlorophyll Content (SPAD index) of Greenhouse Strawberry cv. 'Albion'

Biofertilizer Factor	Mulching Factor			Biofertilizer Average
	Un-mulch	Black Polyethylene	Organic Wheat Straw	
No Biofertilizer	45.44	47.77	45.97	46.39
BioHealth	46.67	47.44	45.33	46.48
Fulzyme	47.59	47.59	46.70	47.30
BioHealth +Fulzyme	51.10	54.10	45.38	50.19
Mulching Average	47.70	49.22	45.85	
LSD 0.05	Mulching 1.888	Biofertilizer 3.011		Interaction 3.971

Discussion

The results of this study highlight the significant individual and combined roles of soil mulching materials and biofertilization in enhancing the morpho-physiological performance and root system development of greenhouse-grown strawberry (*Fragaria × ananassa* Duch. cv. 'Albion').

Impact of Soil Mulching Materials on Vegetative and Root Growth

Soil mulching directly alters the root-zone microclimate, regulating soil moisture, temperature fluctuations, and weed growth [7]. In this trial, black polyethylene mulch consistently outperformed organic wheat straw and bare soil across vegetative parameters, yielding the highest average leaf number and leaf area. The superior performance of black polyethylene film can be attributed to its ability to absorb solar radiation and elevate root-zone soil temperatures, especially during cool early-season growth stages in protected structures [8]. This hydrothermal modulation accelerates metabolic processes in the rhizosphere, driving cell elongation and shoot emergence.

Furthermore, black polyethylene mulch produced the highest root fresh weight and root dry weight. Because strawberries possess a shallow root system highly vulnerable to moisture stress [5], impermeable plastic mulches prevent evaporation, maintaining stable moisture availability. This stability encourages continuous lateral root initiation and nutrient absorption. While organic wheat straw mulch improved growth relative to bare soil, its thermal insulation effect can lower soil temperature beneath the bed during early spring, which slightly retards early

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vegetative development relative to black plastic [10].

Role of Biofertilizers (PGPMs) on Plant Morpho-Physiology

The application of microbial biofertilizers significantly enhanced both shoot canopy dimensions and root system biomass compared to uninoculated controls. Plants treated with the dual inoculant BioHealth + Fulzyme achieved the highest leaf count, leaf area, and root dry weight. Plant growth-promoting microorganisms (PGPMs), such as *Bacillus subtilis* and beneficial fungal strains present in these formulations, facilitate plant growth via several physiological pathways [12]. PGPMs synthesize endogenous auxins (e.g., indole-3-acetic acid) and cytokinins, which directly stimulate root cell division and vascular bundle differentiation [13]. Inoculants enhance the availability of insoluble nutrients, particularly phosphorus and micronutrients, enabling efficient uptake even in alkaline or high-salinity Iraqi soils [4]. The superior performance of the dual application (BioHealth + Fulzyme) indicates a complementary action where diverse microbial populations occupy distinct ecological niches in the rhizosphere, offering broader enzymatic and nutritional support than single-strain treatments.

Chlorophyll Synthesis and Photosynthetic Capacity (SPAD Index)

Leaf chlorophyll content, represented by the SPAD index, directly reflects a plant's photosynthetic capacity and nitrogen status. Black polyethylene mulch recorded the highest main effect for mulching, while the BioHealth + Fulzyme combination achieved the highest biofertilizer main effect. The increased chlorophyll content under biofertilization is likely tied to improved uptake of magnesium, iron, and nitrogen facilitated by PGPM activity. Microbial colonization prevents root degradation from abiotic stresses, maintaining active transpiration stream transport to developing leaves [5]. Enhanced nutrient uptake supports synthesis of chlorophyll precursors and stabilizes photosystem reaction centers in leaf tissues.

Synergistic Interaction of Mulching and Microbial Inoculation

The Black Polyethylene + BioHealth + Fulzyme treatment produced the highest values of leaf area, leaf number, dry weight of the root system, and SPAD, whereas the black polyethylene + Fulzyme produced the highest value of fresh weight of the root system. This additive effect illustrates a strong root-zone interaction: plastic mulching creates an ideal microclimate (stable heat, preserved soil moisture, and protected soil structure), while the PGPM inoculants optimize nutrient utilization and root system architecture within that sheltered zone. Together, these combined management strategies enhance assimilate partitioning, structural biomass, and photosynthetic performance, providing a clear agronomic path forward for sustainable protected strawberry production.

Sustainability Considerations and Mulch Selection

Even though black polyethylene mulch gave the most substantial overall growth response in this study, its agronomic effectiveness should be looked at together with its environmental implications. While polyethylene mulch does offer several production advantages, such as better conservation of soil moisture, suppression of weeds, and a change in the root-zone environment, its non-biodegradable character leads to problems concerning removal, disposal, and the possibility of

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plastic building up. Hence, the practice which resulted in the greatest plant response need not be considered the most sustainable one.

In this experiment, wheat straw mulch also led to improvements in a number of growth characteristics when compared with the un-mulched treatment, even though its performance was generally less than that of black polyethylene. This indicates that there may be a compromise between achieving good short-term plant performance and reducing reliance on persistent plastic materials. If environmental sustainability is a priority, then organic mulches such as wheat straw could serve as an alternative, especially when agricultural residues that are locally available are used.

Biodegradable plastic mulches are also a possible alternative since they could offer some of the agronomic benefits of ordinary polyethylene without requiring the removal of the plastic after cultivation. But in the present experiment, biodegradable materials were not tested; as a result, it is impossible to assess their relative agronomic and environmental performance on the basis of our findings. Future experiments should directly compare conventional polyethylene, biodegradable plastic, organic mulch and bare soil under the same experimental conditions, and should also examine soil moisture, root-zone temperature, weed suppression, mulch degradation, crop yield and economic cost. Only in this way can a more complete evaluation be made of the sustainability of mulch–biofertilizer combinations in the production of strawberries.

Conclusion

This study suggests that integrating soil mulching with biofertilizer inoculation significantly enhances the growth, root development, and physiological efficiency of greenhouse-grown strawberry (*Fragaria* × *ananassa* Duch. cv. 'Albion'). Across the evaluated parameters, soil mulching: Black polyethylene mulch consistently produced the highest values for leaf number, leaf area, fresh and dry weight of the root system, and total chlorophyll content. Biofertilization: The dual microbial inoculant combination of BioHealth + Fulzyme outperformed single microbial strains and the uninoculated control, recording superior overall means across vegetative growth, biomass partitioning, and chlorophyll synthesis. Interactive Effects:

The combination of black polyethylene mulch and the dual biofertilizer (BioHealth + Fulzyme) produced the highest values of leaf number, leaf area, root dry weight, and chlorophyll content. In contrast, the highest root fresh weight was recorded with black polyethylene mulch combined with Fulzyme. Overall, modulating the root-zone microclimate with appropriate soil covers while leveraging beneficial microbial inoculants offers an efficient production strategy under the conditions of the present study to enhance structural development and photosynthetic performance in protected strawberry cultivation.

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