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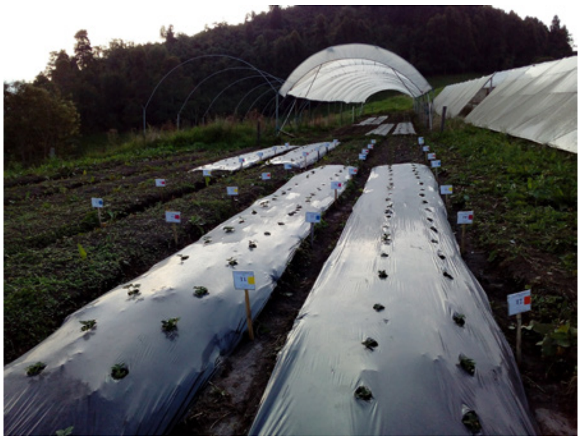
Technical-economic evaluation of bacterial consortia in strawberry cultivation across two production systems

Evaluación técnico-económica de consorcios bacterianos en el cultivo de fresa en dos sistemas de producción



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Strawberry crops under two production systems.

Photo: E.A. Flórez-Hernández

ABSTRACT

Strawberry production is predominantly carried out in open fields, rendering it vulnerable to pest attacks, which can lead to reductions in yield. This susceptibility is further exacerbated by adverse climatic conditions. Another challenge is the high cost of inputs like fertilizers. Consequently, the aim of this study was to evaluate both technically and economically the impact of applying bacterial bio-fertilizers to strawberry crops under two production systems. The experimental design employed was a subdivided-plot arrangement in a randomized complete block, with the main plot focusing on the production system (either open field or macrotunnel), the subplot on plastic mulch (either with or without), and the sub-subplot on bacterial consortia treatments commercial. These were as follows: (a) control, which corresponded to traditional farmer management; (b) *Bacillus subtilis*, (c) consortium 1, comprising a mixture of humic acids and *Rhodopseudomonas palustris*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*; and (d) consortium 2, composed of *Azospirillum brasilense*, *Azotobacter chroococcum*, *Lactobacillus acidophillus*, *Saccharomyces cerevisiae*. The combination of macrotunnel production and plastic mulch, along with the application of bacterial consortium 2, yielded the best results in the second year, producing gross and net yields of 25.041 and 17.330 kg ha^{-1}, respectively. This was associated with the most favorable benefit-cost ratio of 1.41 in the second year.

Additional key words: *Fragaria* spp.; yield components; plasticulture; growth-promoting bacteria; bio-fertilization.

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RESUMEN

La producción de fresas se lleva a cabo predominantemente en campos abiertos, lo que la hace vulnerable a los ataques de plagas, lo que puede provocar reducciones en el rendimiento. Esta susceptibilidad se ve exacerbada aún más por las condiciones climáticas adversas. Otro desafío es el alto costo de insumos como los fertilizantes. En consecuencia, el objetivo de este estudio fue evaluar tanto técnica como económicamente el impacto de la aplicación de biofertilizantes bacterianos al cultivo de fresa bajo dos sistemas de producción. El diseño experimental empleado fue un arreglo de parcelas subdivididas en bloques completos al azar, con la parcela principal centrada en el sistema de producción (ya sea campo abierto o macrotúnel), la subparcela sobre acolchado plástico (con o sin) y la subparcela sobre acolchado plástico (ya sea con o sin) sobre tratamientos de consorcios bacterianos comerciales. Estos eran los siguientes: (a) control, que correspondía al manejo convencional de los agricultores; (b) *Bacillus subtilis*, (c) consorcio 1, que comprendió una mezcla de ácidos húmicos y *Rhodopseudomonas palustris*, *Bacillus subtilis*, *Bacillus amyloliquefaciens*, *Bacillus licheniformis*; y (d) consorcio 2, compuesto por *Azospirillum brasilense*, *Azotobacter chroococcum*, *Lactobacillus acidophillus*, *Saccharomyces cerevisiae*. La combinación de producción de macrotúnel y acolchado plástico, junto con la aplicación del consorcio bacteriano 2, arrojaron los mejores resultados en el segundo año, mostrando rendimientos brutos y netos de 25.041 y 17.330 kg ha^{-1}, respectivamente. Esto se asoció con la relación costo-beneficio más favorable con 1,41 en el segundo año.

Palabras clave adicionales: *Fragaria* spp.; componentes del rendimiento; plasticultura; bacterias promotoras de crecimiento; bio-fertilización.

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INTRODUCTION

Global strawberry production totals 4.8 million tons, with the primary producers being China and the United States (Minagricultura, 2021). In 2020, China stood as the leading strawberry producer globally, generating 3,326,816 t (accounting for 37.5%), followed by the United States of America which produced 1,055,963 t (making up 11.9% of global production) (Axayacatl, 2021). In Colombia, Cundinamarca is the leading strawberry-producing department, accounting for 51% of the total land devoted to strawberry cultivation in 2020. It is followed by Boyaca and Cauca, each with a 10% share, and Norte de Santander, which comprises 8% of the cultivated area (Minagricultura, 2021).

Strawberry cultivation occurs in two primary ways, open-field and controlled conditions. Firstly, open-field cultivation faces various biotic challenges, such as infestations by pests like mites, thrips, and lepidopteran larvae (Mossler, 2010). Diseases, primarily caused by the phytopathogen *Botrytis cinerea* commonly known as "gray mold" can lead to significant losses. These losses can be as high as 25% during the main harvest and 37% during the second production peak (Ceredi *et al*., 2009). Other diseases such as powdery and downy mildew, anthracnose, and leaf spot can cumulatively result in up to 70% of production losses (Rubio *et al*., 2014). In Colombia, specifically, diseases constitute the principal reason for crop losses in strawberries. According to Cano (2013), the most detrimental rot is caused by *Botrytis cinerea*, which significantly hampers strawberry production due to its frequent occurrence, leading to more than 50% production losses (Álvarez-Medina *et al*., 2017; Álvarez *et al*., 2018).

As for abiotic factors, limitations arise from exposure to adverse weather conditions, including high levels of rainfall, the mechanical impact of hail, frost, and strong winds. Secondly, under controlled conditions, strawberry cultivation faces the challenge of high infrastructure costs, such as those for greenhouses, and a low cost-benefit ratio. Therefore, many strawberry farmers globally opt for macrotunnel technology, attributed to its lower costs (Lamont, 2009), ease of installation, adaptability to various topographic conditions, and the longevity of some designs, which can last up to 10 years (Flórez and Mora, 2010; Salamé-Donoso *et al*., 2010). Rubio *et al*. (2014) reported that the utilization of macrotunnels minimizes fertilizer leaching and reduces the volume and frequency of pesticide and fungicide applications. Additionally, it elevates the ambient temperature by 2 to 5°C, thereby hastening the onset of production and providing protection against mechanical damage from precipitation and frost (Lamont, 2009).

Rubio (2014) suggests that further research is needed to explore the impact of macrotunnels on strawberry production, considering various agroecological zones, varieties, and cultivars. Moreover, diversifying production systems like incorporating plastic mulch and microbial consortia for integrated crop management could be viable solutions for enhancing crop sustainability.

In the realm of integrated crop management, numerous studies have demonstrated the effectiveness of bacterial strains such as *Bacillus subtilis, B. pumilus, Azospirillum brasilense*, and *Saccharomyces cerevisiae*. These strains not only inhibit the growth of phytopathogenic fungi but also positively influence the growth and development of strawberry plants (Cano, 2013; Mendoza-Léon *et al*., 2019).

Conversely, there exist physical barriers designed to prevent fruit from coming into contact with the soil. Such barriers include the use of plastic mulch and production in enclosed environments like macrotunnels, which aim to mitigate the impact of rainfall on disease propagation (Calderón *et al*., 2013). In this context, mulching stands as a critical component in strawberry production. It offers multiple advantages over bare soil, including early harvests, higher yields, and the maintenance of moisture levels conducive to plant development (Calderón *et al*., 2013). Soil covers further contribute to plant health by preventing the emergence of weeds and excess moisture on the soil surface, thereby ensuring the cleanliness and quality of the fruit (Calderón *et al*., 2013).

Owing to the limited availability of technical and economic data on the integrated management of strawberry crops that incorporate bacterial consortia and agroplasticulture techniques like plastic mulch and macrotunnels, this study was conducted. The objective was to evaluate both the technical and economic aspects of using microbial consortia in conjunction with plastic mulch and macrotunnels.

MATERIALS AND METHODS

The study was conducted at the Tesorito farm, affiliated with the University of Caldas, situated in the municipality of Manizales in the Department of Caldas, Colombia. The farm is located at an elevation of 2,340 m a.s.l., with a mean annual temperature of 17.5°C, a relative humidity of 78%, an annual rainfall of 2,000 mm, and 1,473 h of sunshine per year (Cenicafe, 2022). The soil is classified as Andisols, originating from volcanic ashes, and has a sandy-loam texture rich in organic matter.

Two production systems served as the experimental setting. The first was a macrotunnel covering an area of 494 m^2, measuring 6,50 m in width, 40 m in length, and 7 m in height. Inside the macrotunnel, four beds each measuring 40 m in length and 1,20 m in width were arranged randomly for the study. Plastic mulch with a 1,2 caliber with 30 microns was used. The second system was an open field that also utilized four furrows, each 36 m long and of the same width as in the macrotunnel system. Strawberry seedlings of Sabrina variety were planted at 40 cm intervals between plants, forming two rows per bed. Each production system had a total of 512 plants for evaluation, amounting to 1,020 plants in total.

The study utilized a split-plot experimental design within a randomized complete block arrangement. The main plot represented the production systems (open field and macrotunnel), while subplots were designated based on the use of plastic mulch (with and without). The smallest plot focused on different bacterial consortia treatments commercial: (a) a control, corresponding to conventional farmer management; (b) *Bacillus subtilis*; (c) Consortium 1, consisting of a mixture of humic acids, *Rhodopseudomonas palustris, Bacillus subtilis, Bacillus amyloliquefaciens*, and *Bacillus licheniformis*; and (d) Consortium 2, composed of *Azospirillum brasilense, Azotobacter chroococcum, Lactobacillus acidophillus*, and *Saccharomyces cerevisiae*. Each experimental unit comprised four plants, and each treatment was repeated four times. Applications were at a dose of 5 cm^3 L^{-1} of water, equating to inoculated rate of 200 mL of bacterial suspension according to the treatments and concentrations described in the experimental design. It is applied to the soil at the time of crop establishment and two more applications with an interval of 25 d each. For a total of three applications in the crop cycle (first year).

To analyze production costs, agronomic labor records were maintained, and efficiency metrics were calculated based on the time spent on each task. Costing was done based on prices quoted in Manizales, Caldas, during the first quarter of 2023. These market prices served as a reference for calculating the benefit-cost ratio (B/C ratio), which was estimated using average regional market prices per kilogram over the past three years (2021, 2022, and 2023).

For estimating production costs, the study adhered to the concept of 'operational cost' as defined by Herrera *et al*. (2015), which encompasses all costs of production except for interest on invested capital. This approach allowed for the calculation of production costs and cash flows, providing a basis for profitability estimation targeted at the local market.

Production cost data were recorded in a spreadsheet adapted from the Colombia International Corporation model (DANE, 2023). All figures were converted to U.S. dollars per hectare (US$ ha^{-1}), using the exchange rate reported for the first quarter of 2023 by the Banco de la República de Colombia.

In these cost estimates, a consistent technological level was maintained, along with the proportionality of manual labor hours and input quantities. Technical coefficients —such as man-day hours and input amounts— were based on the work efficiencies observed at Tesorito farm. Costs were bifurcated into two categories:

Manual operations: These were estimated at an average rate of US$16.20 per man-day. This figure reflects the wages paid to rural workers in the region and does not include contributions to social security. Generally, this work is performed either by family members or by labor hired for specific seasons.

For calculating input costs, we relied on the average pricing from major regional distributors. Subsequently, production costs were divided into initial establishment costs in the first year and maintenance costs in the second year, as detailed in table 1. Cash flow projections spanned a 24-month investment period, with all values presented in US dollars per hectare. Additionally, the construction and annual operational costs for the macrotunnel system, covering an area of 540 m^2, are itemized in table 2.

Table 1. Production cost structure in US$ per hectare for the first and second year of strawberry crop.

First year					
Direct costs	Quantity	Unit	Unit value (US$)	Total value (US$)	Part (%)
Crop cultivation (A)					
Plow	4	Time	$ 21.60	$ 86.41	0.23
Ratovo	4	Time	$ 22.95	$ 91.81	0.25
Construction of threshing floors and drains	70	Day labor	$ 16.20	$ 1.134.16	3.07
Application of corrective	4	Day labor	$ 16.20	$ 64.81	0.18
Fertilizer application	2	Day labor	$ 16.20	$ 32.40	0.09
Soil and foliar fertilizer application	15	Day labor	$ 16.20	$ 243.03	0.66
Plastic installation	18	Day labor	$ 16.20	$ 291.64	0.79
Plastic perforation and dimpling	2	Day labor	$ 16.20	$ 32.40	0.09
Sowing and disinfection of seedlings	48	Day labor	$ 16.20	$ 777.71	2.11
Reseeding	2	Day labor	$ 16.20	$ 32.40	0.09
Phytosanitary control	40	Day labor	$ 16.20	$ 648.09	1.76
Herbicide application	10	Day labor	$ 16.20	$ 162.02	0.44
Desyerba	25	Day labor	$ 16.20	$ 405.06	1.10
Stolon and flower pruning	90	Day labor	$ 16.20	$ 1.458.21	3.95
Sanitary pruning	10	Day labor	$ 16.20	$ 162.02	0.44
Harvesting-harvesting	275	Day labor	$ 16.20	$ 4,455.63	12.07
Sorting and packing	165	Day labor	$ 16.20	$ 2,673.38	7.24
Total (A)				$ 12,751.21	34.54

Continued

Continuation Table 1. Production cost structure in US$ per hectare for the first and second year of strawberry crop.

Inputs (B)	Quantity	Unit	Unit value (US$)	Total value (US$)	Part (%)
Dolomite lime	1,000	kg	$ 0.19	$ 189.03	0.51
Gallinaza	4,000	kg	$ 0.10	$ 388.86	1.05
Seedlings	60,000	Unit	$ 0.28	$ 17,012.42	46.09
Compound fertilizer	1,650	kg-L	$ 1.20	$ 1,981.87	5.37
Foliar fertilizer	10	L	$ 20.39	$ 203.85	0.55
Insecticides	16	kg-L	$ 19.98	$ 319.64	0.87
Fungicides	11	kg-L	$ 39.02	$ 429.23	1.16
Herbicides	3	L	$ 6.40	$ 19.20	0.05
Adjuvants	5	L	$ 8.51	$ 42.53	0.12
Transportation of materials and supplies	1	Contract	$ 75.61	$ 75.61	0.20
Plastic (padding)	9,000	m	$ 0.13	$ 1,156.84	3.13
Baskets	100	Unit	$ 0.81	$ 81.01	0.22
Total (B)				$ 21,900.08	59.33
Indirect costs (C)	**Quantity**	**Unit**	**Unit value (US$)**	**Total value (US$)**	**Part (%)**
Leasing	1	ha/year	$ 1,350.19	$ 1,350.19	3.66
Administration	1	ha/year	$ 540.08	$ 540.08	1.46
Technical assistance	1	ha/year	$ 135.02	$ 135.02	0.37
Soil analysis	1	ha/year	$ 36.46	$ 36.46	0.10
Fuel	1	ha/year	$ 80.17	$ 80.17	0.22
Internal transportation	1	ha/year	$ 119.79	$ 119.79	0.32
Total (C)				$ 2,261.71	6.13
Total cost (A+B+C)				$ 36,913.00	100.00
Second year					
Direct costs	**Quantity**	**Unit value (US$)**	**Unit**	**Total value (US$)**	**Part (%)**
Crop cultivation (A)					
Soil and foliar fertilizer application	10	$ 16.20	Day labor	$ 162.02	1.11
Phytosanitary control	36	$ 16.20	Day labor	$ 583.28	4.01
Herbicide application	8	$ 16.20	Day labor	$ 129.62	0.89
Desyerba	25	$ 16.20	Day labor	$ 405.06	2.79
Stolon and flower pruning	80	$ 16.20	Day labor	$ 1,296.18	8.92
Sanitary pruning	10	$ 16.20	Day labor	$ 162.02	1.11
Harvesting-harvesting	275	$ 16.20	Day labor	$ 4,455.63	30.65
Sorting and packing	201	$ 16.20	Day labor	$ 3,256.66	22.40
Total (A)				10,450,4856	71.88
Inputs (B)	**Quantity**	**Unit value (US$)**	**Unit**	**Total value (USD$)**	**Part (%)**
Compound fertilizer	630	$ 1.20	kg-L	$ 756.71	5.21
Foliar fertilizer	10	$ 20.39	L	$ 203.85	1.40
Insecticides	15	$ 19.98	kg-L	$ 299.66	2.06
Fungicides	10	$ 39.02	kg-L	$ 390.21	2.68
Herbicides	2	$ 6.40	L	$ 12.80	0.09
Adjuvants	5	$ 8.51	L	$ 42.53	0.29
Transportation of materials and supplies	1	$ 75.61	Contract	$ 75.61	0.52
Baskets	100	$ 0.81	Unit	$ 81.01	0.56
Total (B)				$ 1,862.38	12.81

Continued

Continuation Table 1. Production cost structure in US$ per hectare for the first and second year of strawberry crop.

Indirect costs (C)	Quantity	Unit value (US$)	Unit	Total value (US$)	Part (%)
Leasing	1	$ 1,350.19	ha/year	$ 1.350.19	9.29
Administration	1	$ 540.08	ha/year	$ 540.08	3.71
Technical assistance	1	$ 135.02	ha/year	$ 135.02	0.93
Fuel	1	$ 80.17	ha/year	$ 80.17	0.55
Internal transportation	1	$ 119.79	ha/year	$ 119.79	0.82
Total (C)				$ 2,225.25	15.31
Total cost (A+B+C)				$ 14,538.12	100.00

Table 2. Cost structure in US$ for the construction and installation of a macrotunnel for strawberry cultivation.

Construction and installation costs	Unit	Total amount	Unit value (US$)	Total value (US$)	Annual value (US$)	% part
Structure - Inputs (A)						
Galvanized pipe 1" X 6 m C2 mm	Unit	667	$ 14.06	$ 9,381.24	$ 469.06	6.97
1 1/2" X 6 m galvanized pipe	Unit	400	$ 19.87	$ 7,947.84	$ 397.39	5.90
3/4" X 6 m black pipe	Unit	67	$ 13.78	$ 923.11	$ 46.16	0.69
1/8" steel cable	Meter	4,444	$ 0.33	$ 1,471.84	$ 73.59	1.09
Welding reference 6013 X 1/8	kg	67	$ 4.42	$ 295.87	$ 14.79	0.22
Staples 50 - 19	Box	22	$ 2.61	$ 57.32	$ 2.87	0.04
Tamping rope roll X 800	Roll	11	$ 61.82	$ 680.06	$ 34.00	0.51
3/8" galvanized threaded rod	Meter	67	$ 1.21	$ 81.36	$ 4.07	0.06
3/8" galvanized nut	Unit	1,111	$ 0.06	$ 61.33	$ 3.07	0.05
3/8" galvanized washer	Unit	1,111	$ 0.06	$ 61.33	$ 3.07	0.05
Agroclear 7 x 7 x 50	kg	2,667	$ 4.10	$10,923.50	$ 2,184.70	32.46
Agroclear 1*8*50	kg	289	$ 4.10	$1,183.69	$ 236.74	3.52
Anticorrosive paint	Gallon	6	$ 13.23	$ 79.35	$ 3.97	0.06
Total (A)				$33,147.84	$3,473.47	51.60
Construction work (B)						
Plastic construction and installation	Day labor	178	$ 13.25	$ 2,358.12	$ 117.91	1.75
Total (B)				$ 2,358.12	$ 117.91	1.75
Irrigation (C)						
Hose 2" 40 gauge	Meter	1458	$ 0.51	$ 740.42	$ 148.08	2.20
Suction hose 2" water inlet	Meter	2,083	$ 2.63	$ 5,473.07	$ 1,094.61	16.26
Tank 2.000 L	Unit	21	$ 255.22	$ 5,359.63	$ 1,071.93	15.92
Dripline 16 mm dripline 40 cm drippers	Meter	8,333	$ 0.24	$ 1,981.58	$ 396.32	5.89
Motor pump 0.75 HP	Unit	21	$ 92.49	$ 1,942.34	$ 388.47	5.77
Accessories 2" motor pump	Unit	21	$ 9.62	$ 202.00	$ 40.40	0.60
Total (C)				$ 15,699.04	$ 3,139.81	46.65
Total (A+B+C)				$ 51,205.00	$ 6,731.18	100.00

Profitability analyses included the calculation of several key financial indicators: gross income, net income, production costs, and unit-specific economic measures such as the Unit Production Margin (MUP) and the Benefit-Cost Ratio (B/C).

To evaluate yield, variables such as per-plant fruit weight, per-plant production in grams, gross yield in kg ha^{-1}, and net yield in kg ha^{-1} were assessed weekly for two years. Statistical evaluation was conducted using analysis of variance (ANOVA) through the SAS software package, version 9.3 (SAS, 2013). Further, Duncan's test was employed to conduct comparative mean tests at a 5% significance level.

RESULTS AND DISCUSSION

The first-year production costs for a hectare for all treatments of strawberry cultivation totaled on average US$36,913 with inputs comprising 59.33% of the total costs. Specifically, seed costs accounted for 46.09% of these input costs. Importantly, we acknowledged the rising cost of agricultural inputs in recent ten years, which has a significant impact on production.

In the second year, a cost reduction of 60.61% was observed for all treatments, amounting on average to US$14,538.12 per hectare. Crop work constituted the majority of these costs at 71.88% (Tab. 1). Noteworthy cost fluctuations were attributed to material and labor expenses, particularly those linked to the installation of plastic mulch, weed management, and harvesting activities. These variations were in line with the crop's variable productivity. Additionally, the macrotunnel system incurred a one-time construction and installation cost of US$51,205 and an annual operational cost of US$6,731.18 (Tab. 2).

In a study carried out by Rubio *et al*. (2014), it was determined that the crop preparation and establishment phases required less labor in both macrotunnel and open-field systems when compared to crop maintenance activities. Moreover, establishment activities under macrotunnels required more labor compared to open fields due to the necessity to install supportive poles and assemble the macrotunnels. The labor cost for the construction of the macrotunnel in that study was US$70.3, compared to the US$117.91 in our study, thereby highlighting the increase in labor costs from 2014 to 2023. According to Rubio *et al*. (2014), they found that growers invest in macrotunnels due to their low cost and long useful life. This is particularly noteworthy when considering that losses caused by *B. cinerea* disease are greater in open fields than under macrotunnels. This represents a higher cost in terms of management, making the semi-controlled system a viable option for strawberry production.

Yield components

There were statistical differences significant ($P<0.05$) in the yield components revealed differences in annual per plant production in production system and coverage. The macrotunnel system excelled, yielding an average of 433.37 g/plant, while the open-field system lagged behind, producing 149.38 g/plant (Tab. 3). Utilizing plastic mulch in conjunction with the macrotunnel resulted in optimal production at 470.5 g/plant; conversely, the absence of mulch led to the least production, registering 396.25 g/plant. In particular, the microbial consortium 2, in combination with the macrotunnel and mulch, exhibited superior performance, producing 602 g/plant (Tab. 3).

Mixquititla-Casbis *et al*. (2020), who assessed the effects of nutrient regimes on strawberry yields in hydroponic systems with plastic mulch, recorded optimal yields of 289.28 g/plant utilizing a 10:1:7 (NPK) ratio. Moor *et al*. (2004) documented a yield of 252 g/plant when fertilized with Kemfos® and KemiraFerticare® products during various phenological phases of the strawberry cultivar Bounty. Similarly, Romero-Romano *et al*. (2012) achieved a yield of 189.42 g/plant using a combination of organic-mineral nutrition (composed of chemical fertilizer + fulvic acids + growth regulator + vermicompost), while Furlani and Fernandez (2007) reported yields ranging from 50 to 300 g. Considering the outstanding results obtained from microbial consortium 2 when used in a macrotunnelsystem with mulch, it stands as an attractive alternative, having demonstrated the highest yield of 602 g/plant.

This consistency in superior performance by microbial consortium 2 was also evident in its impact on the macrotunnel and mulch production system, as reflected in the highest gross and net yields of 25,041 and 17,330 kg ha^{-1}, respectively (Tab. 3). These figures surpassed the yields from the conventional control treatment and microbial consortium 1, which registered net yields of 13,849 and 12,742 kg ha^{-1}, respectively without statistical differences between them ($P<0.05$) (Tab. 3). According to Agronet (2023), the

Table 3. Average strawberry crop yield components under two production systems using microbial consortia.

Production system	Coverage	Bacteria	Gross weight (g/plant)	Net weight (g/plant)	Gross yield (k ha^{-1})	Net yield (kg ha^{-1})	% Losses
Open field B	Mulch A	Consortium 1	165 c	72 d	6,891 c	2,990 cd	57
		Consortium 2	197 c	103 c	8,195 c	4,299 c	48
		B. subtilis	175 c	76 d	7,307 c	3,180 cd	56
		Control	186 c	91 cd	7,729 c	3,781 c	51
	No mulch B	Consortium 1	105 c	52 d	4,362 c	2,180 cd	50
		Consortium 2	83 c	43 d	3,458 c	1,775 d	49
		B. subtilis	142 c	77 d	5,904 c	3,195 cd	46
		Control	142 c	68 d	5,906 c	2,838 cd	52
Average			149.37 B	72.75 B	6,219 B	3,029.75 B	51.12 B
Macro tunnel A	Mulch A	Consortium 1	427 ab	306 b	17,776 ab	12,742 b	28
		Consortium 2	601 a	416 a	25,041 a	17,330 a	31
		B. subtilis	371 b	269 b	15,440 b	11,208 b	27
		Control	483 ab	332 b	20,112 ab	13,849 b	31
	No mulch B	Consortium 1	445 ab	284 b	18,528 ab	11,812 b	36
		Consortium 2	365 b	226 b	15,190 b	9,409 b	38
		B. subtilis	359 b	228 b	14,966 b	9,479 b	37
		Control	416 ab	272 b	17,330 ab	11,338 b	35
Average			433.37 A	291.62 A	18047.87 A	12145.87 A	32.87 B

Different letters indicate statistical differences at 95% reliability by means of the Duncan test. Capital letters indicate statistical differences between each factor. Lowercase letters indicate statistical differences between smaller plots.

average yield for Colombia in 2020 stood at 42,400 kg ha^{-1}. For the scope of our study, the yields were lower than the national average, a fact attributed to our deliberate omission of mildew control treatments. Table 3 reports the percentage of losses evaluated by mildew. With the use of protected production systems such as macrotunnels and plastic covers additional to use microbial consortia, the agroecological conditions for the development of the crop are improved, resulting in better production and fruit quality. This was done to evaluate the effectiveness of microbial consortia and macrotunnels in minimizing losses due to biotic factors such as *B. cinerea*. Vázquez-Gálvez *et al*. (2008) achieved a yield of 25,504 kg ha^{-1} by applying the highest dose of nitrogen at a rate of 1,537 kg ha^{-1}. Given that our study yielded a gross output of 25,041 kg ha^{-1} using microbial consortium 2 in a macrotunnel system with mulch, this approach appears to be a viable supplement to traditional fertilization strategies.

Losses in the macrotunnel production system averaged 32.87%, while those in the open field averaged 51.12%, indicating lower losses in the macrotunnel system, contrary to initial appearances. It's important to mention that we limited the use of chemical defensives in order to assess the disease control efficacy of the bacterial consortia in use. According to Rubio *et al*. (2014), losses in the macrotunnel production system were 22.3 g/plant from a total yield of 340.2 g/plant, equating to 6.55%. In contrast, in the open field, losses amounted to 62.9 g/plant from a total yield of 251.3 g/plant, representing a loss of 25.01% considerably higher than losses in the macrotunnel system.

In the open field, the rate of loss is more than 18.25% higher compared to using macrotunnels, translating to a financial burden of approximately US$7,337.2. This financial difference accounts for 14.32% of the total cost of constructing a macrotunnel. Given that macrotunnels can last up to 10 years, their construction becomes a cost-effective choice for strawberry growers. Rubio *et al*. (2014) concluded that, from a financial standpoint, the losses incurred in open-field systems are roughly one-fifth the cost of investing in macrotunnel construction (US$395.6). Taking into account the lifespan of this infrastructure, its construction proves to be a viable investment. Rubio *et al*. (2014) also observed that yields in macrotunnel systems tend to be superior to those in open-field systems.

Economic viability

The average commercial value of strawberries is US$1.85 per kg. According to DANE (2023) in Colombia, the pricing of strawberries generally fluctuates based on supply and demand. Botero-Hoyos *et al*. (2022), mentioned that Colombia's National Administrative Department of Statistics (DANE) is responsible for monitoring and reporting price trends for this product across various supply centers in the country. The buying and selling prices of strawberries in the region are influenced by market supply and demand. These prices are subject to daily fluctuations, and the purchase price offered to producers depends on the specific day the crop is sold. In the last half of the year, strawberry prices varied between a minimum of US$1.62 per kilogram and a maximum of US$2.07, experiencing a maximum fluctuation of US$0.45 per kilogram for the first category. This information is based on data from the Weekly Bulletin of the Agricultural Sector Price and Supply Information System (SIPSA), which also considered wholesale prices in Manizales, with an average price of US$1.85 recorded over the past 26 weeks.

It is important to mention that none of the treatments tested in conjunction with the production systems yielded a benefit-cost ratio greater than one in the first year, as indicated in table 4. This outcome likely results from our decision to limit the use of defensives in order to assess the efficacy of bacterial consortia in mitigating losses from biotic factors, as outlined in table 3. In the second year, however, bacterial consortium 2 —when used in a macrotunnel production system with mulch— achieved a benefit-cost ratio greater than 1 (Tab. 4), resulting in

Table 4. Economic analysis of strawberry cultivation under two production systems using microbial consortia.

Production system	Coverage	Bacteria	Year 1			Year 2		
			VUP US$	MUP US$	R B/C	VUP US$	MUP US$	R B/C
Open field	Mulch	Consortium 1	$ 4.38	$ 10.08	0.15	$ 1.72	$ 3.97	0.38
		Consortium 2	$ 3.68	$ 7.01	0.22	$ 1.45	$ 2.76	0.55
		B. subtilis	$ 4.13	$ 9.48	0.16	$ 1.62	$ 3.73	0.4
		Control	$ 3.90	$ 7.97	0.19	$ 1.54	$ 3.14	0.48
	No mulch	Consortium 1	$ 6.63	$ 13.28	0.11	$ 2.72	$ 5.45	0.28
		Consortium 2	$ 8.37	$ 16.30	0.09	$ 3.43	$ 6.69	0.23
		B. subtilis	$ 4.90	$ 9.06	0.17	$ 2.01	$ 3.72	0.41
		Control	$ 4.90	$ 10.20	0.15	$ 2.01	$ 4.18	0.36
Macro tunnel	Mulch	Consortium 1	$ 2.07	$ 2.89	0.52	$ 1.05	$ 1.46	1.03
		Consortium 2	$ 1.47	$ 2.13	0.71	$ 0.74	$ 1.07	1.41
		B. subtilis	$ 2.39	$ 3.29	0.46	$ 1.20	$ 1.66	0.91
		Control	$ 1.83	$ 2.66	0.57	$ 0.92	$ 1.34	1.12
	No mulch	Consortium 1	$ 1.92	$ 3.02	0.5	$ 1.00	$ 1.57	0.96
		Consortium 2	$ 2.35	$ 3.79	0.4	$ 1.22	$ 1.98	0.76
		B. subtilis	$ 2.38	$ 3.76	0.4	$ 1.24	$ 1.96	0.77
		Control	$ 2.06	$ 3.15	0.48	$ 1.07	$ 1.64	0.92

VUP= unique production value; MUP = unit production margin; R B/C= cost benefit ratio.

an income of US$10,777, thus indicating significant potential for profitable production. Conversely, all other treatments and production systems recorded a benefit-cost ratio less than or equal to 1, making them financially unappealing, as reflected in table 4.

Given the substantial initial investments required, a production system is deemed efficient if it demonstrates sustainability starting from the second year onward. Therefore, our economic analysis highlights the precarious nature of the financial sustainability of strawberry cultivation in macrotunnels, both with and without plastic mulch and in conjunction with microbial consortia. This fragility arises both from price volatility and from unforeseen spikes in the cost of inputs.

CONCLUSION

The interaction of the macrotunnel production system combined with plastic mulch and utilizing bacterial consortium 2 yielded the highest gross and net yields of 25,041 and 17,330 kg ha^{-1}, respectively. With a favorable cost-benefit ratio of 1.41 in the second year, this approach proves to be a sustainable alternative for growers in the study area.

Additionally, using the macrotunnel production system resulted in a 35.71% reduction in losses when compared to the open-field system.

Conflict of interests: The manuscript was prepared and reviewed with the participation of the authors, who declare that there exists no conflict of interest that puts at risk the validity of the presented results.

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