PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.8160

eISSN 2348-1900

RESEARCH ARTICLE

Synergistic effects of colored polytunnels and fish effluent irrigation on growth, yield and phytochemical composition of Camarosa strawberry

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Received: 10 March 2025; Accepted: 03 July 2025; Available online: Version 1.0: 24 July 2025

Cite this article: Aditi T, Amit K, Joshi T, Vishal J, Rahul K, Sapna T, Pallvi V. Synergistic effects of colored polytunnels and fish effluent irrigation on growth, yield and phytochemical composition of Camarosa strawberry. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.8160

Abstract

The rising demand for sustainable, high-yield strawberry production calls for innovative practices that enhance growth and resource efficiency. Open-field cultivation exposes plants to environmental fluctuations, resulting in inconsistent growth, lower yield and reduced fruit quality. The current study investigates the synergistic impact of varying polytunnel colors (transparent, red, blue and yellow) and fish effluent irrigation on Camarosa strawberry plants. Twelve treatments were associated with the study and observation of yield and biochemical parameters were performed in November 2023-2024 at the Agricultural Farm of Lovely Professional University, Phagwara, Punjab, India. The results indicated that RPE (Red polytunnel + Pineapple peel fish feed effluent) exhibited the highest effects on fruit length (6.51 cm), fruit weight (23.33 g) and yield per plant (500.87 g). However, the lowest effect was recorded in TW (Transparent polytunnel + Absolute water irrigation). Similarly, for fruit quality attributes, RPE and RBE (Red polytunnel + Banana peel fish feed effluent) showed better results. Treatments based on red polytunnel i.e., RPE and RBE showed the highest nutrient uptake resulting in improved physiological performance and enhanced fruit quality and yield. Multivariate analysis helped in visualizing the data and its interpretation. Also, Pearson's correlation measured the strength and direction of individual treatments and variables which showed the direct and indirect effects of variables. Thus, the study concludes that treatments RPE and RBE are best treatments for enhancing the yield, quality and nutrient uptake of Camarosa strawberries making them the most recommended for controlled production optimization.

Keywords: *Ananas comosus*; *Fragaria anannasa*; Koi fish; *Musa paradisiaca*; nutrient uptake; PCA

Introduction

The global agricultural landscape faces unprecedented challenges, including climate change, water scarcity and the increasing demand for sustainable food production (1). Among strawberry varieties, Camarosa is a widely cultivated cultivar known for its exceptional fruit quality, high yield potential and adaptability to diverse growing conditions. Developed by the University of California, Camarosa strawberries are prized for their large, firm and uniformly shaped berries, which exhibit a vibrant red color, sweet flavor and excellent shelf life. However, like other strawberry varieties, Camarosa is sensitive to environmental stressors such as temperature fluctuations, water availability and nutrient deficiencies, which can hinder its productivity and phytochemical composition (2).

Traditional farming practices often rely on synthetic fertilizers and pesticides, which can lead to environmental degradation, soil health deterioration and reduced phytochemical content in fruits (3). As consumers become more health-conscious and environmentally aware, there is a growing need for innovative agricultural practices that enhance crop productivity while minimizing ecological footprints (4). One promising approach is the integration of colored polytunnels and fish effluent irrigation, which offers a synergistic solution to these challenges. Colored polytunnels can modify the light spectrum, optimize photosynthetic efficiency and influence plant morphology (5), while fish effluent irrigation provides a nutrient-rich, organic alternative to synthetic fertilizers (6). Light is a key factor that affects quality, growth, ripening and color, together with the fruit's nutritional value. Plants respond to the quantity of light expressed in flux, duration expressed in photoperiod, direction as tropism and quality as wavelength during their cycle of development, from germination through transition to flower initiation and ripening of fruit (7). Plants perceive light through various families of photoreceptors i.e., phytochromes, which are red/far-red light receptors having a wavelength from 600 to 750 nm, phytotropin and cryptochromes, which are blue light with a wavelength of 320-500 nm; and UV-Bs photoreceptors ranging from 282 to 320 nm wavelength. For the regulation of better plant growth, the photoreceptors either act independently or in grouping (8). In a system integrating aquaculture and agriculture, fish effluents are defined as waters that are rich in nutrients containing both inorganic and organic nutrients that can be substituted for commercial fertilizers (9). Studies have revealed that fish feed carries most of the nutrients for plant growth. In this regard, irrigation with fish farm effluents can replace about 50 % of the fertilizer needed for summer crops and 100 % of that required by winter crops (10). The nutrients from fish effluents are either defecated unswervingly into the water by the fish or made available through the breakdown of microbes from organic wastes: either way, the nutrients usually exist in water-soluble form, thus allowing easy absorption by plants (11). The combination of the different colored polytunnel and fish effluents not only addresses the limitations of conventional farming but also promotes sustainable agriculture by recycling waste and reducing dependency on chemical inputs.

Also, this study explores the synergistic effects of colored polytunnels and fish effluent irrigation on the growth, yield and phytochemical composition of Camarosa strawberries. By investigating these innovative practices, we aim to provide insights into how they can enhance strawberry production, improve fruit quality and contribute to sustainable agricultural systems. The current study thus is designed with the hypothesis that the interaction of red polytunnel with pineapple peel and banana peel feed fish effluent improves the yield, biochemical attribution and nutrient uptake of Camarosa strawberries. These findings could have significant implications for addressing global food security, environmental sustainability and the demand for nutrient-rich produce.

Materials and Methods

Site of experimentation

The study was carried out in November 2023-2024 at the Agricultural Farm of Lovely Professional University, Phagwara, Punjab, India. The experimental area is longitudinally situated at 75°42′4′′ and at a latitude of 31°14′41′′ at an elevation of 240 meters above sea level. The experimental region from November 2023 to June 2024 received an annual rainfall of 0.9 mm, having a maximum temperature of up to 27.2 °C and a minimum temperature of 12.5 °C. The relative humidity was measured to be 86.5 %.

Treatment combinations

In the current study, the Camarosa plants were obtained from Gunjan Strawberry, Solan, Himachal Pradesh and Koi fish from Fish World, Aquarium Home, Jalandhar, Punjab. The colored polysheets were obtained from Sheltertech India Pvt. Ltd. The plants were subjected to 25 treatment combinations of four different colored polytunnel sheets i.e., transparent, red, blue and yellow color and three different types of irrigation i.e., absolute water, pineapple peel fish feed effluent and banana peel fish feed effluent (Table 1) (Fig. 1).

The effluents were prepared by feeding the Koi fish with pineapple peel and banana peel fish feed. The effluents were collected at an interval of 3 days and 250 mL of irrigation for each plant was applied to strawberry plants at 4-5 days intervals, falling within the range of 90-150 mL per plant per day irrigation to strawberry (12).

Agronomic practices

Camarosa plants were planted in polybags with a mixture of soil and FYM, respectively. FYM was used when the plants were transplanted in the polybags. These polybags were placed at 20 cm × 25 cm spacing. The mixture had a pH of 6.5 and the electrical conductivity was measured to be 0.22 Ds m^{-1}.

Observations recorded

Yield attributes

Yield parameters like fruit number, fruit length (cm), fruit weight (g) and yield per plant (g) were observed. The fruits were manually harvested every 5-6 days. An electronic balance was used to weigh the fruits and the average weight of the berries was calculated and displayed in grams (g). The total fruit number from each plant was multiplied by the average fruit weight to observe the average yield of fruits expressed in g/ plant (13).

Yield (g) = Total number of fruits x Average fruit weight (Eq. 1)

Biochemical attributes

Total protein (mg/g): A plant sample weighing 100 mg was obtained and put into a mortar. Cold extraction (10 mL) was added. Until a fine slurry was created, the mortar was kept in the ice bucket and cursed with a pestle. For fifteen minutes, the homogenates were centrifuged at 15000 revolutions per minute. A crude protein extract was made from the collected supernatant. Mix thoroughly and let the color develop for at least five minutes, but no more than 30 min, using 5 mL of diluted dye, 0.2 mL of crude protein extract obtained from the leaf and 0.8 mL of distilled water. When the red dye attaches to

Table 1. Details of different treatment combinations used in the study

Abbreviations	Treatment details	Light intensity and irrigation applied per plant on alternate days
TW	Transparent polytunnel + Absolute water	7200 lux + 250 mL
TPE	Transparent polytunnel + Pineapple peel fish feed effluent	7200 lux + 250 mL
TBE	Transparent polytunnel + Banana peel fish feed effluent	7200 lux + 250 mL
RW	Red polytunnel + Absolute water	4900 lux + 250 mL
RPE	Red polytunnel + Pineapple peel fish feed effluent	4900 lux + 250 mL
RBE	Red polytunnel + Banana peel fish feed effluent	4900 lux + 250 mL
BW	Blue polytunnel + Absolute water	5900 lux + 250 mL
BPE	Blue polytunnel + Pineapple peel fish feed effluent	5900 lux + 250 mL
BBE	Blue polytunnel + Banana peel fish feed effluent	5900 lux + 250 mL
YW	Yellow polytunnel + Absolute water	6050 lux + 250 mL
YPE	Yellow polytunnel + Pineapple peel fish feed effluent	6050 lux + 250 mL
YBE	Yellow polytunnel + Banana peel fish feed effluent	6050 lux + 250 mL

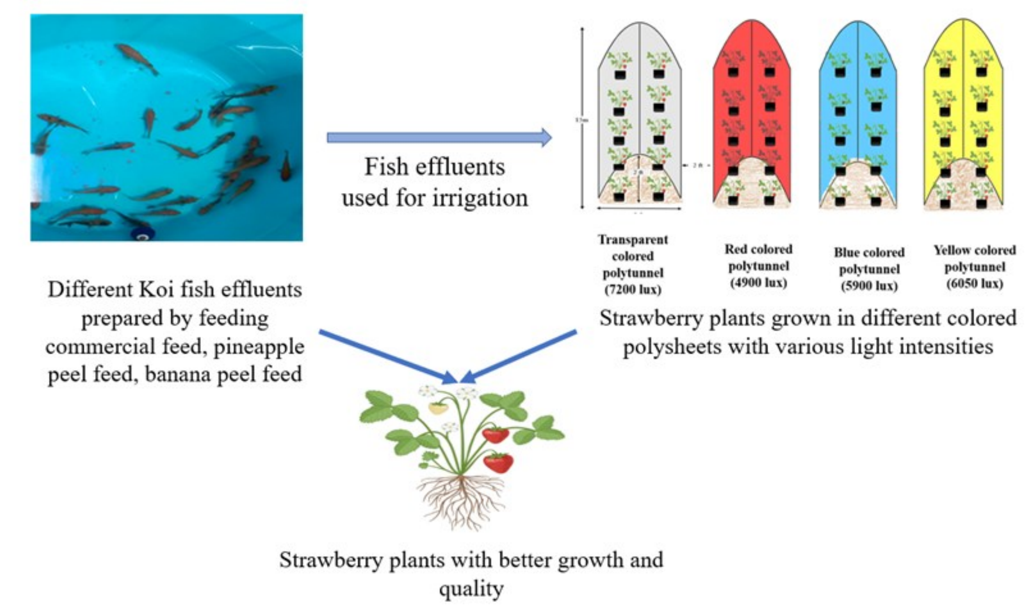

Fig. 1. Influence of interaction of fish effluent and colored polytunnels on Camarosa strawberry.

proteins, it turns blue. Measure the absorbance in a spectrophotometer at 595 nm (14).

Total phenolics (mg/g): The total phenols were estimated by Folin Ciocalteau Reagent (15). Aqueous Na_2CO_3 (4 mL, 1 M) and Folin Ciocalteau Reagent of 5 mL volume diluted in 1:10 ratio with distilled water were combined with the leaf extract samples. The combination was then kept still for around 15 min and the phenols were determined by a spectrophotometer at a wavelength of 765 nm. It is expressed as gallic acid equivalent per gram.

TSS (°B) and titratable acidity (%): 10 mL of fruit juice was titrated against 0.1 N NaOH (Sodium hydroxide), yielding the titratable acidity (TA) as a citric acid percentage. Brix degree (° Brix), a measurement of total soluble solids (TSS), was ascertained by using a refractometer (16).

Ascorbic acid (mg/g): The reagent solution was combined with 5.32 g sodium phosphate, 2.47 g ammonium molybdate and 0.6 M sulfuric acid (500 mL) (17). The sample up to volume 0.3 mL and 3 mL of the reagent were combined and the combination was incubated in a water bath at a temperature of 95 °C for about 90 min. Before the absorbance measurement at a wavelength of 695 nm, it was cooled in water for 5 min following incubation. Findings presented in mg/g of ascorbic acid equivalent. V is the pipette sample volume (L), W is the sample weight (g), Fp is the dilution factor and C is the concentration of the sample (mg/L) to compute vitamin C levels.

$$\text{Ascorbic acid content (mg/g)} = \frac{C \times V \times Fp}{W} \quad \text{(Eq. 2)}$$

Statistical analysis

The observed data was analyzed statistically using R studio for two factors CRD. The importance of various treatments was assessed using qualitative and quantitative characteristics. The average value of each trait was analyzed statistically to estimate correlation. Pearson's correlation and PCA were computed in R studio using the packages Corrplot and factoMineR to quantify the impact of each trait on strawberry yield (18).

Results

Yield attributes

The results showed very wide divergences between the treatments for the number of fruits, fruit length, fruit weight and yield per plant (Table 2). In respect to fruit length, RPE (Red polytunnel + Pineapple peel fish feed effluent) yielded the highest (6.51 cm), fruit weight (23.33 g) and yield per plant (500.87 g), covering the highest advantageous effect on fruit development and productivity. In terms of fruit weight and yield, RBE (Red polytunnel + Banana peel fish feed effluent) gave close values with RPE, reporting 22.71 g and 464.35 g, respectively. Maximum number of fruits produced TBE (Transparent polytunnel + Banana peel fish feed effluent) with 21.44 fruits, RW (Red polytunnel + Absolute water) came second with 20.44 fruits. At the bottom is BPE (blue polyethylene) with the lowest number of fruits (13.89) followed by TW (Transparent polytunnel + Absolute white) and YPE (Yellow polytunnel + Pineapple peel fish feed effluent) with 14 fruits, implying less effectiveness on enhancing fruit production. For length of fruits, the highest value was recorded in RBE (6.83 cm), which ranked similarly with the RPE (6.51 cm) treatment. The least in fruit length, on the other hand, was shown with TW (4.38 cm) and YW (4.41 cm), thereby indicating a limited influence on fruit elongation. In the instance of fruit weights, RPE (23.33 g) and RBE (22.71 g) markedly outperformed other treatments. Furthermore, TW (6.72 g) expressed the lowest fruit weight which was taken as unimpressive in its effects on fruit bulking under said treatment.

Yield per plant had RPE being the highest yield (500.87 g), followed by RBE (464.35 g) and RW (343.77 g), confirming a good influence of red-based treatments on productivity. In contrast, TW (86.67 g) attained the lowest yield, confirming its ineffectiveness in improvement in fruit number. The statistical similarity among a few was found for two or three specific parameters. Thus, no significant differences were observed

Table 2. Impact of treatment combinations on yield and biochemical attributes of Camarosa strawberry

Treatments	Observations			
	Number of fruits	Fruit length (cm)	Fruit weight (g)	Yield per plant (g)
TW	14.00^{d}	4.38^{e}	6.72^{h}	86.67^{g}
TPE	17.67^{c}	4.73^{de}	7.73^{gh}	113.5^{g}
TBE	21.44^{a}	4.67^{de}	8.38^{g}	117.10^{fg}
RW	20.44^{ab}	5.13^{cd}	19.45^{b}	343.77^{c}
RPE	17.56^{c}	6.51^{a}	23.33^{a}	500.87^{a}
RBE	19.89^{b}	6.83^{a}	22.71^{a}	464.35^{b}
BW	19.89^{b}	4.51^{e}	10.93^{ef}	189.49^{e}
BPE	13.89^{de}	5.50^{bc}	13.16^{cd}	261.54^{d}
BBE	19.33^{b}	5.81^{b}	13.88^{c}	276.10^{d}
YW	18.00^{c}	4.41^{e}	10.67^{f}	148.19^{f}
YPE	14.00^{d}	5.16^{cd}	11.46^{ef}	221.65^{e}
YBE	17.67^{c}	5.34^{bc}	12.05^{de}	216.72^{e}

Values are the average of three replicates. According to Duncan's multiple range test, the averages followed by subscript letters differ significantly at $p \leq 0.05$.

among RW, RBE, BW and BBE with respect to fruits. In fruit weight and yield terms, BPE and BBE were on a par level, too.

Fruit quality attributes

The results, therefore, show markedly distinct variations in the several treatments as regards total protein, phenolics, total soluble solids (TSS), titratable acidity and ascorbic acid contents (Table 3). Amongst the treatments, RBE (Red polytunnel + Banana peel fish feed effluent) contained the exceptionally higher values for total protein (0.61 mg/g), total phenolics (0.20 mg/g) and ascorbic acid (56.62 mg/g), meaning that these treatments significantly influenced the improvement of biochemical properties. RPE (Red polytunnel + Pineapple peel fish feed effluent) possessed the statistically highest TSS (12.27 ° Brix), with RBE comparable (12.10 °Brix), suggesting that red-based treatments are effective in improving the sweetness of fruits. TW (Transparent polytunnel + Absolute water) had the least total protein (0.13 mg/g), total phenolics (0.13 mg/g) and TSS (5.43 °Brix) values among all treatments, meaning this treatment had almost negligible influence on biochemical enhancement. For ascorbic acid, TW (41.20 mg/g) and BW (41.58 mg/g) were lowest, indicating that it had almost no impact on enhancing vitamin C content.

The values of titratable acidity were highest in RBE (0.78 %), with values such as RPE (0.88 %) indicating that red-based treatments contributed to retaining fruit acidity. By contrast, YW had the least titratable acidity (0.35 %), indicating that this treatment caused low acidity in fruits. For total phenolics, RBE (0.20 %) had a significantly higher value, followed by RPE (0.19 %), indicating greater build-up of phenolic compounds from red-based treatments. By contrast, TW had the lowest phenolic content of 0.13 mg/g. TW's low level of total phenolics reaffirms that TW was ineffective in enhancing antioxidant properties. In addition, equal treatment remained in statistical terms for certain parameters. No significant differences existed among RPE, BPE, BBE, YPE and YBE on total protein content; TPE, TBE and BW were comparable in total phenolics.

Nutrient composition in Camarosa fruits

The nutrient composition of Camarosa strawberries differed substantially due to varying treatments, which affected the plant growth, fruit development and resulting yield. Such vital macronutrients include potassium, phosphorus, magnesium and calcium, whereas micronutrients like zinc and iron boost the physiological and biochemical processes in strawberry plants (Table 4).

Amongst the treatments, RPE (Red polytunnel + Pineapple peel fish feed effluent) recorded the best values of potassium (295.49 mg/100 g), phosphorus (1.64 mg/100 g), magnesium (23.31 mg/100 g), calcium (8.94 mg/100 g) and iron (2.36 mg/100 g), indicating that this treatment promotes nutrient uptake better than the others. The resultant due increase in these nutrient levels improved vegetative growth, fruit quality and yield. RBE (Red polytunnel + Banana peel fish feed effluent) closely followed with decent amounts of these macronutrients, which indicates higher uptake efficiency for nutrients. However, the lowest amount of potassium, phosphorus, magnesium, calcium and iron was found in TW (Transparent polytunnel + Absolute water), with the following values: 185.97 mg/100 g, 0.47 mg/100 g, 17.59 mg/100 g, 7.67

Table 3. Impact of treatment combinations on biochemical attributes of Camarosa strawberry

Treatments	Observations				
	Total protein (mg/g)	Total phenolics (mg/g)	TSS (°Brix)	Titratable acidity (%)	Ascorbic acid (mg/g)
TW	0.13^{k}	0.13^{c}	5.43^{g}	0.39^{b}	41.20^{g}
TPE	0.24^{j}	0.14^{bc}	6.61^{f}	0.45^{b}	50.83^{d}
TBE	0.26^{i}	0.14^{a-c}	6.78^{f}	0.43^{b}	51.50^{cd}
RW	0.36^{h}	0.14^{bc}	11.51^{b}	0.49^{b}	42.50^{fg}
RPE	0.55^{bc}	0.19^{ab}	12.27^{a}	0.88^{b}	54.60^{b}
RBE	0.61^{a}	0.20^{a}	12.10^{a}	0.78^{a}	56.62^{a}
BW	0.40^{f-h}	0.17^{a-c}	8.29^{e}	0.39^{b}	41.58^{g}
BPE	0.55^{bc}	0.19^{a-c}	9.79^{d}	0.46^{b}	52.35^{c}
BBE	0.58^{ab}	0.17^{a-c}	10.13^{cd}	0.47^{b}	53.80^{b}
YW	0.38^{gh}	0.17^{a-c}	8.55^{e}	0.35^{b}	43.23^{f}
YPE	0.55^{bc}	0.18^{a-c}	10.04^{cd}	0.41^{b}	48.88^{e}
YBE	0.55^{bc}	0.18^{a-c}	10.52^{c}	0.42^{b}	51.70^{cd}

Values are the average of three replicates. According to Duncan's multiple range test, the averages followed by subscript letters differ significantly at $p \leq 0.05$.

Table 4. Nutrient contents in Camarosa strawberry

Treatments	Nutrients (mg/100 g edible portion of fruits)					
	Potassium	Phosphorus	Magnesium	Calcium	Zinc	Iron
TW	185.97^{k}	0.47^{h}	17.59^{f}	7.67^{f}	0.27^{e}	1.77^{f}
TPE	250.41^{f}	0.80^{f}	19.24^{cd}	8.05^{b-d}	0.28^{de}	1.92^{de}
TBE	230.89^{g}	0.72^{g}	18.87^{e}	7.93^{e}	0.31^{b-e}	1.87^{e}
RW	195.34^{j}	1.11^{c}	23.00^{b}	8.08^{b}	0.33^{a-e}	2.02^{c}
RPE	295.49^{a}	1.64^{a}	23.31^{a}	8.94^{a}	0.32^{a-e}	2.36^{a}
RBE	290.41^{b}	1.45^{b}	23.25^{ab}	8.89^{a}	0.27^{e}	2.26^{b}
BW	200.60^{i}	0.48^{h}	17.76^{f}	7.71^{f}	0.28^{de}	1.77^{f}
BPE	270.49^{d}	0.86^{e}	19.46^{c}	8.06^{bc}	0.31^{b-e}	1.94^{d}
BBE	250.45^{f}	0.75^{fg}	19.03^{de}	7.96^{de}	0.35^{a-c}	1.90^{de}
YW	205.71^{h}	0.52^{h}	17.83^{f}	7.72^{f}	0.32^{a-e}	1.79^{f}
YPE	280.49^{c}	0.93^{d}	19.50^{c}	8.14^{b}	0.34^{a-d}	1.95^{d}
YBE	260.78^{e}	0.77^{fg}	19.08^{de}	7.98^{c-e}	0.32^{a-e}	1.93^{d}

Values are the average of three replicates. According to Duncan's multiple range test, the averages followed by subscript letters differ significantly at $p \le 0.05$.

mg/100 g and 1.77 mg/100 g, respectively. This indicates poor nutrient availability, thus suggesting the ineffective uptake of nutrients in Camarosa strawberry plants under transparent treatments, which may have compromised plant growth and fruit development.

The highest concentrations were observed in RPE (295.49 mg/100 g), followed by RBE (290.41 mg/100 g), while TW had the least concentration at 185.97 mg/100 g. Potassium contributes to water accumulation and enzyme activation, as well as the growth of chlorophyll. As K was increasingly present in red-based treatments, further development of fruit firmness, accumulation of sugar and elevated yield could be due to such. The RPE (1.64 mg/100 g) was the richest in phosphorus, which is essential for root development, energy transfer (ATP synthesis) and flowering. TW (0.47 mg/100 g) and BW (0.48 mg/100 g) exhibited the least phosphorus content, reflecting decreased root vigor and limited reproductive growth. As an essential part of chlorophyll, magnesium promotes the efficiency of photosynthesis as well as enzyme activation. The highest Mg level was in RPE (23.31 mg/100 g), followed closely by RW (23.00 mg/100 g) and RBE (23.25 mg/100 g), contributing to its increased biomass and fruit size. Lower Mg content of TW (17.59 mg/100 g) and BW (17.76 mg/100 g) indicate decreased chlorophyll synthesis and energy formation.

Calcium was essential for cell wall integrity and fruit firmness, with RPE (8.94 mg/100 g) and RBE (8.89 mg/100 g) having the maximum amount, leading to better quality of fruits and enhanced shelf life. Compared to these varieties, TW had the lowest calcium content at 7.67 mg/100 g, making it more susceptible to certain physiological disorders, such as softening of the fruit or tip burn. Zn operates as a cofactor in various enzymatic reactions; it plays a role in hormonal balance, flower induction and development of fruit. The Zn content was the highest in BBE (0.35 mg/100 g), while YPE contained 0.34 mg/100 g, which again indicates better reproductive growth. The lowest content was found in RBE (0.27 mg/100 g) and TW (0.27 mg/100 g); this will severely limit the activity of many enzymes, adversely affecting fruit set. Sometimes irreplaceable throughout plant metabolism, iron is critical for chlorophyll formation and electron transfer to excite photosynthetic activity. The maximum Fe was in RPE (2.36 mg/100 g) and RBE (2.26 mg/100 g), which helped in better vegetative growth and fruit quality. Minimum Fe content in TW (1.77 mg/100 g) and BW (1.77 mg/100 g) might limit chlorophyll synthesis, thus leading to pale foliage.

Principal component analysis

The PCA was performed on individuals and variables and the results offer some insights into how treatments relate to key parameters determining strawberry growth, yield and quality (Fig. 2). The individuals' PCA graph illustrates the distribution of different treatments with respect to the first two principal components: Dim 1 accounts for 77.76 % of the total variance while Dim 2 accounts for 10.12 %. Treatments RPE and RBE are located towards the extreme right, thus showing high positive contribution to Dim 1, while TW, TPE and TBE are situated towards the left, reflecting weak association. The second dimension shows even greater differentiation among the treatments, as YBE, BPE and BBE have higher contributions and RW and TW have the opposite.

The PCA graph of variables indicates the correlations that exist amongst different parameters that are measured and principal components. Important parameters like total phenols (TP), total protein (TPr), number of fruits (NF), fruit length (FL), total soluble solids (TSS), yield per plant (YPP), fruit weight (FW) and titratable acidity (TA) have a strong contribution to Dim 1. This indicates that treatments lying on this axis are associated with higher yield and quality traits. The variable ascorbic acid (AA), with a higher contribution to Dim 2, depicts a contrasting trend of variation. Integrating the PCA outputs of individuals and variables shows that RPE and RBE treatments closely inclined to the principal yield and quality indicators, hence the most effective to enhance strawberry productivity and biochemical composition. In contrast, treatments such as TW and TPE are placed negatively in Dim 1, indicating their lesser association with the key growth and quality attributes.

Pearson's correlation

Pearson correlation matrix uncovers the existence of strong to very strong positive linear relationships among the variables as shown in Table 5 and Fig. 3: TA (titratable acidity), TSS, TP (total phenols), TPr (total protein), YPP (yield per plant), FW (fruit weight), FL (fruit length) and NF (number of fruits). Correlations have been found ranging from 0.44 to 0.99, varying in their degree of linear association. TA had almost perfect correlation with FW (0.99): that is to say that total acidity and fresh weight are very dependent on one another, while TSS is positively correlated with FL (0.91), that is, total suspended solids and

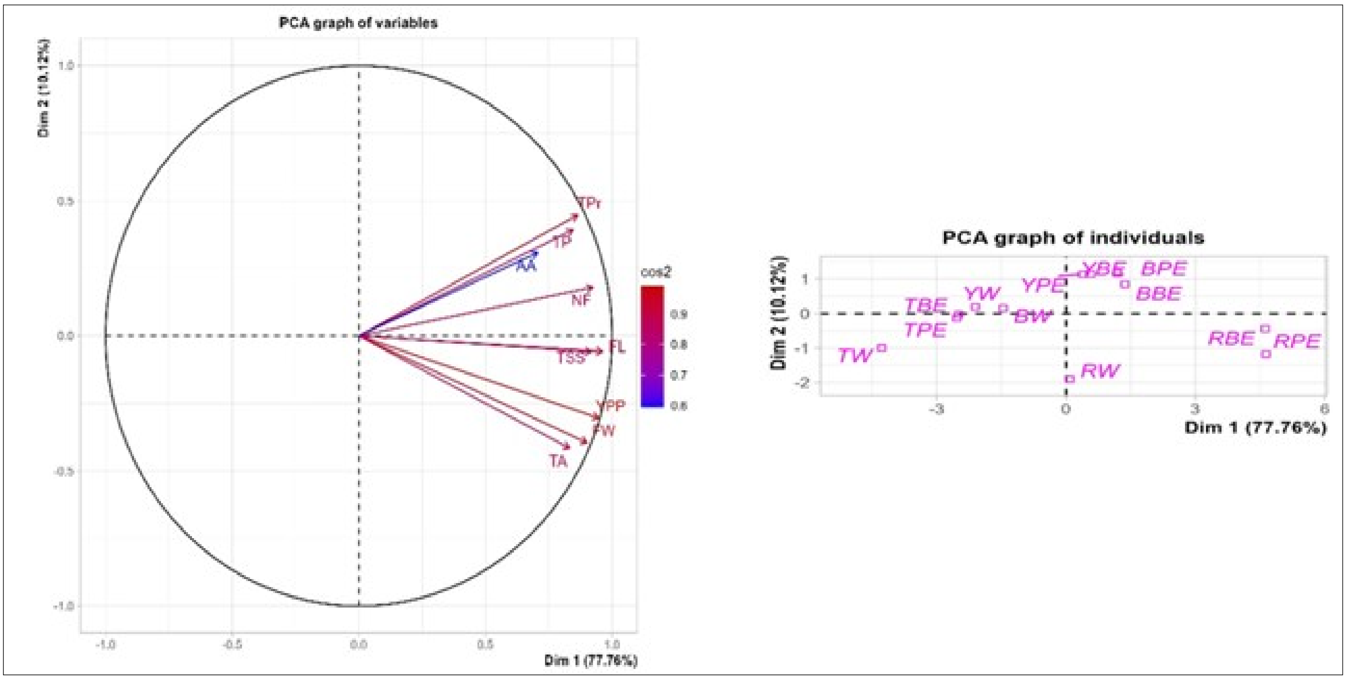

Fig. 2. Principal component analysis of variables (observations) and individuals (treatment combinations). [NF: Number of fruits; FL: Fruit length (cm); FW: Fruit weight (g); YPP: Yield per plant (g); TPr: Total protein (mg/g); TP: Total phenolics (mg/g); TSS: Total soluble solids (°B); TA: Titratable acidity (%); AA: Ascorbic acid (mg/g); TW (Transparent polytunnel + Absolute water); TPE (Transparent polytunnel + Pineapple peel fish feed effluent); TBE (Transparent polytunnel + Banana peel fish feed effluent); RW (Red polytunnel + Absolute water); RPE (Red polytunnel + Pineapple peel fish feed effluent) ; RBE (Red polytunnel + Banana peel fish feed effluent); BW (Blue polytunnel + Absolute water); BPE (Blue polytunnel + Pineapple peel fish feed effluent); BBE (Blue polytunnel + Banana peel fish feed effluent); YW (Yellow polytunnel + Absolute water); YPE (Yellow polytunnel + Pineapple peel fish feed effluent); YBE (Yellow polytunnel + Banana peel fish feed effluent)].

fruit length are significantly related. TP and TPr have shown strong correlations with YPP at 0.91 and 0.89, respectively, since both total phosphorus and total protein influence yield per plant. On top of such correlations, FW maintains a strong correlation with TA and TPr and FL correlates well with TSS and YPP. Whereas NF shows strong correlations with TP and TPr, signifying that the number of fruits is influenced by total phosphorus and total protein. The foregoing findings said about the matrix indicate complex interaction between the variables, which are strongly dependent on each other, meaning proportional changes in a variable are likely to be accompanied by changes in the correlating variables.

Discussion

Harnessing the power of sustainable agricultural innovations, this study explores the dynamic interplay between colored polytunnels and fish effluent irrigation in optimizing the growth, yield and phytochemical richness of Camarosa strawberries. By merging controlled light conditions with nutrient-rich organic irrigation, this approach offers a promising pathway toward enhancing strawberry production while promoting eco-friendly farming practices. Significant variations in yield parameters were observed in the current study under different colored polytunnels i.e., transparent, white, red, blue and yellow. Plants grown under red and blue polytunnels exhibited the highest fruit yield and number of fruits per plant. This is attributable to the enhanced light quality under these coverings, which promoted flowering and fruit set. Moreover, fish effluent irrigation provided an additional nutrient supply, improving fruit size, weight and overall productivity. The improved fruit set percentage under these treatments suggests a positive influence on reproductive physiology, likely due to enhanced nitrogen and phosphorus availability from the effluent. Similar findings of increased yield and maximum fruit number were observed in the study of sweet pepper grown under red-colored shade nets with 40 % relative shading and flux density of 1661 µmol m^{-2} s^{-1} (19). The application of fish effluent increased the fruit number, fruit weight and yield of cucumber (20). It has been shown that using red and UV light combinations with a wavelength of 280-330 nm in polytunnels acted to stimulate the accumulation of anthocyanin and enhance the total flavonoids and phenolic content in tomatoes (21). The accumulation of flavanols in

Table 5. Correlation matrix

	NF	FL	FW	YPP	TPr	TP	TSS	TA	AA
NF	1	0.11	0.28	0.19	-0.02	-0.14	0.17	0.18	0.09
FL	0.11	1	0.86	0.91	0.77	0.72	0.82	0.88	0.79
FW	0.28	0.86	1	0.99	0.64	0.59	0.91	0.86	0.44
YPP	0.19	0.91	0.99	1	0.71	0.66	0.91	0.89	0.52
TPr	-0.02	0.77	0.64	0.71	1	0.92	0.85	0.46	0.63
TP	-0.14	0.72	0.59	0.66	0.92	1	0.73	0.51	0.57
TSS	0.17	0.82	0.91	0.91	0.85	0.73	1	0.66	0.47
TA	0.18	0.88	0.86	0.89	0.46	0.51	0.66	1	0.62
AA	0.09	0.79	0.44	0.52	0.63	0.57	0.47	0.62	1

*NF: Number of fruits; FL: Fruit length (cm); FW: Fruit weight (g); YPP: Yield per plant (g); TPr: Total protein (mg/g); TP: Total phenolics (mg/g); TSS: Total soluble solids (°B); TA: Titratable acidity (%); AA: Ascorbic acid (mg/g).

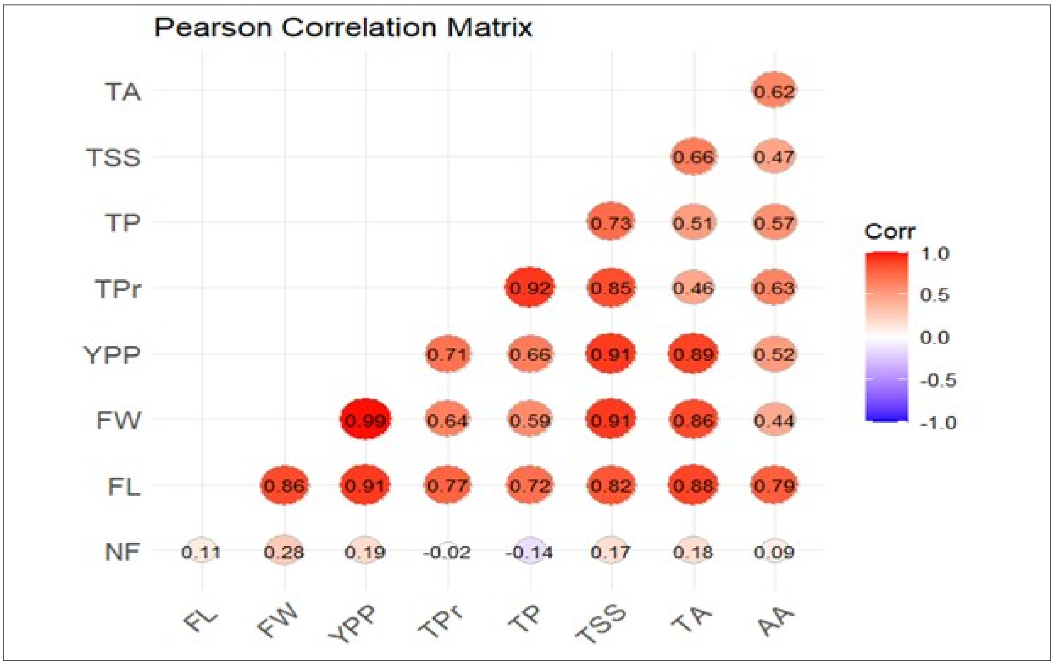

Fig. 3. Pearson's correlation matrix [NF: Number of fruits; FL: Fruit length (cm); FW: Fruit weight (g); YPP: Yield per plant (g); TPr: Total protein (mg/g); TP: Total phenolics (mg/g); TSS: Total soluble solids (°B); TA: Titratable acidity (%); AA: Ascorbic acid (mg/g)].

leaves of Arabidopsis after exposure to UV-B for 6 hr was interrupted with a recovery of 0.5 hr. It was found to be far stronger than with the continuous 6 hr exposure, demonstrating that adapting irregular stress treatments may be viable in the practices of cultivation in the greenhouse (22).

The study also highlighted significant enhancements in phytochemical constituents such as total phenols, anthocyanins and flavonoids in strawberries grown under specific polytunnel treatments. Red and blue polytunnels resulted in higher anthocyanin accumulation, which is consistent with studies linking red light to increased secondary metabolite biosynthesis, such as in lettuce (23). The improved phytochemical profile under fish effluent irrigation could be attributed to the presence of bioavailable nutrients and beneficial microorganisms, which may have stimulated secondary metabolism pathways. Additionally, the combined effect of modified light conditions and organic nutrient enrichment may have triggered stress responses in the plants, leading to an increased synthesis of bioactive compounds. A study observed an increase in the biochemical attributes of strawberries (24) and the application of fish effluent to cucumbers showed better results (20). The nutritional status of strawberry plants is of major relevance for achieving the anticipated levels of productivity and overall quality of fruit. In the present investigation, the application of pineapple peel fish feed effluent increased the nutrient content in Camarosa. The statistical analysis showed the significance among the studied parameters of yield and biochemical characteristics, micro- and macronutrients uptake by Camarosa. Fish farm water increased Cu, Mn, K, P and in basil and N, P, Mg and Cu in purslane, while river water enhanced Ca and Zn in both plants (25). The highest protein and antioxidant levels are observed in treatments with optimal nutrient availability, reinforcing the role of balanced fertilization in improving fruit quality. Additionally, calcium contributes to fruit firmness, while zinc and iron support enzyme activation and stress resistance, further boosting nutritional value. Similar findings were found in strawberries, where foliar application of zinc and calcium improved biochemical attributes (26). The nutrient uptake in the current study aligns somewhat similar with the study where the application of potassium increased fruit production and yield of strawberries (27). Magnesium enhances biochemical properties such as total phenolics and ascorbic acid, crucial for chlorophyll synthesis. Magnesium and its potential for increasing the yield and quality of horticultural crops was reviewed (28).

The synergic interaction observed between investing in colored polytunnels and applying fish effluent irrigation suggests that the two strategies work together in fostering strawberry growth, development and improved yield and quality. Organic effluents also comply with sustainable agricultural practices due to their provision for reducing dependency on chemical fertilizers while improving soil fertility. With this perspective, colored polytunnels also offer a cheap way of manipulating the microclimate by optimizing light availability for enhanced productivity of the plants. All these factors pointed to an increased efficiency of strawberry production, especially in controlled environments, given the combined adoption of those methods.

Conclusion

The study emphasized that the application of colored polytunnels along with fish effluent irrigation has greatly enhanced growth and yield and phytochemical composition in Camarosa strawberries. The major improvements resulted under red and blue polytunnel treatments in terms of high fruit yields as well as improved biochemical properties like total protein, total phenolics, total soluble solids (TSS), ascorbic acid content and titratable acidity. The results imply that colored polytunnel with organic nutrient supplementation via fish effluents can provide an optimum microenvironment for strawberry cultivation, thereby increasing productivity and enhancing the quality of fruits. Correlation analysis also substantiates this observation since a strong association between the weight of fruit-total phenolics and yield applies, thus making it obvious that these factors must be included in any balanced agronomic plan. The results, thus fulfilling the hypothesis, indicate that for effective nutrient uptake by Camarosa strawberries and getting enhanced yield and better quality, selecting red colored polytunnel and using effluent obtained by feeding pineapple and banana peel fish feed to the fish offers a sustainable and eco-friendly alternative to conventional farming practices. This study represents how modifying the practices of protected cultivation for the cultivation of strawberries provides some alerts for growers who want to maximize yield and make use of synthetic fertilizer less. The data emphasizes the suitability of combinative light manipulation with organic nutrient management for developing resource-efficient and sustainable agricultural systems.

Acknowledgements

The authors are thankful for the amenities provided by the School of Agriculture of Lovely Professional University, India, to carry out the research study with ease.

Authors' contributions

AT performed the statistical analysis and drafted the manuscript. AK and JT participated in drafting the manuscript. VJ, RK, ST and PV participated in the paraphrasing of the manuscript. All the authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: No conflicts of interest have been disclosed by the authors.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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