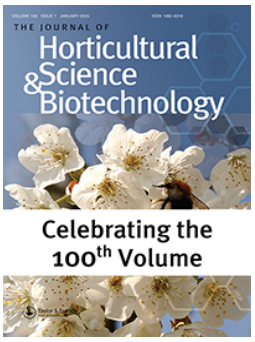

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REVIEW

A review of strawberry under protected cultivation: yields are higher under tunnels than in the open field

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ABSTRACT
Strawberries are grown under tunnels to protect the plants from cold, frosts, rain, and fruit diseases. A review was conducted to determine the performance of plants under plastic tunnels. Information was collected on yields and fruit weight under tunnels and in the open field ($n = 133$ experiments) and on environmental conditions in the two areas. In a global analysis, plants under tunnels had higher relative marketable (Tunnel/Open = 1.34 ± 0.76) and total yields (Tunnel/Open = 1.30 ± 0.83) than those in the open ($p < 0.001$). In contrast, fruit weight was similar in the two growing areas (Tunnel/Open = 1.04 ± 0.22) ($p = 0.094$). Relative marketable yields (Tunnel/Open) were similar in plants in Northern and Southern Europe, and in Northern and Southern America ($p > 0.05$). Relative marketable yields were similar in areas with cool or cold winters or with spring/summer or winter/spring production seasons, and under low or high tunnels ($p > 0.05$). Lower yields under tunnels were associated with low light levels and high temperatures under the plastic and a higher incidence of powdery mildew. The use of tunnels under global warming will require attention to ventilation under the covers.

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Fruit weight; light; profitability; temperature; yield

Introduction

Strawberries (*Fragaria ×ananassa* Duch.) are the most common fruit across the berry catalogue and account for 72% of berry production worldwide (Symington & Glover, 2024; Xu et al., 2023). Major producers include China (36.2% of global production), the United States, Mexico, and several countries throughout Europe. Total production is about 10 million tonnes worth US $22 billion from about 400,000 ha (FAOSTAT, n.d.). Average yields have remained stable over the last decade and ranged from 21.0 to 22.4 t/ha. Strawberry growing in Spain is concentrated in the southwestern region of the country in Huelva Province (de Los Santos et al., 2021). This area makes up 93% of the total Spanish production, with 6,867 ha, 377,596 tons and a market value of €392 million in 2016. Huelva is the leader in European strawberry production, producing 25% to 33% of total European production and is the world's largest exporter. Average yields under tunnels in Spain are twice those achieved in the United Kingdom (Webb et al., 2013).

Strawberry plants are adapted to a range of environments, with production in areas with a cool temperate climate (e.g. Latvia, Norway, and Canada), a warm, subtropical climate (e.g. Florida, Queensland, and Argentina), or a Mediterranean climate (e.g. California, Spain, and Türkiye) (Ahmadi et al., 2024; Amyotte & Samtani, 2023; Gullickson et al., 2024; Holmes, 2024; Kirschbaum et al., 2024; Ramos et al., 2024, Zheng et al., 2024a; Tabatabaie & Murthy, 2016). In the tropics, the plants are grown at elevation (e.g. Arif et al., 2019; and Suminarti et al., 2023 in Indonesia). Different cultivars are grown in the various locations, with plant breeding improving yield, disease resistance, and fruit quality (Knapp et al., 2023; Porter et al., 2023; Alam et al., 2024; Fan et al., 2024; Feldmann et al., 2024; Lima et al., 2024; Prohaska et al., 2024a; Prohaska et al., 2024b).

The plants are susceptible to extreme temperatures, with frosts and heat-waves damaging the flowers, fruit, and leaves, and decreasing yields (Cordeiro & Dötterl, 2023; Hernández-Martínez et al., 2023; Johnson & Hoffmann, 2024; López et al., 2024; Luo et al., 2024; Martínez-Ferri et al., 2014; Matsui & Mochida, 2024; Montague et al., 2024; Nestby et al., 2001; Pedrozo et al., 2024; Silva et al., 2024; Ullah et al., 2024; Unnikrishnan et al., 2024). Prolonged periods of cool weather shorten the harvest period in several areas where there are low temperatures in autumn or spring. High temperatures during the peak of summer inhibit flowering and fruit set.

Production is affected by heavy or prolonged rain. The fruit are damaged directly by rain, with water-soaking and cracking of the skin. The fruit have a high water content and a thin peel or skin (Ma et al., 2024; Shanthini et al., 2025). Nearly all cultivars are susceptible when the fruit are close to harvesting (Herrington et al., 2011; Hurtado & Knoche, 2021; Hurtado et al.,

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2024; Straube et al., 2024). The incidence of several fruit diseases such as grey mould (*Botrytis cinerea*), anthracnose fruit rot (*Colletotrichum acutatum* and related species), and powdery mildew (*Podosphaera aphanis*) is promoted by direct rain contact or by high humidity (Aldrighetti & Pertot, 2023; Filippi et al., 2021; Gama et al., 2023; Lynn et al., 2024).

Crops, including strawberry, are grown under protected cultivation (protected cropping or protected agriculture) to protect the plants, flowers, and fruit from extreme weather, including heavy rain and frosts (Maier et al., 2022; Verteramo Chiu et al., 2024). This article reviews the performance of strawberry under protected cultivation. Information was collected on total yield, marketable yield, and fruit weight from experiments where the plants were grown under low or high tunnels and in the open field. Additional information was collected on environmental conditions in the two systems, the incidence of the major fruit diseases affecting strawberry and on profitability of the plants. Finally, the role of protected cultivation in minimising the impacts of global warming on strawberry production is discussed.

Overview of horticultural production under protected cultivation

Many crops are grown under protected cultivation around the world, with the importance of the technology varying with the species, growing area, climate, and access to capital (Jiang & Yu, 2008 in China; Bertuglia & Calatrava, 2012 in Spain; Sabir & Singh, 2013 across the globe; Meland et al., 2017 in Norway; Asseng et al., 2020 in the United States; Gu, 2021 in the United States; Jiménez-Lao et al., 2021 in South America; Yamanaka & Kawashima, 2021 in Japan; Lubna et al., 2022 across the globe; Morel & Cartau, 2023 in France; Argento et al., 2024 in the Mediterranean area; Azad et al., 2024 in the Desert Southwest of the United States; Cusworth et al., 2024a in the United Kingdom; Cusworth et al., 2024b in China; Kaiser et al., 2024 across the globe; Kim, 2024 in Korea; Lakhiar et al., 2024 across the globe; Ranasingha et al., 2024 in the United Kingdom; Rantanen et al., 2024 in Finland; Stone et al., 2024 in Australia; and Sturiale et al., 2024 in Italy, Spain, Tunisia, and Türkiye). In Southern Spain, intensive horticulture contributes 40% of the gross domestic product in some regions (Egea & Glass, 2017; Egea et al., 2018; Talavera et al., 2024). There are 40,000 ha of plantings under plastic greenhouses or macro-tunnels. These structures produce more than 4 million tons of vegetable and berry crops that are shipped to the rest of Europe and valued at €3 billion each year.

Low-technology polytunnels contribute to 80% to 90% of the area under protected cultivation globally, with glasshouse production less important (Jayasuriya et al., 2024). The area of the protected horticulture was 2.67 million hectares in China in 2021, accounting for more than 80% of the global protected horticulture area (Dong et al., 2024). The area under protected cultivation in the United States is about 0.3% to 1.0% of the global area (Janke et al., 2017). Cultivation under plastic is expanding in many locations within Europe, with the largest area in Spain and Italy (Scarascia-Mugnozza et al., 2011). There are 13,932 ha under protected cultivation in Australia, with 64.8% under nets and 30.0% under poly-houses and poly-tunnels (Clark et al., 2023). Glasshouses and shade houses are less important (5.2%). The total area of horticultural crops under protected cultivation in India is 30,000 to 40,000 ha (Sharma et al., 2024). Protected cultivation of fruit is at an early stage, with strawberry the only fruit crop grown commercially in greenhouses.

Rantanen et al. (2024) examined the benefits of protected cultivation for raspberry in Finland. About 70% of the crop in this area is produced under tunnels to reduce the impacts of cold and rain. Yields were up to ten times higher under tunnels than in the open field. The main environmental impacts from tunnel production came from the fertilisers and the substrates, the tunnel structures, and other materials, all explaining two-thirds of the impacts on climate change gas emissions. In contrast, the main environmental impacts from field production came from the growing activities, which explained over half of the climate change impacts. Eutrophication and land use were 60% and 70% lower with the tunnels than with field production. It was concluded that higher yields and more efficient production can reduce the environmental impacts of tunnel production.

Overview of strawberry production under tunnels in different areas

Strawberries are grown under protected cultivation using plastic covers to protect the plants from cold weather, frosts, and rain (Akpenpuun et al., 2021; Cayambe et al., 2023; Chavan et al., 2022; Clark & Mousavi-Avval, 2022; Domínguez et al., 2016; Osman et al., 2024; Santos et al., 2013; Soria et al., 2009). There are two main structures used to protect the crops from extreme weather, including low and high tunnels. Low tunnels include row covers and small portable tunnels that just cover the growing crop. High tunnels are generally permanent, although sometimes the plastic can be stored between seasons. In the United Kingdom, many of the poly-tunnels have disposable plastic covers fitted in early spring and removed in late autumn and replaced on an annual basis, although new poly-tunnel designs are moving to multi-year covers to reduce the costs of installation and removal of the plastic (Sakrabani et

Figure 1. Production of commercial strawberries under high tunnels in the United Kingdom. From top to bottom: planting without tunnels; extensive tunnel production; tunnel structures before the plastic covers are employed; close-up of tunnels; flower production on benches under tunnels; and heavy fruit production on benches under tunnels.

al., 2023; Figure 1). High tunnels allow the crop to be harvested without removing the plastic. The tunnels generally lack heating and cooling, thereby providing some of the benefits of a greenhouse at a lower cost (Argento et al., 2024; Giacomelli, 2009; Gupta et al., 2024; Nemali, 2022; Pierre et al., 2024).

There are various methods to control the temperature under high tunnels, including passive and active venting (Tian et al., 2023). The sides of the tunnels can be rolled up during warm weather to prevent excessive temperatures inhibiting plant growth and flowering. Temperatures during the day can be excessive for plant growth without venting. Temperatures during the night decrease without some method of heating (Grisey et al., 2023; Zhang et al., 2023). Most tunnels are not heated.

A range of plastics can be used to cover the plants, with different light transmission properties (Lewers et al., 2020; Ordidge et al., 2012; Pandey et al., 2023; Romero-Gámez et al., 2012). The transmission of light through the covers decreases slightly over time as the plastic ages (Uchanski et al., 2020). A major limitation on the employment of plastic covers in tunnels is their disposal after use, which leads to pollution of soil and water environments (Divya & Sarkar, 2019; Galafton et al., 2023; Pergola et al., 2023; Gupta et al., 2024; Logan et al., 2024a; Logan et al., 2024b). Numerous photo- and bio-degradable films have been developed to reduce the impacts of plastics on the environment (Kasirajan & Ngouajio, 2012). However, these perishable films often degrade too quickly or incompletely in the air and soil. Biodegradable films for tunnels have a lifetime of 6 months, much shorter than standard films (Kapanen et al., 2008). Balocco et al. (2018) indicated that low-density polyethylene (LD-PE) degraded slowly, with new and 5-year-old plastic having similar light-transmissions.

The use of protected cultivation for strawberry varies across growing areas. Protected cultivation is important in the United Kingdom, Spain, and some other areas in Europe (Fountain et al., 2023;

Khoshnevisan et al., 2013; Kulak et al., 2013; Martínez et al., 2017; Martínez-Ferri et al., 2016; Neri et al., 2012; Nestby & Guéry, 2017; Port & Scopes, 1981; Roca et al., 1998; Romero-Gámez & Suárez-Rey, 2020; Savvas et al., 2016; Soode Schimonsky et al., 2017; Verteramo Chiu et al., 2024). In Northern America, protected cultivation is used in Canada and parts of the United States where there is the risks of frosts or snow (e.g. Arkansas, Kansas, Minnesota, New York, Texas, and Utah) (Garcia et al., 2017; Hodgdon et al., 2024; Maughan et al., 2015; Scott et al., 2021). Most of the crop in California is grown in the open. Overall, less than 10% of the crop in the United States is grown under tunnels.

Protected cultivation is well developed in Europe, particularly in the United Kingdom and Spain. Poly-tunnels account for more than 80% of the area in the United Kingdom, including Scotland (Beech & Simpson, 1989; Carter et al., 1993; Warner et al., 2010). Protected cultivation and other strategies have been associated with increases in the yields of strawberry over the past two to three decades in the United Kingdom, with yields increasing from 9.9 t/ha in 1996 to 2000 to 22.3 t/ha in 2011 to 2015 (Cusworth et al., 2022). Ninety-seven percent of the area in Spain is under protected cultivation and three percent is in the open (Evans, 2013; García-Tejero et al., 2018; Romero-Gámez & Suárez-Rey, 2020). Eighty-two percent of the area is under macro-tunnel and eighteen percent is under micro-tunnel. Ninety-six percent of the plants are planted in soil, with a mixture of fumigated and non-fumigated fields across the industry. An increase in yield under tunnels in Spain of 20 g/plant was associated with an increase in income of €1,300/ha (Guéry et al., 2018). In the United Kingdom, 55% of production takes place in substrate or soil-less cultivation with fertigation provided by drippers, while 45% is in the soil (British Summer Fruits, 2017). There are efforts to re-use peat in the soil-less systems to reduce the impacts on the environment (Gruda et al., 2024; Vandecasteele et al., 2024).

In the United Kingdom, strawberries are produced from March to December (Raffle et al., 2010). The earliest crops are harvested under glass in Southern England in early April, although additional heat and night-break lighting bring crops as early as March. The season continues under closed-fixed plastic tunnels, followed by field-grown crops under French and Spanish tunnels. The traditionally grown, unprotected field crops are available in June and July. Hancock and Simpson (1995) provided a similar analysis for Europe and identified seven areas with different climates and production systems (Table 1).

Verteramo Chiu et al. (2024) reviewed the performance of strawberry in the open, under un-heated tunnels (plasticulture) and in heated greenhouses. Mean yields (± standard deviation or s.d.) were higher under the tunnels (33.5 ± 16.9 t/ha) and in the greenhouses (47.7 ± 26.7 t/ha) than in the open (18.7 ± 16.9 t/ha) ($p < 0.01$). Information was collected from forty-four tunnel experiments, eight greenhouse experiments and twenty-seven open field experiments. Some of the differences in productivity across the growing systems could be due to variations in plant densities, with plants in greenhouses grown at higher densities than in the other systems.

Performance of strawberry under tunnels around the globe

Productivity and fruit weight varied across the regions, climatic zones, production seasons, and types of tunnels (Supplementary files S1 and S2; Tables 2 to 4). Mean (± s.d.) marketable yield was 422 ± 351 g/plant under the tunnels and 364 ± 321 g/plant in the open. Mean total yields were 403 ± 282 g/plant and 367 ± 299 g/plant, and mean fruit weights were 13.9 ± 4.8 g and 13.7 ± 5.2 g.

In the global analysis, plants under tunnels had higher relative marketable (Tunnel/Open = 1.34 ± 0.76) and total yields (Tunnel/Open = 1.30 ± 0.83) than those in the open ($p < 0.001$). In contrast, fruit weight was similar in the two systems (Tunnel/Open = 1.04 ± 0.22) ($p = 0.094$). Variations in relative yields and fruit weight across the globe are shown in Figure 2.

Relative marketable yield (Tunnel/Open) was similar in Northern (1.13 ± 0.44) and Southern Europe (0.93 ± 0.38), and in Northern (1.42 ± 0.89) and Southern America (1.29 ± 0.29) ($p > 0.05$). Relative total yield was similar in Northern (0.99 ± 0.31) and Southern Europe (1.18 ± 0.73), and in Northern (1.39 ± 1.03) and Southern America (1.44 ± 0.39) ($p > 0.05$). Relative fruit weight was similar in Northern (1.07 ± 0.46) and Southern Europe (0.99 ± 0.20), and in

Table 1. Characteristics of strawberry-growing areas in Europe. Data are from Hancock and Simpson (1995).

Region	Climate	Production system
Spain & Southern Italy	Mild Mediterranean	Tunnels & open
Northern Italy & South-eastern France	Mild, occasionally cold winters	Tunnels & open
Germany	Continental, cold winters	Open & tunnels
The Netherlands & Belgium	Continental, cold winters	Open, greenhouse & tunnels
United Kingdom & the Republic of Ireland	Mild, maritime	Tunnels & open
Poland	Continental, severe winters	Mostly open, with some tunnels
Scandinavia	Short growing season, severe winters	Mostly open, with some tunnels

Table 2. Marketable yield of strawberries grown in the open field and under tunnels across different geographical zones, climatic zones, production seasons, and type of tunnel (low or high tunnel). Data are from Supplementary files S1 and S2. There were two studies in the Asia-Pacific region and one in Africa. s.d. = standard deviation.

	Open field		Tunnel		
	Mean yield (g/plant) ± s.d.	Median yield (g/plant)	Mean yield (g/plant) ± s.d.	Median yield (g/plant)	*n*
Global data set	364 ± 321	317	422 ± 351	362	66
Geographical zone					
Northern Europe	221 ± 154	200	241 ± 186	200	18
Southern Europe	467 ± 230	538	401 ± 223	397	21
Northern America	339 ± 184	322	408 ± 220	371	57
Southern America	752 ± 826	500	866 ± 837	534	11
Asia-Middle East	327 ± 360	327	339 ± 357	339	23
Climatic zone					
Cool winter	315 ± 179	312	371 ± 215	357	69
Cold winter	436 ± 450	324	496 ± 481	367	64
Production season					
Winter/spring	423 ± 463	290	485 ± 493	334	67
Spring/summer	329 ± 190	321	384 ± 225	367	66
Type of tunnel					
Low tunnel	325 ± 169	314	395 ± 291	391	58
High tunnel	390 ± 390	317	440 ± 417	346	75

Table 3. Total yield of strawberries grown in the open field and under tunnels across different geographical zones, climatic zones, production seasons, and type of tunnel (low or high tunnel). Data are from Supplementary files S1 and S2. There were two studies in the Asia-Pacific region and one in Africa. s.d. = standard deviation.

	Open field		Tunnel		
	Mean yield (g/plant) ± s.d.	Median yield (g/plant)	Mean yield (g/plant) ± s.d.	Median yield (g/plant)	*n*
Global data set	367 ± 299	307	403 ± 282	343	97
Geographical zone					
Northern Europe	283 ± 192	256	263 ± 209	175	15
Southern Europe	505 ± 244	494	522 ± 247	491	16
Northern America	403 ± 239	389	472 ± 280	429	36
Southern America	384 ± 301	339	512 ± 357	500	6
Asia-Middle East	278 ± 436	159	292 ± 272	202	23
Climatic zone					
Cool winter	394 ± 354	310	428 ± 290	357	52
Cold winter	335 ± 219	307	375 ± 274	301	45
Production season					
Winter/spring	381 ± 344	301	412 ± 271	370	51
Spring/summer	351 ± 242	313	393 ± 296	302	46
Type of tunnel					
Low tunnel	365 ± 335	319	404 ± 286	342	46
High tunnel	369 ± 265	285	403 ± 281	343	51

Table 4. Fruit weight of strawberries grown in the open field and under tunnels across different geographical zones, climatic zones, production seasons, and type of tunnel (low or high tunnel). Data are from Supplementary files S1 and S2. There were two studies in the Asia-Pacific region and one in Africa. s.d. = standard deviation.

	Open field		Tunnel		
	Mean fruit weight (g) ± s.d.	Median fruit weight (g)	Mean fruit weight (g) ± s.d.	Median fruit weight (g)	*n*
Global data set	13.7 ± 5.2	12.8	13.9 ± 4.8	13.7	73
Geographical zone					
Northern Europe	12.5 ± 3.5	11.8	12.6 ± 3.9	12.7	8
Southern Europe	13.7 ± 5.5	11.4	13.2 ± 4.7	11.7	12
Northern America	14.6 ± 5.1	14.0	14.6 ± 4.8	14.0	29
Southern America	13.8 ± 5.5	11.7	15.0 ± 5.1	13.8	7
Asia-Middle East	12.6 ± 5.6	11.6	13.2 ± 4.7	12.8	15
Climatic zone					
Cool winter	14.9 ± 6.4	14.0	14.8 ± 5.6	14.9	39
Cold winter	12.4 ± 3.1	12.6	12.9 ± 3.4	13.1	34
Production season					
Winter/spring	14.5 ± 6.0	13.9	14.4 ± 5.2	14.4	38
Spring/summer	12.9 ± 4.1	12.6	13.4 ± 4.3	13.2	35
Type of tunnel					
Low tunnel	13.0 ± 4.1	13.6	13.4 ± 4.0	13.2	33
High tunnel	14.3 ± 6.0	12.2	14.4 ± 5.3	13.9	40

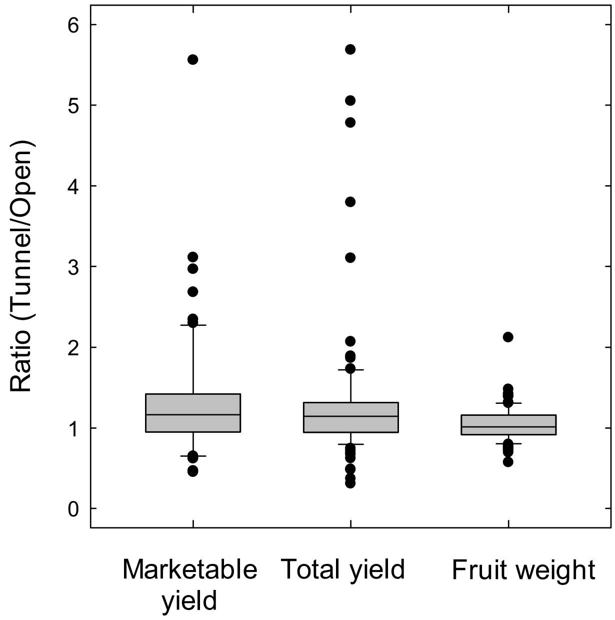

Figure 2. Box plots showing the distribution of relative yield (marketable and total yield in g/plant) and relative fruit weight (g) in strawberry plants grown under tunnels and in the open field (Tunnel/Open). Data are from Supplementary files S1 and S2.

Northern (1.01 ± 0.14) and Southern America (1.12 ± 0.21) ($p > 0.05$). These results suggest that the plants responded in the same way to protected cultivation in the different areas.

Marketable yields were higher in areas with cold winters than those with cool winters and higher under tunnels than in the open in both climates (Table 2). Relative marketable and total yield and fruit weight (Tunnel/Open) were similar in areas with cool (1.32 ± 0.63, 1.38 ± 0.89, and 1.03 ± 0.19) or cold winters (1.34 ± 0.84, 1.22 ± 0.76, and 1.06 ± 0.26) ($p > 0.05$). These results suggest that the behaviour of the plants under protected cultivation was similar in the different climates.

Marketable production was affected by the cropping season and cultivation (Table 2). Yields were high in areas with harvests over winter and spring than harvests over spring and summer. Yields were also high in under tunnels than in the open. Relative marketable and total yield and fruit weight (Tunnel/Open) were similar with fruit produced in winter and spring (1.35 ± 0.65, 1.38 ± 0.90, and 1.03 ± 0.19) or spring and summer (1.33 ± 0.82, 1.22 ± 0.75, and 1.06 ± 1.15) ($p > 0.05$).

Average marketable yields were higher under high (440 ± 417 g/plant) than under low tunnels (395 ± 291 g/plant) (Table 2). Relative marketable and total yields and fruit weight (Tunnel/Open) were similar under the low (1.28 ± 0.46, 1.35 ± 0.83, and 1.05 ± 0.16) or high tunnels (1.37 ± 0.90, 1.27 ± 0.84, and 1.04 ± 0.26) ($p > 0.05$). This indicates that the relative performance of the plants under the two types of tunnels were similar.

Plants under tunnels had higher total and marketable yields than those in the open. In contrast, fruit weight was similar in the two systems. The response to protected cultivation was similar in different geographic areas, locations with different climates or production seasons, and in the low or high tunnels.

Light levels under tunnels

Light levels under tunnels vary across the globe. The information available suggests that shading under the plastic covers can reduce the yields and quality of strawberry plants.

Total light receipts are lower under tunnels than in the open, although there is a higher proportion of diffuse light under the covers (Al-Helal et al., 2020; Al-Madani et al., 2024; Jayalath et al., 2017; Maynard & O'Donnell, 2019; Retamal-Salgado et al., 2015; Rho et al., 2020; Salvadores & Bastías, 2023). There are changes in the transmission of different wavelengths, including the transmission of ultraviolet (UV) light (Fletcher et al., 2004; Gude et al., 2022; Kotilainen et al., 2018; Matamala et al., 2023; Mishra et al., 2023). In experiments in Spain, the yields of 'Camarosa' and 'Ventana' were 20% to 30% higher under UV-light blocking plastic than under UV-light transmitting plastic (Casal et al., 2009). Ripening was delayed with the UV-light blocking film, while fruit weight was increased.

Shading under the covers can reduce plant growth and yields. The impact of the plastic on productivity varies with the crop, latitude, and the season. Low light levels are more of an issue at high latitudes than at low latitudes and over winter than over summer (Robson et al., 2022). Cloud, fog, and aerosols (small particles in the atmosphere) also reduce ambient light levels. Changes in the transmission of UV light effect the development of plant diseases (Barnes et al., 2023). Onofre et al. (2022) found that UV-transmitting plastics reduced the severity of powdery mildew in strawberry under tunnels in Florida. The severity of the disease was higher under all plastics than that in the open field.

He and Li (2014) examined the performance of strawberry under tunnels in Taiwan. Light levels under the tunnels were 30% lower than those outdoors. This response was associated with a 30% decrease in net CO_2 assimilation by the canopy compared with plants in the open, a 35% decrease in leaf area, and a 60% decrease in plant dry weight. The number of flowers per plant was 55% lower under the plastic. The results of this study demonstrate that shading under tunnels can reduce the growth and yield of strawberry.

Plastic covers alter total light receipts and the levels of ultraviolet light. Anderson et al. (2019) investigated the performance of strawberry under tunnels and in the open in Minnesota. Two types of covers were used, including a UV-transmitting and a UV-blocking film. In the first year, the UV levels were 89.1 ± 7.8 $\mu mol/m^2/s$ in the open and 59.1 ± 5.2 and 4.8 ± 0.3 $\mu mol/m^2/s$ under the two types of covers ($p < 0.001$). Total solar irradiance was 32.7 ± 1.1 $\mu mol/m^2/s$, 22.0 ± 0.9 $\mu mol/m^2/s$, and 22.7 ± 1.0 $\mu mol/m^2/s$ in the open, UV-transmitting and UV-blocking treatments ($p < 0.001$). Total yields were higher under the UV-transmitting film (669 ± 25 g/plant) and lower in the open (520 ± 31 g/plant) and under the UV-blocking film (570 ± 37 g/plant) ($p = 0.0058$). Total light levels were adequate for high yields under the tunnels, with the UV-transmitting film beneficial for production. Mean maximum temperatures varied by less than 3°C across the different areas, suggesting adequate ventilation under the tunnels.

Condori et al. (2017) studied the relationship between yield and the environment in five strawberry cultivars under tunnels and in the open in Maryland. Average yields were 40% higher under the tunnels than in the open. Higher productivity under the tunnels was attributed to warmer conditions under the plastic and higher light-use efficiency. Average maximum temperatures were 3.5°C higher under the tunnels than in the open. Changes in temperature and solar radiation accounted for 41% of the variation in yield over the season. It was estimated that the optimum temperature for yield was 26.8°C. Higher temperatures and adequate light levels under the tunnels provided acceptable fruit production in this area. Nakayama et al. (2024) grew strawberry plants under controlled-environment conditions and reported that a photosynthetic photon flux (PPF) of 359 $\mu mol/m^2/s$ for 10.5 h each day was sufficient for fruit production. Maximum values of PPF at noon on sunny days in many locations are 2,500 $\mu mol/m^2/s$.

Dias et al. (2015) found that temperatures under tunnels were adequate for fruit production in strawberry in Brazil. Mean daily temperatures varied by less than 2°C under the tunnel and in the open and ranged from 26.0° to 28.0°C over the season. In contrast, the average solar radiation level under the tunnel was less than half of that in the open. Total yields were 32% lower under the tunnel (7.2 t/ha) than in the open (10.7 t/ha). Productivity was lower under the tunnel due to shading by the plastic. Henschel et al. (2024) investigated the effect of different films on the performance of two strawberry cultivars under tunnels in Brazil. 'Albion' had higher yields under transparent, opaque, or red covers or in plots without a cover (control) compared with plots with a blue cover. In contrast, the yields of 'Camarosa' weres not affected by the covers. Overall, 'Albion' produced twice the yield of 'Camarosa'.

Solar radiation levels under tunnels vary with the type of cover and season. Shading under the tunnels can be severe enough to reduce yields compared with plants in the full sun. The covers can reduce the amount of solar radiation transmitted through the plastic and mediate extreme temperatures under the tunnels.

Temperatures under tunnels

Strawberry plants are sensitive to temperature conditions during the growing season. Plastic covers can protect the plants from cold weather and frosts. On the other hand, temperatures under the tunnels can be excessive for growth if ventilation is inadequate.

Crops can be grown under tunnels to protect the plants from cold weather and extend the production season in areas prone to cold weather or frosts (Ogden & van Iersel, 2009 in Georgia; Bruce et al., 2019 in the Mid-West of the United States; Zheng et al., 2019 in Tennessee; Arancibia et al., 2023 in Missouri; Shaik et al., 2023 in Texas; and Gaisser et al., 2024 in Massachusetts). In some situations, temperatures can be too low under the tunnels for acceptable growth, while in other situations, temperatures can be excessive (Black, 2010).

Several factors influence conditions under the tunnels. These include the location of the tunnel and the weather, the type of plastic used to cover the plants, the height of the tunnel and ventilation within the tunnel (Guttormsen, 1972; Kapanen et al., 2008; Lang et al., 2016; Lewus & Both, 2020; Lozano et al., 2016; Savage, 1980; Tan et al., 1984; Villagrán et al., 2021; Wien & Pritts, 2009; Zhang et al., 2022). Heat stress for workers under plastic tunnels or greenhouses can be problematic if temperatures are above 35°C and relative humidities are excessive (Jung & Kim, 2022 in Korea; Simane et al., 2022 in Ethiopia; Tiwari et al., 2023 in India; and Isoyama et al., 2024 in Japan). Workers can also be at greater risks of exposure to pesticides under the plastic (Cerruto et al., 2018 in Italy; and Requena et al., 2019; Ruiz-González et al., 2024 and Zheng et al., 2024b in Spain), although some reports suggest that this risk is over-stated (see Hernández et al., 2020; Swaen, 2020).

Zheng et al. (2017) modelled the energy balance and airflow within a naturally ventilated tunnel in Tennessee. The tunnel was 15 m long and 9 m wide, with sliding doors at each end. The plastic reflected 20% of the incoming solar radiation, with 1% of the solar energy stored in the air (considered negligible), 5% of the energy stored in the soil, with most of the heat from the solar radiation (74%) removed through natural ventilation. The average temperature outside was 17°C, while the temperature inside the tunnel increased from 2° to 16°C, depending on cloud cover, wind speed and direction, and how wide the tunnel doors were opened. It was recommended that the side panels of the tunnel be raised during warmer weather to prevent over-heating.

Most of the tunnels used by commercial producers do not use heating. Heating is more important at high latitudes and cooling and heating is important at low latitudes. Yao et al. (2019) found that it was not economically feasible to use heating to avoid frost damage to apricot trees under tunnels in New Mexico. Venting within the tunnels can be passive, or active with a specific setpoint or threshold for an individual crop (Gent, 1992). There can be large spatial variations in temperature within a tunnel and differences between days and nights (Arabia et al., 2024; Hull et al., 2024; Palma et al., 2023; Yuan et al., 2004).

Wien (2009) demonstrated it was 4°C warmer at 0800 h and 1800 h under a tunnel than outdoors in Ithaca, New York. In contrast, it was 10°C warmer during the middle of the day (Figure 3). Shading under the tunnels decreases ambient temperatures during the day, whereas poor ventilation has the opposite effect. Mean temperatures from 0800 to 1800 h were 24.8° ± 1.9°C under the tunnel and 14.8° ± 1.3°C in the open. Lozano et al. (2016) conducted similar work in Almonte in Southern Spain. Mean solar radiation from November to June was 12.4 ± 1.9 MJ/m^2/day under the tunnels and 15.3 ± 2.4 MJ/m^2/day in the open (Figure 4). Mean maximum temperatures were 23.3° ± 0.9°C under the tunnels and 20.4° ± 1.3°C in the open. Mean minimum temperatures were similar in the two areas (8.6° ± 0.8°C and 8.5° ± 0.9°C).

Ogden et al. (2011) found that tunnels in Georgia warmed up during the day and cooled to ambient or below ambient at night. This response was more pronounced during clear days and nights. Ward and Bomford (2013) indicated that a high tunnel gave 4.3°C of frost protection for flax in Kentucky and increased temperatures by up to 7.4°C on the coldest days. Yields of tomato in South Africa were higher in a tunnel with a fan and pad cooling system than one dependent on natural ventilation for cooling (Maboko et al., 2012). The temperature in the first tunnel ranged from 13.2° to 38.0°C and from 14.6° to 44.2°C in the second tunnel. Sharaf-Eldin et al. (2023) conducted similar work with tomato in Egypt. They examined various growing systems, including open field, a shaded tunnel with natural ventilation, a net tunnel with fogging and a plastic tunnel with evaporative cooling using a wet pad and fans. The tunnel with evaporative cooling produced the highest yield (3.6 kg/plant) compared with the open field (1.1 kg/plant). The other two treatments were intermediate.

Tunnels can protect strawberry plants from cold weather or frosts and increase fruit yields. However, sometimes temperatures under the tunnels are excessive for acceptable growth and fruit production, for at least part of the season. Leaves in strawberry were on average 2.6°C warmer than the air inside a tunnel in Spain (Peñuelas et al., 1992). This was because it was humid under the plastic and because the leaves were mostly horizontal, and mostly perpendicular to sunlight in the afternoon when they were measured.

Fernandez (2001) examined the potential of tunnels to protect strawberry plants from cold weather in North Carolina. Floating row covers were placed over plots of ‘Chandler’, ‘Camarosa’ and ‘Sweet Charlie’. Daily minimum and maximum temperatures were higher under the covers than in the open when ambient temperatures were above 10°C. The covers increased marketable and total yields by 80 to 100 g/plant compared with plants in the open. Photosynthetic photon flux (PPF) at midday was higher in the open (1,171 μmol/m^2/s) than under the covers (689 μmol/m^2/s). The covers protected the plants from the cold, with adequate light levels for growth under the plastic. Hernandez et al. (2016)

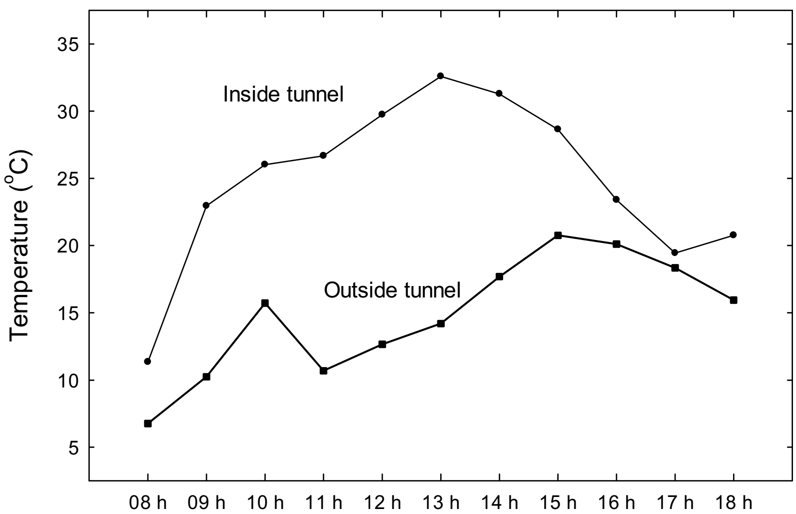

Figure 3. Changes in temperature inside and outside a plastic high tunnel (greenhouse) in Ithaca, New York. Data are from Wien (2009).

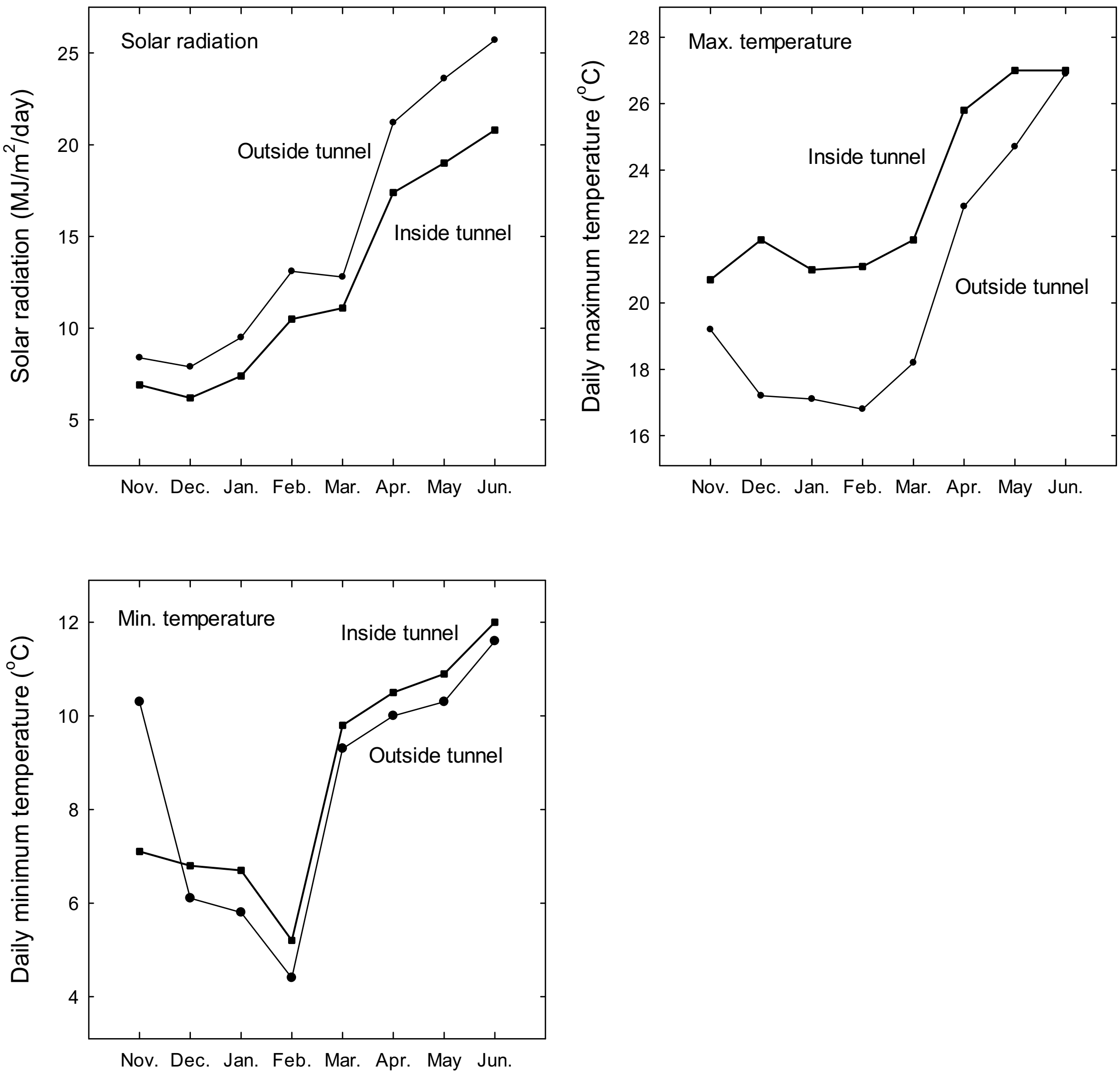

Figure 4. Changes in solar radiation and temperatures inside and outside a plastic high tunnel with strawberries in Almonte, Southern Spain. Data are from Lozano et al. (2016).

also investigated the impact of cold weather on strawberry, with the experiments conducted further south in Florida. During the study, there were eight freezing or near-freezing events with a minimum air temperature of −2.8°C. Minimum temperatures inside the row covers ranged between 0.6° and 4.4°C at the canopy level. Plants under the covers had higher marketable yields (21.8 to 23.9 t/ha) than those in the open where sprinklers were used to mitigate against the frosts (16.7 to 17.8 t/ha) ($p < 0.05$).

In another study in Florida, Salamé-Donoso et al. (2010) examined the effect of protected cultivation on the performance of 'Strawberry Festival', 'Winter Dawn', and 'Florida Elyana' over 2 years. Production in this area is affected by cold weather at the start of the season and wet weather for the whole of the season. The plants were grown under tunnels or in the open. In the first year, there was a single freeze event in early January where the minimum temperature under the tunnel was 1°C compared with −3°C in the open. In the second year, there were five freeze events in January and February. The minimum temperature under the tunnels was 1°C compared with −3°, −6°, −5°, −3°, and −1°C in the open. Both the early and total marketable yields were higher under the tunnels than in the open (Table 5). During the first freeze, 'Strawberry Festival' under the tunnel had the highest early yield (4.8 t/ha) across all the treatments. The same response occurred with the next two freeze events. It was concluded that the other two cultivars were sensitive to freeze events in the open, whereas 'Strawberry Festival' was tolerant to low temperatures, regardless of the production system.

Tunnels can be used to extend the harvest in strawberry, especially in areas that have a cool start to the season. Liu et al. (2024) grew eight cultivars under high tunnels and in the open in Virginia. Fruit were harvested from January to June under the tunnels and from April to June in the open. Average marketable yields were lower under the tunnels (334 ± 26 g/plant) than in the open (516 ± 28 g/plant), with a wide variation in the response across the cultivars. Maximum temperatures under the tunnels in February and March were above 42°C. It was concluded that the

Table 5. Effect of growing system on early and marketable yields of three strawberry cultivars over two seasons in Florida. Means in a column within a treatment group followed by a common letter are not significantly different by the Fisher's least significant test at 5% level of significance. Early yield was from late December to early February. Data are from Salamé-Donoso et al. (2010).

	Early marketable yield (t/ha)		Total marketable yield (t/ha)	
Production system or cultivar	2007–2008	2008–2009	2007–2008	2008–2009
Open field	5.0 b	7.3 b	30.4 b	35.9 b
Tunnel	3.2 a	6.4 a	18.8 a	24.1 a
Strawberry Festival	5.9 c	8.2 c	30.9 c	46.5 b
Winter Dawn	4.1 b	6.8 b	23.4 b	22.5 a
Florida Elyana	2.5 a	5.0 a	19.3 a	20.9 a

tunnels extended the production season, but achieving acceptable yields was challenging in this environment.

Demirsoy et al. (2024) found that temperatures under tunnels were too high for acceptable yields in northern Türkiye. These authors grew nine cultivars under high tunnels and in the open. Mean marketable yield was slightly lower under the tunnels (606 g/plant) than in the open (637 g/plant) ($p > 0.05$). In contrast, fruit weight was higher under the tunnels (14.2 g) than in the open (11.7 g) ($p < 0.01$). Temperatures under the tunnels were higher than in the open. The average daily maximum temperatures in June, July, and August were 38.1°, 35.8°, and 36.4°C under the tunnels and 30.1°, 33.5°, and 31.5°C in the open. The day-neutral (DN) cultivars performed better under the tunnels than the short-day (SD) cultivars.

Tunnels can be used to increase yields, extend the production season and protect strawberry plants from frosts. Temperatures under tunnels are variable, and depend on the weather, the type of tunnel and the use of heating and cooling. Inadequate ventilation or cooling can lead to extreme temperatures and lower yields under the plastic.

Incidence of diseases under tunnels

There are mixed reports on the incidence or severity of diseases when strawberry plants are grown under tunnels. Protecting the plants from rain can eliminate the need for fungicide sprays to control some diseases under the plastic. In contrast, the development of other diseases can be promoted by the high humidity under the tunnels.

There are differences in the development of diseases when crops are grown under protected cultivation. Plastic covers alter light levels, temperatures, and relative humidities, but protect the plants from rain. Differences in the incidence or severity of diseases across growing systems vary with the crop, the pathogen, and the environment (Beacham et al., 2023; O'Connell et al., 2012; Rogers & Wszelaki, 2012; Shishido, 2011; Solís-Mera, 2021). High temperatures and high humidities promote the development of many fungal and bacterial pathogens. Overall, disease issues are less problematic under tunnels. The impact of many diseases is expected to increase under climate change, with higher temperatures predicted to increase the level of damage to plant tissues (Gallego-Tévar et al., 2024).

Hanson et al. (2011) found that the incidence of grey mould in raspberry incited by *Botrytis cinerea* was only 1% under tunnels and 13% in the open. Leaf and cane diseases were rare under the tunnels and common in the open. Børve and Stensvand (2003) demonstrated that fungicides were not required when cherry trees were grown under a rain shelter in Norway. In contrast, high levels of disease in some crops can make production under tunnels not viable (e.g. Babadoost, 2011 with leaf mould in tomato in Illinois; Buckland et al., 2023 with conventional tomato in Oregon; and Díaz-Pérez et al., 2024 with organic tomato in Georgia). There are also heightened concerns about worker safety that limit the chemicals available for use in enclosed tunnels.

Protected cultivation alters the incidence and severity of several diseases in strawberry, including anthracnose fruit rot (AFR) incited by *Colletotrichum acutatum*, grey mould (BGM) incited by *Botrytis cinerea* and powdery mildew (PM) incited by *Podosphaera aphanis*. The impacts of AFR and BGM are more severe in the open than under tunnels, while the impact of PM is more severe under tunnels (Burlakoti et al., 2013; Evenhuis & Wanten, 2006; Nes et al., 2017; Riikonen et al., 2024). However, some authors have reported the opposite response or no difference between the two systems (Cosseboom et al., 2023; Kennedy et al., 2013). In some experiments, the difference in disease between tunnels and the open varies with the cultivar (e.g. Carisse et al., 2013 with powdery mildew in Canada). Some cultivars have a higher incidence of the disease under the tunnels than others. Applications of UV-C light reduce the severity of PM under both field and tunnel conditions (Mello et al., 2022; Onofre et al., 2021, 2022; Riikonen et al., 2024).

Differences in the development of the three main diseases affecting strawberry are due to variations in temperature and water conditions between the protected and non-protected environments. Both AFR and BGM are promoted by prolonged rain, whereas PM is promoted by high humidity but not by free water (Aldrighetti & Pertot, 2023; Russi et al., 2024; Yousef et al., 2024). The application of fungicides reduces the differences in diseases between the two systems (e.g. Onofre et al., 2021 with powdery mildew in Florida). Alternatively, steam can be applied to the nursery plants to reduce the infection of plants in the production fields (Stensvand et al., 2024). Burlakoti et al. (2013) examined the effect of protected cultivation on diseases in strawberry over 2 years in Ontario, Canada. The incidences of AFR and BGM were low under tunnels compared with the open field. There was a five- to a twenty-fold lower incidence of AFR under the tunnels and a five-fold lower incidence of AFR. The incidence of PM was higher under the tunnels (7.0% to 12.9% of fruit affected) than in the open (0.6% to 4.9% of fruit affected). Marketable yields were two to three and half times higher under the tunnels than in the open. Tunnels protect plants from rain or free moisture and help to reduce the number of fungicide sprays needed to control AFR (Burlakoti et al., 2014; Xiao et al., 2001). For instance, Burlakoti et al. (2014) indicated that the incidence of AFR in non-sprayed plots was 0.9% to 3.1% under tunnels and 16.0% to 19.3% in the open. Marketable yields in the two plots ranged from 2.364 to 2.460 kg/1.2 m^2 and from 0.831 to 0.970 kg/1.2 m^2.

Protected cultivation alters the development of fruit diseases affecting strawberry. The incidence of AFR and BGM is lower under tunnels than in the open, whereas the incidence of PM shows the opposite trend. Tunnels that offer protection from rain can reduce or eliminate the number of fungicide sprays used to control AFR and BGM. In contrast, the incidence of PM can be problematic under plastic covers.

Pollination under tunnels

Strawberry plants require bees or other insects for effective seed and fruit set. This can be a problem under tunnels, with fewer pollinators under tunnels than in the open field.

Pollination is important for seed and fruit set in most flowering plants (Bishop et al., 2021; Kendall et al., 2021). Managed and wild bees, along with flies are the major pollinators of crop and wild species (Faure et al., 2024; Nacko et al., 2022; Feltham et al., 2015; Fenton et al., 2025; Feuerbacher et al., 2024; Mateos-Fierro et al., 2023; Thomasz et al., 2024; Warren et al., 2024).

The importance of pollination for the fertility of plants can be assessed by estimating pollination dependence (PD). This parameter can be calculated by determining fertility after self- and open-pollination (Menzel, 2023). There are various indices of fertility used in the research, including the rate of seed or fruit set, the number of seeds in a fruit, fruit weight, or yield. Species vary in their dependence on pollinators for seed or fruit set (Ryan et al., 2023; Siopa et al., 2024). The dependence on pollinators ranges from zero (fertility not dependent on pollinators) to one (fertility completely dependent on pollinators). In some plants, the availability and transfer of pollen limit seed or fruit set (Layek et al., 2023; Makowski et al., 2024). Pollen limitation (PL) or pollination deficit varies with the plant and the methods used to assess seed or fruit set. Pollen limitation can be estimated by comparing the fertility of flowers with and without supplementary insects or by comparing the fertility of hand- and open-pollinated flowers. Low values of PL are associated with abundant pollinators and frequent visits of pollinators to the flowers.

Tunnels are a barrier to the movement of pollinating insects, and disrupt their interaction with flowers (Cao et al., 2023; Leach & Isaacs, 2018; Mateos-Fierro et al., 2024; Taniguchi et al., 2025; Wszelaki et al., 2013). Bees have a shorter life-span when placed under plastic covers, due to changes in light levels, temperatures, and relative humidity and may not be effective pollinators (Ogden & van Iersel, 2009). Hall et al. (2020) examined the success of pollination in blueberry and raspberry under tunnels with open ends in New South Wales, Australia. They found a higher abundance and a greater number of visits to the flowers by stingless bees (*Tetragonula carbonara*) and honey bees (*Apis mellifera*) at the ends of the tunnels and less frequent visits towards the middle of the tunnels. The middle of the tunnels had higher temperatures and lower wind speeds. In blueberry, yield ($p < 0.001$) and berry weight ($p < 0.05$) were positively correlated with the abundance of pollinators and were lower at the middle than at the edge of the tunnels. In raspberry, the fruit had better shape in areas when there were high populations of pollinators.

Strawberry plants are moderately dependent on pollination from bees and other insects, with fruit set limited by the availability of pollinators under natural open conditions (Gudowska et al., 2024; Hodgkiss et al., 2019; Menzel, 2023; Pioltelli et al., 2024; Tuohimetsä et al., 2014). Menzel (2023) demonstrated that the mean (± s.d.) pollinator dependence (PD) in strawberry (self-pollination versus open- or insect-assisted pollination) was 0.36 ± 0.26 ($p < 0.001$, $n = 52$ studies). The fertility of plants exposed to supplementary insects was higher than those exposed to pollinators under natural open conditions, with a calculated pollen limitation (PL) of 0.20 ± 0.17 ($p < 0.001$, $n = 20$ studies). Nishimoto et al. (2023) demonstrated that there were no differences in the percentage of marketable fruit in strawberry after pollination by hand or with robots under protected cultivation in Japan. There were also no differences in fruit weight or the number of achenes per fruit between the two treatments.

Piovesan et al. (2019) collected data on potential pollinators for strawberry under tunnels in Brazil. The flowers were visited by 47 species of insects. *Apis mellifera* or honey bee (Hymenoptera: Apidae) was the most abundant, constant, dominant, and frequent species. Twelve species of native bees were identified, including *Tetragonisca fiebrigi*, *Tetrapedia* sp., *Trigona spinipes*, *Schwarziana quadripunctata*, *Plebeia emerina*, *P. remota*, *Bombus pauloensis* (Hymenoptera: Apidae), *Dialictus* sp.1, *Dialictus* sp.2, *Augochloropsis* sp.1, *Augochloropsis* sp.2, and *Augochlora* sp.1 (Hymenoptera: Halictidae). It was concluded that all these species were potential pollinators of the crop under covers. The native species, *T. fiebrigi*, *P. emerina,* and *P. remota* were the most abundant potential pollinators and were relatively easy to manage under the tunnels.

Antunes et al. (2007) found that the yields of four strawberry cultivars under protected cultivation in Brazil were increased when hives of jatai bees (*Tetragonisca angustula*) were introduced into the growing area. Average yields were 686 g/plant in the control and 968 g/plant with four hives per growing area. Wilkaniec and Radajewska (1997) reported similar results using the solitary bee (*Osmia rufa*) under tunnels in Poland. Average yields were 289 ± 77 g/plant with self-pollination and 434 ± 153 g/plant with bees. Howard et al. (2021) indicated that honey bees were better pollinators than other insects when strawberry plants were grown under tunnels in Victoria, Australia. Their work showed that the honey bees spent more time visiting the flowers than the other insects. Willden et al. (2022) investigated the pollination of strawberry under tunnels in New York. There was evidence that UV-blocking plastics resulted in poorly pollinated fruit compared with UV-transmitting plastic and open-field treatments. However, the mechanism causing this response was not clear.

Ariza et al. (2012) studied the effect of pollination on the performance of strawberry under tunnels in Spain. Plots under the tunnels were provided with bumble bees (*Bombus terrestris*) or pollinated under natural conditions (controls). From January to March, the incidence of misshapen fruit was 25.7 ± 2.3% with supplementary bees and 61.3 ± 3.8% without bees ($p < 0.05$). From April to May, the incidence of misshapen fruit was 13.4 ± 2.8% with bees and 20.3 ± 1.9% without bees ($p < 0.05$). Supplementary pollination was advisable for strawberry under covers, especially in cultivars such as 'Camarosa' that were prone to misshapen fruit. Sarıdaş et al. (2021) collected similar information in Türkiye. One tunnel was covered with a monofilament UV-stabilised white net (88% to 98% light transmission) to prevent pollinators from visiting the flowers. One commercial honey bee hive was placed near that tunnel, which allowed bees to enter the other tunnel. The plants supplied with bees had 54% higher yields (1,175 g/plant) than those not supplied with bees (763 g/plant) ($p < 0.05$). The plants with bees also had larger fruit (17.6 g versus 15.0 g) ($p < 0.05$).

Strawberry requires successful pollination for acceptable productivity and quality. Yields and fruit weight are lower under tunnels if the insects have poor access to the flowers compared with conditions in the open field. Supplementary pollination with bees or other insects can improve production under tunnels.

Profitability under tunnels

The economics of growing strawberry plants under tunnels varies around the globe. Most studies indicate that production under plastic covers is profitable, although there are exceptions.

The costs of production are higher when crops are grown under tunnels than in the open field. The economics of tunnels depends on the costs of production, yields, and the price received for the product (DiGiacomo et al., 2023; Ho et al., 2018; Sydorovych et al., 2013). In some cases, tunnels offer improved control of pests and diseases, but the technology is not economically viable (Nordey et al., 2020). Different analyses can be used to determine profitability, including net returns, net present worth, internal rate of return, benefit-to-cost ratio, and the pay-back period (Bodiroga et al., 2022; Morris et al., 2023; Nian et al., 2022; Sengar & Kothari, 2008; Subedi et al., 2023).

Galinato and Miles (2013) found that lettuce and tomato yielded three to four times more under tunnels than in the open in Washington State. Given the base crop yield and average price, it was 43% more profitable to grow lettuce in the open than under the tunnels. In contrast, tomatoes under the tunnels were three-times more profitable than those in the open. Ward et al. (2011) investigated the economics of speciality crops under tunnels in the United States. They found that even when land prices were high, tunnels were profitable, provided the produce was grown out-of-season and sold at farmers' markets. Chase (2013) investigated the production of vegetable crops under tunnels in Iowa. He found that the costs of the low-technology tunnels were paid back within a year, which is unusual in horticulture. Ernst (2020) indicated that it took 3 years to recover the additional costs of vegetables under low tunnels in Kentucky. Waterer (2003) examined the profitability of muskmelons, peppers, and tomatoes under low or high tunnels in Saskatchewan, Canada. The high tunnels were more costly to purchase and construct than low tunnels, but they were durable enough to be used for multiple seasons. Based on wholesale commodity prices, it took 2–5 years for the returns obtained with high tunnels to cover their higher capital costs.

Research on the profitability of strawberry under tunnels has given mixed results, with both positive and negative returns over costs (Clark, 2023;

Mbarushimana et al., 2022; Salamé-Donoso et al., 2010). Marin and Garcia (2004) collected economic data under tunnels in Spain. They indicated that there was range in income for different enterprises in Andalusia. The total net margin (€ × 1000/ha) was variable across the areas (mean ± s.d.): Almeria (14.75 ± 57.6), Granada (12.57 ± 48.85), Huelva (23.2 ± 114.29), and Málaga (21.80 ± 38.48). This response was due to differences in production strategies, the availability of water, the type of irrigation technology, and the weather. The net margin was higher under the tunnels than in the open due to a more stable environment and more stable yields.

Zhao et al. (2015) demonstrated that overall net returns were higher under high tunnels (USD 51,755 ± 26,317/ha) than in the open in Florida (USD 29,335 ± 7,871/ha). The difference in returns between the two systems decreased with the increasing costs of the tunnels and the shorter life-span of the plastic. When the plastic lasted 8 years and the tunnel cost USD 56/m^2, tunnel production was less profitable than open production. However, when the plastic lasted 9–15 years, tunnel production was more profitable, even when the tunnels cost USD 57/m^2. Mbarushimana et al. (2022) investigated the performance of eight cultivars under high tunnels and in the open in Virginia. Averaged over three marketing strategies, net returns were lower under the tunnels (minus USD 35,055 ± 19,807/ha) than in the open (positive USD 77,926 ± 29,641/ha). Poor returns under the tunnels were due to low yields and high costs.

Salamé-Donoso et al. (2010) grew three strawberry cultivars under high tunnels and in the open over 2 years in Florida. Early marketable yields were up to 54% higher under the tunnels than in the open, and total marketable yields were up to 63% higher (Table 5). Higher yields under the tunnels were due to protection from frosts. The higher yields provided an additional USD 28,875/ha in gross returns, off-setting the costs of the tunnels of USD 15,000/ha each season. The costs of harvesting and marketing were not included in the analysis.

Lewers et al. (2017) examined the profitability of strawberry under low tunnels in Maryland. Marketable yields were 313% higher under the tunnels than in the open. The costs of the material used to construct the tunnels were calculated to determine if they could be off-set by the extra production. An increase in the production value of USD 0.59/plant over 2 years was required to pay for the materials needed to construct a tunnel. Yields increased from 230 g/plant in the open to 720 g/plant under the tunnels, suggesting higher profitability under the plastic. The cost of labour to construct the tunnels was not included in these calculations. Orde and Grube Sideman (2021) evaluated the performance of day-neutral (DN) strawberry under low tunnels and in the open over 2 years in New Hampshire. Marketable yields were unaffected by the covers in the first year and were higher under the tunnels in the second year. Plants under the tunnels had a market value of USD 3,899 to 95,647/ha, depending on the cultivar and year. The covers costed USD 1,557/ha, assuming a life-span of 3 years. The row covers were profitable in this environment.

Maughan et al. (2015) investigated the costs and returns for strawberry under high tunnels in Utah. The tunnels provided a net return of USD 15,549/ha. The economics of open production was not recorded in the study. Sullivan et al. (2022) provided similar data in Oregon. These authors grew strawberry under high tunnels or in the open. They reported that a 15.2 m long tunnel gave a return of USD 1,970 compared with USD 1,344 for the open field, a 46.6% increase. No information was provided on the costs of the tunnel or on the life-span of the plastic.

Schmutz et al. (2011) examined the economics of organic strawberry under high tunnels in the United Kingdom. The field was planted out at 50,000 plants/ha and produced yields of 15 t/ha worth £60,000/ha. The cost of establishment was £15,624, variable costs were £40,424 and the gross margin was £19,576. Jirgena et al. (2013) studied the risks and returns of strawberry under different production systems in Latvia. The tunnels provided a better environment than the open field with fewer pests in the crop. This response contributed to a longer and more predictable shelf life for the fruit (Table 6). The tunnels extended the harvest season, with earlier harvests than in the open and higher prices for the crop. In the open area with minimum investments, aggregate expenditure exceeded total revenue and the system provided a negative return (Table 7). The open area managed

Table 6. Probabilities and severities of yield risks in strawberry production under different growing systems in Latvia. Risk severity is expressed from zero (no risk) to ten (severe risk). Data are from Jirgena et al. (2013).

		Severity of risk to yield			
Risks	Probability	Open area, with minimum investment	Open area	Plastic cover	High tunnel
Winter frost damage	0.1	10.0	10.0	10.0	10.0
Early moderate frosts	1.0	1.8	1.8	0	0
Early severe frosts	0.4	8.5	8.5	2.0	2.0
Hail	0.1	9.0	9.0	9.0	0
Heavy rain	0.3	4.5	4.5	4.5	1.0
Pests & diseases	0.5	7.5	7.5	7.5	1.0

intensively provided better returns on investment than that under the tunnels. Production in open areas under cover provided the best returns on investment.

McIntosh (2018) examined the performance of different production systems in southern Australia. Yields and gross margins were higher with substrate production under tunnels or in glasshouses than with soil production in the open field (Table 8). However, capital costs were much higher under protected cultivation than in the open. McIntosh (2018) indicated that the plants under protected cultivation had a lower incidence of some fruit diseases than those in the open.

Greco et al. (2020) and de Tommaso et al. (2021) analysed the performance of strawberry under tunnels and in the open in Europe. This market is worth € 2.4 billion at a consumer level, about 1% of the total value of agricultural production in the area. In the two studies, yields were higher under the tunnels in Spain and Belgium, and lower in the open in Italy and France (Table 9). Net returns were higher under the tunnels in Italy and lower in the open in Italy and Belgium. Where there was a direct comparison of the two systems, average returns were €13,229 ± 2,202/ha under the tunnels and €8,160 ± 1,265/ha in the open.

The economic performance of strawberry under tunnels is highly variable. Net returns vary with yields, marketing strategies, and the costs of the tunnels. In some cases, plants under tunnels have higher yields than those in the open or they produce fruit out-of-season when prices are high. In these cases, the returns for the fruit can exceed the costs of the tunnels. In other cases, plants under tunnels have lower yields than those in the open or they produce fruit during the traditional season. In these cases, the returns for the fruit can be lower than the costs of the tunnels. The life-span of the covers has a strong effect on profitability. Plastics that last 8 or 10 years are more economical than those that last for shorter periods.

Use of tunnels to minimize the impacts of global warming on strawberry production

Several studies indicate that the yields of strawberry will be lower under global warming. Modelling in California demonstrated that productivity will decrease by 10% by 2050 and by 40% by 2099 (Deschenes & Kolstad, 2011; Lobell & Field, 2011). Higher temperatures under tunnels might exacerbate the effects of global warming on commercial production in the future.

Protected cultivation can be used to mitigate against the effects of climate change on the

Table 7. Return on investment for strawberry production under different growing systems in Latvia. Data are from Jirgena et al. (2013).

Growing system	Revenue (€/ha)	Investment (€/ha)	Expenditure (€/ha)	Gross profit (€/ha)	Return on investment
Open area, with minimum investment	12,177	11,666	15,972	−3,975	−33%
Open area	19,997	13,893	17,312	2,665	19%
Plastic cover	35,177	23,102	25,943	9,234	40%
High tunnel	104,209	81,866	97,250	6,959	9%

Table 8. The costs and returns of strawberries growing in the open field, under tunnels with substrates, and in greenhouses with substrates in Australia. Values are in AUD (Australian dollars). Data are from McIntosh (2018).

Costs, yields & gross margins	Open field	Tunnel/substrate	Greenhouse/substrate
Total capital costs ($ per ha)	142,239	422,239	887,239
Total variable costs ($ per ha)	183,399	300,799	396,331
Marketable yield (t/ha)	48.7	72.7	90.2
Gross returns ($/ha)	205,434	446,855	558,249
Gross margin ($/ha)	22,035	146,056	161,919
Gross margin (% of gross returns)	11%	33%	29%

Table 9. Yields and net returns of strawberries growing in the open field and under tunnels in Europe with soil fumigation. Mean values and standard errors (s.e.) also shown where there was a direct comparison of the two systems (values for tunnels in Spain excluded). Data are from Greco et al. (2020) and de Tommaso et al. (2021).

Country	Growing system	Yield (t/ha)	Net returns (€/ha)
Spain	Tunnel	55.1	13,611
Italy	Open field	12.7	7,892
	Tunnel	35.0	18,338
Belgium	Open field	18.4	5,624
	Tunnel	50.0	9,195
France	Open field	11.1	10,965
	Tunnel	22.6	12,154
Mean (± s.e.)	*Open field*	*14.1 ± 1.8*	*8,160 ± 1,265*
	Tunnel	*35.9 ± 6.5*	*13,229 ± 2,202*

productivity of some crops (Gruda et al., 2019; Jamarkattel et al., 2023; Nordey, Faye, et al., 2020; Rabbi et al., 2019; Sandison et al., 2023). Tunnels or similar structures can be modified to improve light levels, temperature, or relative humidity for better growth and yields (Fernandes de Oliveira & Nieddu, 2015 in Italy; Gruda et al., 2021 in Greece; Ahmad et al., 2023 in Pakistan; Sharaf-Eldin et al., 2023 in Egypt). Strawberry plants are grown under tunnels to protect the plants from cold weather, frosts, and rain. Temperatures under the plastic covers can be excessive for acceptable growth and yields, in the absence of adequate ventilation. Close attention to this issue is important for growing strawberry and other plants under plastic (Conner & Demchak, 2018; Yoneda & Kawashima, 2024).

Fatnassi et al. (2009) demonstrated that ventilation within a tunnel decreased with the height and density of the plants under the plastic, along with the direction of the wind. They recommended that the sides of tunnels should be rolled up to improve wind movement and ventilation. Bartzanas et al. (2004) modelled air movement and temperatures within a tunnel in France. The mean temperature in the middle of the tunnel varied from 28.2° to 29.8°C for an outside temperature of 28.0°C. However, there were regions inside the tunnels that were 6.0°C warmer than outside. Average air velocity in the tomato crop canopy varied according to the arrangement of the vents in the tunnel from 0.2 to 0.7 m/s. Ventilation can aid air movement within a tunnel, but it does not always lower the temperature. Lewus and Both (2022) modelled air-flow and temperatures under a high tunnel with different side and roof vents in Pennsylvania, United States. The roof vents increased mass-based ventilation through the tunnel by 20% to 78% compared with that in the standard tunnel with rolled-up, side vents only. However, the roof vents only lowered the temperature inside the tunnel by 0.1°C.

Rogers and Wszelaki (2012) demonstrated temperatures under tunnels growing tomatoes could be excessive in Tennessee. Despite having the side and end walls of the tunnels open, average temperatures reached 37.8°C during the middle of the day. The highest temperature recorded over a single day over the 2-year experiment under the tunnels was 51.7°C. The mean temperature range from April to August (in 2009) was 10.6° to 13.9°C in the open, a difference of 3.3°C. The mean temperature range under the tunnels during the same period was 22.2° to 27.2°C, a difference of 5.0°C. This trend was repeated in 2010. The tunnels did not retain heat into the evening, where average temperatures were similar with those in the open. Ventilation within the tunnel was inadequate for control of the temperature under the plastic.

Gázquez et al. (2008) examined different cooling strategies for sweet pepper under tunnels in Spain. Fogging was the most efficient method for controlling maximum air temperatures and vapour pressure deficits (VPDs). In contrast, it was the least efficient method for controlling canopy temperatures. Plants that had been shaded and grown under plastic that had been white-washed had higher yields (10.23 kg/m^2) than those grown under shade and fogging (8.41 kg/m^2) ($p < 0.05$). Plants subjected to fogging had the highest incidence of blossom-end rot (BER). An economic evaluation showed that whitening was the most profitable cooling treatment. The researchers concluded that a combination of whitening and natural ventilation was the most efficient cooling system in terms of water and energy use. O'Connell and Tate (2017) investigated the use of protected cultivation to produce organic broccoli and cauliflower in Georgia. They recommended that the side curtains should be opened when the temperature was higher than 15.6 ± 1°C. Conversely, tall side walls (1.8 m openings) and end walls (4.9 m openings) helped to ventilate the tunnels on warm days and keep temperatures and relative humidity levels near the crop canopy similar to those in the open.

Sethi et al. (2009) examined the growth of vegetables under protected cultivation in Ludhiana, India (latitude 31°N). They reported that a combination of low tunnels in winter and shade nets in summer gave 37.6% and 11.5% higher yield in the brinjal crops compared with a conventional net house or plastic-covered greenhouse for the whole year. This was because the combined strategy provided optimum temperature and light conditions for growth. Thipe et al. (2020) collected data on the microclimate in a fan-pad evaporative cooled tunnel (FPVT) and an open-ended, naturally ventilated tunnel (NVT) in Pietermaritzburg, South Africa (latitude 29.7°S). The tunnels had floor areas of 144 m^2 and ridge heights of 3.5 m, and were 18 m in length, with a floor width of 8 m. The temperature in the NVT was 4° to 5°C higher than in the FPVT at midday when solar radiation levels peaked. At night, there was no difference in temperature between the two tunnels. Relative humidity in the NVT ranged from 49% to 90% and 59% to 95% in the FPVT. Kittas et al. (2005) modelled temperatures inside a plastic greenhouse in Greece and found that the difference between the inside and outside temperature was related to the ventilation rate and the incoming solar radiation. Temperatures inside the greenhouse were up to 8°C higher inside when there was poor ventilation. In contrast, temperatures were similar in the two areas when there was good ventilation.

Plastic tunnels can have the ends of the structures open and the sides of the tunnels rolled up to assist ventilation. Temperatures within single tunnels are easier to manage than those in multiple tunnels, although the costs of construction are higher. Menzel et al. (2014) grew strawberry under tunnels in southern Queensland, Australia. The sides of the tunnels were rolled up when it was not raining. They showed that temperatures at canopy level were similar inside and outside the tunnels. In the first year of the experiment, the average daily maximum temperature was 26.0°C inside the tunnel and 26.5°C outside. Minimum temperatures were 11.9° and 10.5°C. In the second year, the average daily maximum temperature was 25.4°C inside the tunnel and 26.3°C outside. Minimum temperatures were 13.1° and 11.7°C.

Light-blocking films can be used to reduce heat-generating light from the 780 to 2,500 nm (infrared and far-infrared) region, while allowing most light in the photosynthetic active radiation (400 to 700 nm) region. However, their use in greenhouses and similar structures usually results in lower yields compared with control plots (no light-blocking films) (Chavan et al., 2023; He et al., 2024; Lin et al., 2024; Maier et al., 2023). Further research is required to determine if these films can reduce the impact of global warming for plants growing under protected cultivation.

Tunnels protect strawberry crops from cold, frosts, and rainfall. Temperatures under the covers can be too high for acceptable growth, depending on the weather, type of plastic, and ventilation. Temperatures inside the tunnels can be up to 10°C higher than those outside during the day. Temperatures inside the tunnel are similar to those outside during the night. The use of tunnels under global warming will depend on good ventilation and other strategies (light shading) to prevent excessive temperatures building up under the plastic.

Conclusions

Plants under tunnels had higher relative marketable (Tunnel/Open = 1.34 ± 0.76) and total yields (Tunnel/Open = 1.30 ± 0.83) than those in the open field. In contrast, fruit weight was similar in the two systems (Tunnel/Open = 1.04 ± 0.22). The response to protected cultivation (tunnel versus open field) were similar in Northern and Southern Europe, in Northern and Southern America, in areas with cool or cold winters or with spring/summer or winter/spring production seasons, and under low or high tunnels. Lower yields under the tunnels were associated with shading and high temperatures under the plastic and a higher incidence of powdery mildew (PM). Tunnels offer protection from rain and can help to reduce or eliminate fungicides for the control of anthracnose fruit rot (AFR) and botrytis grey mould (BGM). In contrast, the incidence of PM can be problematic under covers. Yields and fruit weight are lower under tunnels without supplementary pollination by bees or other insects. The economics of strawberry under tunnels is highly variable. Net returns vary with yields, marketing strategies, and the costs of the tunnels. Protected cultivation can be used to mitigate against the effects of climate change on productivity, but producers need to pay close attention to ventilation under the plastic. There are concerns about the impact of the different plastics on the environment, and potential issues with the exposure of farm workers to pesticides under the tunnels.

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Data availability statement

The author confirms that the data supporting the findings of this study are available within the supplementary materials published online with this paper or available from the author on reasonable request.

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