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Influence of the Use of Double Roof with Increased Ventilation on the Development of Fungal Diseases in a Mediterranean Greenhouse

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Abstract

Mediterranean greenhouses commonly rely on passive climate control techniques to reduce dependence on energy-intensive systems. This study was conducted in Almería (Spain) in a multi-span greenhouse divided into two sectors: a West sector equipped with a double-roof system using a pink sunlight spectrum photoconverter film combined with an increased natural ventilation surface, and an East control sector with standard ventilation and a calcium carbonate-whitened roof. The effects of this integrated passive climate management configuration on the development of naturally occurring fungal diseases were evaluated in tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum* L.), and cucumber (*Cucumis sativus* L.). Powdery mildew (*Leveillula taurica*) and early blight (*Alternaria linariae*) were observed in tomato; powdery mildew in pepper; and downy mildew (*Pseudoperonospora cubensis*), powdery mildew (*Podosphaera xanthii*), and gummy stem blight (*Stagonosporopsis* spp.) in cucumber. Across crop cycles, the sector combining double roofing and enhanced ventilation consistently exhibited lower disease severity for powdery mildew, downy mildew, and gummy stem blight compared with the control sector. In contrast, early blight did not show a clear or consistent response to the greenhouse configuration. Overall, the results indicate that the combined use of a double-roof system with a sunlight spectrum photoconverter film and increased natural ventilation can contribute to improved microclimate regulation and reduced fungal disease pressure under Mediterranean greenhouse conditions. This integrated passive approach may therefore represent a useful complementary component of sustainable disease management strategies in protected horticulture.

Keywords: greenhouse; double roof; crop protection; powdery mildew; downy mildew

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1. Introduction

The Mediterranean coastal region offers favourable climatic conditions for the production of early horticultural crops due to its mild winters [1]. In particular, the province of Almería (Spain) hosts one of the highest concentrations of greenhouses worldwide, reaching 32,554 ha in 2020 [2]. Greenhouse production systems in this area are characterised by a high reliance on passive climate control strategies, which reduce energy consumption and associated carbon footprint while maintaining suitable growing conditions for high-value crops [3–5].

Among the most widely used passive climate control techniques for greenhouses in Almería are natural ventilation and the use of double-roof structures. Natural ventilation, achieved by regulating the opening of greenhouse vents, is a key tool for controlling temperature and humidity without energy inputs [6,7]. Double-roof systems are commonly used during colder periods, as they increase minimum night-time temperatures, reduce thermal oscillations, and improve insulation from external climatic conditions [8–10]. When combined with adequate ventilation management, double roofs can contribute to more stable microclimatic conditions around the crop [9–13]. In addition, plastic coverings and double-roof systems have been associated with improvements in tomato yield and fruit quality, including increased lycopene content [14,15].

In recent years, agricultural plastic films designed to modify the spectral composition of incoming solar radiation have been introduced as an additional passive tool in greenhouse production. Light quality plays an important role in plant growth and development, influencing photosynthesis and morphogenetic responses [16–21]. Spectrum-converting films have been reported to alter the proportion of photosynthetically active radiation reaching the crop, with potential effects on crop performance [22–26]. However, the use of double roofs and modified plastic films may also affect greenhouse microclimate, particularly humidity levels, which are closely linked to plant disease development [27,28].

High relative humidity and the persistence of free water on leaf surfaces create favourable conditions for the development of several fungal diseases in greenhouse crops. In cucurbits, downy mildew caused by *Pseudoperonospora cubensis* and gummy stem blight caused by *Stagonosporopsis* spp. are strongly associated with relative humidity levels above 90% and mild temperatures [29–33]. Therefore, appropriate management of climatic conditions within the greenhouse can be a key tool in reducing the incidence of these diseases [34]. The use of double roofs has been shown to influence the development of some tomato diseases such as grey mold caused by *Botrytis cinerea* [35].

Powdery mildew is another widespread disease in cucumber crops, characterised by rapid colonisation of plant tissues, defoliation, and reduced fruit quality, and is commonly associated with *Podosphaera xanthii* under greenhouse conditions [36–40]. Downy mildew caused by *Pseudoperonospora cubensis* is one of the pathogens responsible for the greatest yield losses in cucumber crops worldwide, in both open-field and protected conditions, and is characterised by chlorotic leaf lesions that may progress to necrosis and leaf loss [41–43].

Gummy stem blight represents an additional major constraint in cucumber production, affecting all aerial plant organs and causing foliar lesions, stem cankers, and black rot of fruits, which results in significant yield losses during cultivation and storage [44–47]. In pepper crops, powdery mildew caused by *Leveillula taurica* is one of the most important diseases worldwide, leading to substantial yield losses, severe defoliation, and high fungicide expenditure [48–50]. In tomato crops, early blight caused mainly by *Alternaria linariae* is favoured by warm temperatures and high humidity and can result in yield losses of up to 78% [51–55].

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Interrupting pathogen life cycles through environmental management is a key component of integrated pest management strategies. Modifying greenhouse microclimate through passive techniques such as ventilation and roof configuration represents a potential approach to reducing disease pressure while minimising chemical inputs [34,56–59]. However, the combined effects of these passive strategies on fungal disease development under commercial greenhouse conditions remain insufficiently documented.

The aim of this study was to evaluate the effect of an integrated passive climate management strategy combining a double-roof system and increased natural ventilation on the development of naturally occurring fungal diseases in cucumber, tomato, and pepper crops in a Mediterranean greenhouse.

2. Materials and Methods

2.1. Experimental Setup

The experimental trials were conducted in a multi-span greenhouse at the Centre for Innovation and Technology Transfer UAL-ANECOOP Foundation "Catedrático Eduardo Fernández" of the University of Almería (36°51′ N, 2°16′ W; 87 MAMSL) (Figure 1). The sidewalls of the rigid polycarbonate greenhouse consisted of corrugated panels. The roof was covered with a 200 μm three-layer thermal film (Politiv Ltd., Kibbutz Einat, Israel) with the following characteristics: colourless and diffuse; 85% transmission of photosynthetically active radiation (PAR); 55% light diffusion; 24% ultraviolet light transmission; 85% thermal efficiency. The greenhouse was transversely divided by a polyethylene sheet, creating two physically separated sectors with similar structural characteristics, hereafter referred to as the West sector and the East sector (Table 1).

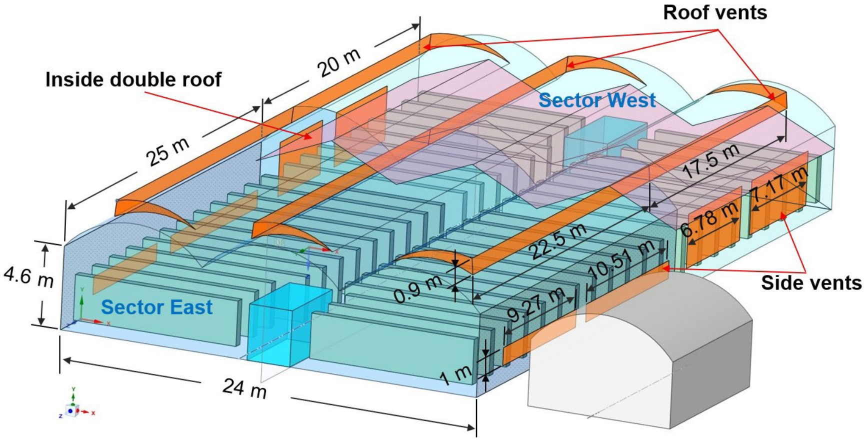

Figure 1. Dimensions of the experimental greenhouse, vent sizes, and configuration of the double roof.

Table 1. Characteristics of the two sectors of the experimental greenhouse. Greenhouse surface, S_C [m²]; side ventilation surface, S_{VS} [m²]; roof ventilation surface, S_{VR} [m²]; ratio of ventilation surface/greenhouse surface S_V/S_C [%].

Sector	Double Roof Type	Dimensions	S_C	S_{VS}	S_{VR}	S_V/S_C
West	Spectrum conversion film	24.3 m × 20.1 m	480	77.49	47.25	26.0
East	Without double roof	24.3 m × 25.1 m	600	38.90	60.75	16.6

The West sector was equipped with a double-roof system consisting of an internal plastic film with solar spectrum-conversion properties, combined with an increased natural ventilation surface area. Specifically, this sector included two side vents with a maximum opening of 3 m and three roof vents with a maximum opening of 0.9 m. In contrast,

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the East sector served as the control configuration and consisted of a single roof with standard natural ventilation, including two side vents with a maximum opening of 1 m and three roof vents with a maximum opening of 0.9 m, with no double roof installed (Figures 1 and 2). Ventilation in both sectors was controlled using Synopta software version 5.4.2.3931422 (Ridder Growing Solutions B.V., Maasdijk, The Netherlands), a centralised climate control and data-logging system integrated with a weather station.

The double-roof system and the increased ventilation surface were applied simultaneously in the West sector as part of a single integrated passive climate management strategy; therefore, the experimental design does not allow the individual effects of roof configuration and ventilation to be evaluated separately (Figure 2).

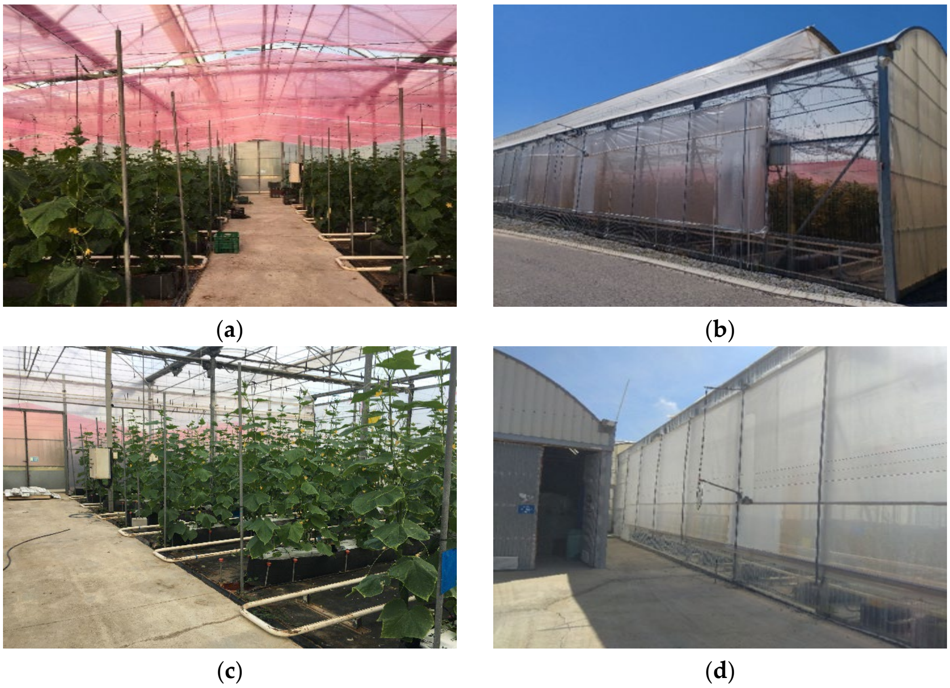


Figure 2. Crops in the West sector with double roof with sunlight spectrum photoconverter film (**a**) and 3 m high side vents (**b**). East sector with single roof (**c**) and with 1 m high side vents (**d**).

The film used as a double roof integrating the LIGHT CASCADE® (LC®) technology was developed by the French company CASCADE (Clamart, France). The material incorporates optically active additives into the polymer matrix, resulting in a modification of the spectral distribution of transmitted sunlight. As shown in Figure 3, the spectrum transmitted through the LIGHT CASCADE® double roof exhibits a relative redistribution of radiation within the visible range, including the red region (600–700 nm).

To assess the potential effect of the double roof on deficit irrigation stress, two irrigation regimes were applied: (i) in the northern zone of the greenhouse, a standard irrigation regime was employed using drippers with a flow rate of 3 L h^{-1} and a maximum irrigation duration of 50 min day^{-1}; (ii) in the southern zone, the irrigation time was reduced by 25% compared with that of the northern zone.

The experiment was conducted over four crop cycles: two autumn–winter cucumber cycles (*Cucumis sativus* L.), one spring–summer tomato cycle (*Solanum lycopersicum* L.), and one spring–summer pepper cycle (*Capsicum annuum* L.) (Table 2). The double-roof system was installed taking into account the prevailing climatic conditions, mainly in response to temperature requirements during the crop cycles. Transplants were established in a coconut fibre substrate at a plant density of 1 plant m^{-2}. All commercial varieties were supplied by Rijk Zwaan Ibérica, S.A. (Almería, Spain).

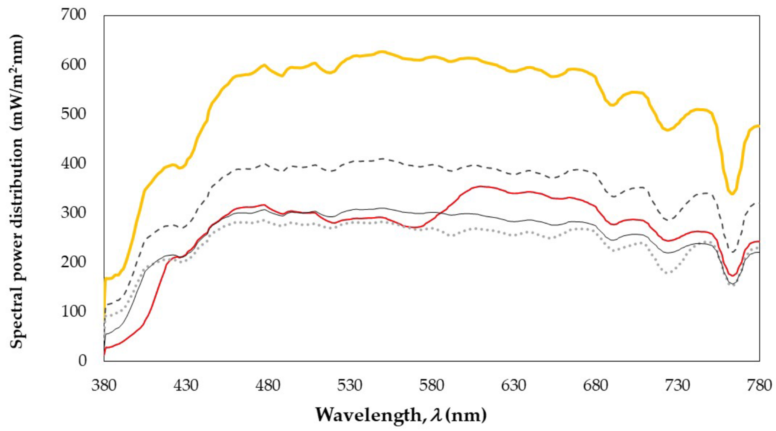


Figure 3. Spectral power distribution of sunlight outside the greenhouse (▬), light transmitted inside the greenhouse by the plastic cover without whitening (- - -), using a standard double roof (——), the LIGHT CASCADE® double roof (▬), and inside the greenhouse with cover whitewashing for a dose of 0.250 kg L^{-1} and 23.7 g m^{-2} (·····).

Table 2. Description of the experimental crops, varieties, and key dates.

Crop	Commercial Variety	Data of Transplant	Double Roof Installation	Final Crop Data
Cucumber (*Cucumis sativus* L)	Insula RZ F1	7 September 2020	12 October 2020	2 January 2021
Tomato (*Solanum lycopersicum* L)	Ramyle RZ F1	7 February 2021	28 January 2021	15 July 2021
Cucumber (*Cucumis sativus* L)	Insula RZ F1	5 September 2021	20 October 2021	2 January 2022
Pepper (*Capsicum annuum* L.)	Bemol RZ F1	20 February 2022	19 February 2022	29 July 2022

Crop management practices, including cleaning, trellising, and pruning, were performed simultaneously and identically in both greenhouse sectors. Likewise, throughout the four crop seasons, fungicide applications were carried out uniformly in both sectors (Table 3). These applications were conducted in a targeted manner by aerial application, being restricted to crop areas where disease symptoms were detected rather than as full-coverage treatments, and were applied simultaneously using the same products, doses, and application dates in both greenhouse sectors in order to ensure comparability between treatments.

Table 3. Fungicide applications carried out over the four crop seasons.

Crop	Active Substance	Application Data	Applied Dose
Cucumber 2020–2021	Azoxistrobin	9 October 2020	45 cc/100 L
	Azoxistrobin	5 November 2020	75 cc/100 L
	Ciflufenamida	17 November 2020	20 cc/100 L
	Azoxistrobin	25 November 2020	75 cc/100 L
	Sulphur	1 December 2020	300 cc/100 L
	Metrafenona	1 December 2020	30 cc/100 L
Tomato 2021	Sulphur	17/04/2021	150 cc/100 L
Cucumber 2021–2022	Azoxistrobin	1 November 2021	20 cc/100 L
	Azoxistrobin	4 November 2021	70 cc/100 L
	Azoxistrobin	23 November 2021	80 cc/100 L
Pepper 2022	Azoxistrobin	8 June 2022	80 cc/100 L
	Azoxistrobin	17 June 2022	80 cc/100 L
	Metrafenona	24 February 2022	30 cc/100 L

2.2. Microclimate Measurement Equipment

At the centre of each sector, an aspirated radiation shield EKTRON II-C, (Ridder Growing Solutions B.V., Maasdijk, The Netherlands) was installed at a height of 2 m. The shield housed a Pt1000 IEC 751 class B temperature sensor (Vaisala Oyj, Helsinki, Finland) with a measurement range of −10 to 60 °C and an accuracy of ±0.6 °C, a capacitive humidity sensor HUMICAP® 180R(Vaisala Oyj, Helsinki, Finland) with a measurement range of 0–100% and an accuracy of ±3%, and a CO_2 probe EE871 (E + E Elektronik Ges.m.b.H., Engerwitzdorf, Austria) with a measurement range of 0–2000 ppm and an accuracy of ±2% of the measured value.

Outdoor climatic conditions were recorded by a meteorological station installed at a height of 9 m and equipped with a BUTRON II measurement box (Ridder Growing Solutions B.V., Maasdijk, The Netherlands) containing temperature and relative humidity sensors equivalent to those used in the indoor measurement system.

2.3. Measurement of Infection Level in Plants

The identification of disease-causing fungi in cucumber crops (*Podosphaera xanthii*, *Pseudoperonospora cubensis* and *Stagonosporopsis* spp.) and in solanaceous crops (*Leveillula taurica* and *Alternaria linariae*) was carried out through direct visual inspection and microscopic examination of mycelia, spores, and conidia, following standard diagnostic procedures [55,60–63].

The experimental design and disease assessment procedures followed the standards of the European and Mediterranean Plant Protection Organisation (EPPO). Disease severity was visually quantified as the percentage of leaf area affected for each disease. Assessments were conducted at 7-day intervals from the appearance of the first symptoms, allowing disease progression to be monitored throughout the crop cycles. For the evaluation of downy mildew and powdery mildew, the assessment protocols were based on EPPO Standard PP 1/181 (Conduct and Reporting of Efficacy Evaluation Trials), EPPO Standard PP 1/152 (Design and Analysis of Efficacy Evaluation Trials), EPPO Standard PP 1/57 (Powdery Mildews in Cucurbits), EPPO Standard PP 1/65 (Downy Mildew of Lettuce and Other Vegetables, PSPECU), EPPO Standard PP 1/263 (Alternaria solani and *Alternaria alternata* in Potato and Tomato), EPPO Standard PP 1/135 (Phytotoxicity Assessment), and EPPO Standard PP 1/121 (Leaf Spots of Vegetables).

In each greenhouse sector, assessment plots were established in both the northern and southern zones to capture within-sector spatial variability. In each plot, six plants were evaluated, and for each plant a minimum of eight evenly distributed leaves of similar physiological age were assessed (Figure 4). Overall, approximately 200 leaves were evaluated in the northern zone and 200 leaves in the southern zone of each sector for each treatment.

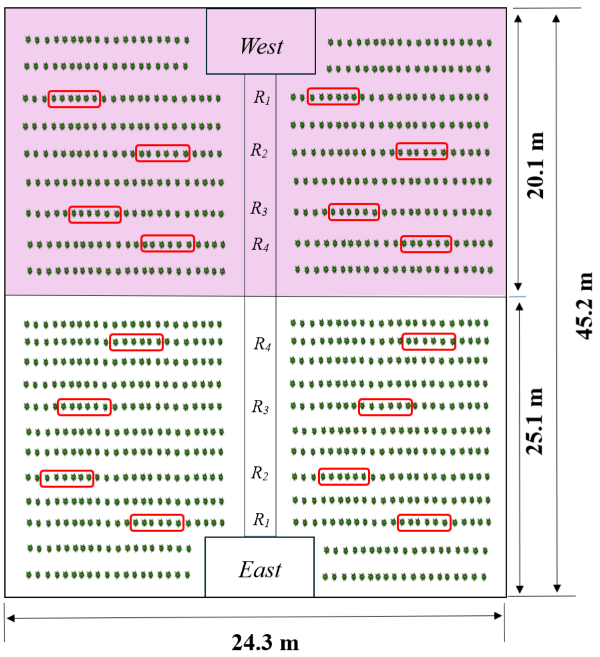


Figure 4. Location of the plant plots used to assess the incidence of fungal diseases. Red boxes indicate the sampling plots. Shaded areas (pink and white) represent the different double-roof plastic types used in the experiment.

2.4. Statistical Analysis

The analysed data correspond to measurements obtained from repeated assessments conducted within a greenhouse divided into two sectors with contrasting passive climate management configurations. The greenhouse sector was considered the experimental unit for the climate management treatment, while plant rows and assessment plots within each sector were treated as sampling units to account for spatial variability.

Data were analysed using a multifactor analysis of variance (ANOVA) performed with Statgraphics® 19 software (Manugistics Inc., Rockville, MD, USA). Differences were considered statistically significant at $p \leq 0.05$, and mean values were compared using Fisher's least significant difference (LSD) test. The factors included in the analysis were greenhouse sector (two levels), plant row (four levels), and assessment date, analysed separately for each crop season.

Prior to ANOVA, data normality was assessed using the Kolmogorov–Smirnov test. Bartlett's, Cochran's, and Hartley's tests were applied to evaluate homogeneity of variances. When the assumptions of parametric analysis were not met, a non-parametric Friedman test was applied, using assessment date as the blocking factor. Results from non-parametric analyses were presented using box-and-whisker plots.

3. Results

The comparison between the standard ventilation configuration (East sector) and the alternative treatment combining increased lateral ventilation and a double roof with a spectrum-conversion film (West sector) was performed by analysing the greenhouse microclimate and the development of fungal diseases in the different crop cycles.

3.1. Microclimatic Parameters Inside the Greenhouse

3.1.1. Autumn–Winter Crop Season

During the 2020/2021 cucumber growing season, air temperature inside the greenhouse showed greater temporal variability in the East sector than in the West sector.

Higher maximum temperature values and wider daily thermal amplitudes were recorded in the East sector, whereas the West sector showed lower maximum temperatures and reduced temperature fluctuations (Figure 5a).

Absolute humidity values during the 2020/2021 season were higher than those recorded in the 2021/2022 season in both sectors. In both cucumber cycles, absolute humidity values were consistently higher in the East sector, while the West sector showed lower and more stable values over time (Figure 5b). Relative humidity followed a similar pattern, with longer periods of high relative humidity observed in the East sector during the 2020/2021 cycle (Figure 5c).

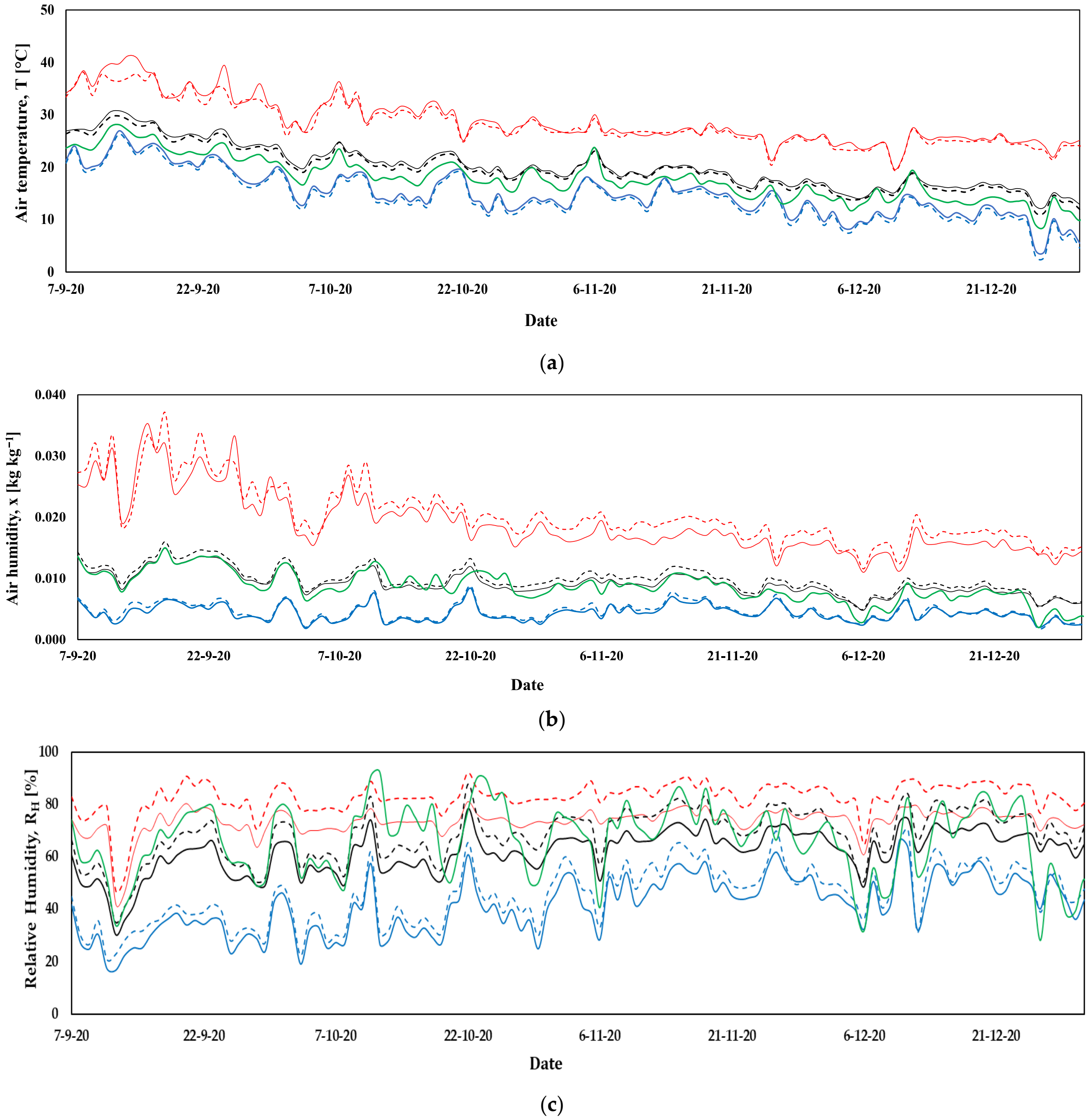
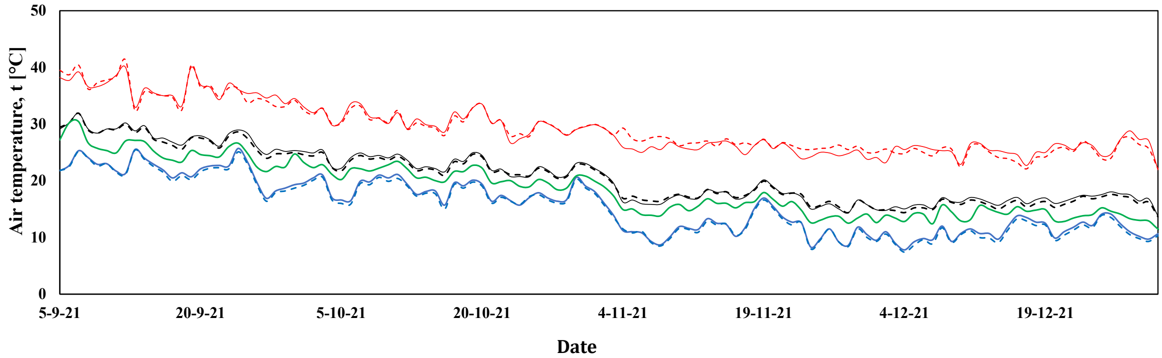


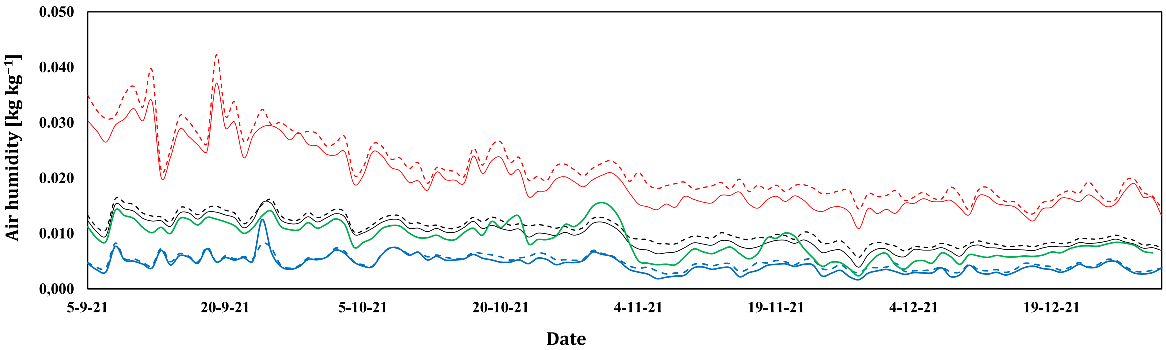
Figure 5. Evolution of values of temperature (**a**), absolute humidity (**b**), and relative humidity (**c**) outside the greenhouse (——); average (- - -), maximum (- - -), and minimum (- - -) inside of the West sector with double roof and increased side vents; and average (——), maximum (——) and minimum (——) inside the East sector with single roof and standard side vents. Cucumber season 2020/2021.

During the 2021/2022 season, overall temperature conditions were milder and more stable in both sectors (Figure 6a). Differences between the East and West sectors were less pronounced than in the previous season, although maximum temperatures remained slightly higher in the East sector throughout the crop cycle.

Relative humidity levels were generally lower and showed reduced variability in both sectors during the 2021/2022 cycle, although maximum values remained higher in the East sector (Figure 6c).



(**a**)



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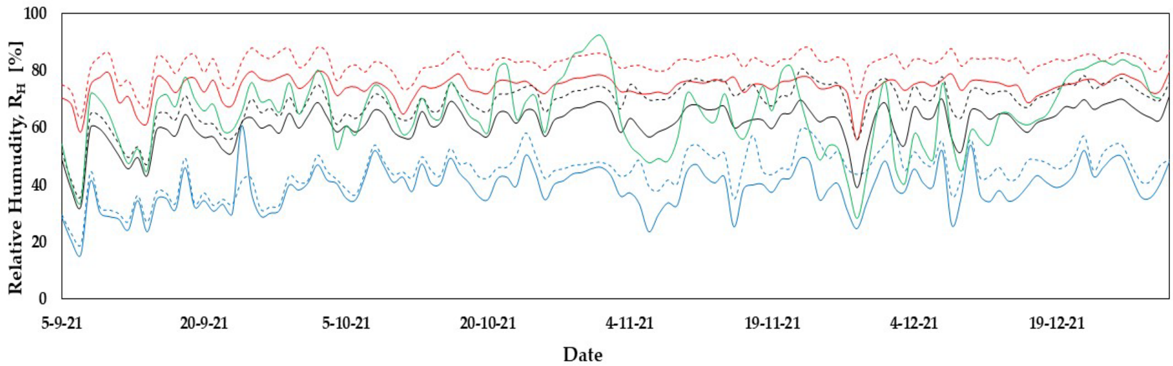

(**c**)

Figure 6. Evolution of values of temperature (**a**), absolute humidity (**b**) and relative humidity (**c**) outside the greenhouse (——);average (- - -), maximum (- - -) and minimum (- - -) inside of the West sector with double roof and increased side vents; and average (——), maximum (——) and minimum (——) inside the East sector with single roof and standard side vents. Cucumber season 2021/2022.

Overall, during the autumn–winter cucumber crop cycles, the West sector exhibited a more stable thermal regime and consistently lower absolute and relative humidity levels than the East sector, particularly during periods of low external temperatures.

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3.1.2. Spring–Summer Crop Season

During the tomato crop cycle in 2021, higher average and maximum air temperatures were recorded in the East sector compared with the West sector (Figure 7a). Temperature peaks were more pronounced in the East sector, while the West sector showed lower maximum values and reduced daily variability. Absolute and relative humidity values were also higher in the East sector throughout the crop cycle (Figure 7b,c).

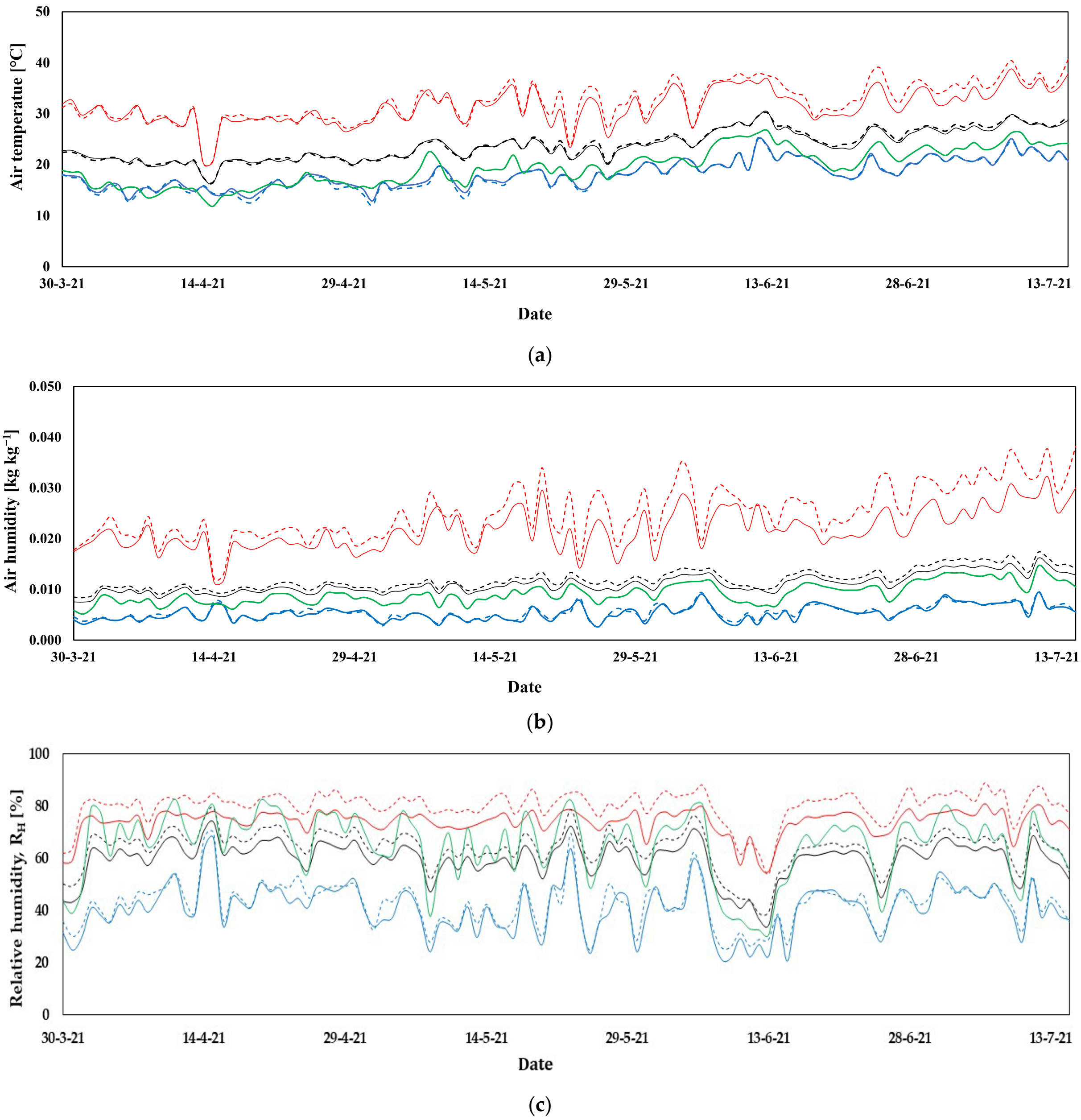

Figure 7. Evolution of values of temperature (**a**), absolute humidity (**b**) and relative humidity (**c**) outside the greenhouse (——); average (- - -), maximum (- - -), and minimum (- - -) inside of the West sector with double roof and increased side vents; and average (——), maximum (——), and minimum (——) inside the East sector with single roof and standard side vents. Tomato season 2021.

A similar temperature pattern was observed during the pepper crop cycle in 2022, when overall temperature conditions were more extreme (Figure 8a). The highest temperature values were again recorded in the East sector, whereas lower maximum temperatures were observed in the West sector throughout the season. Absolute and relative humidity values remained higher and more variable in the East sector (Figure 8b,c).

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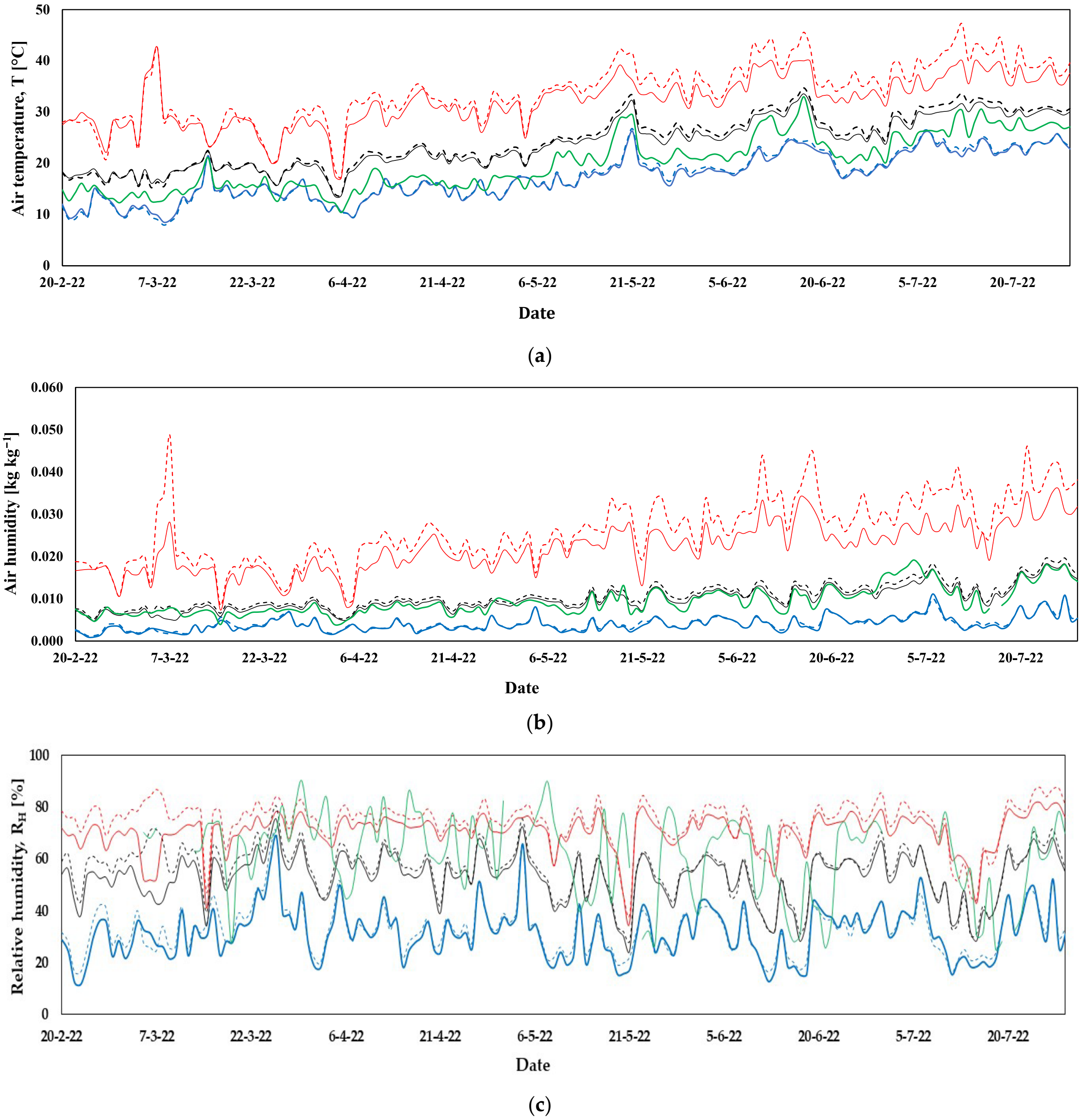

Figure 8. Evolution of values of temperature (**a**), absolute humidity (**b**), and relative humidity (**c**) outside the greenhouse (——); average (- - -), maximum (- - -) and minimum (- - -) inside of the West sector with double roof and increased side vents; and average (——), maximum (——), and minimum (——) inside the East sector with single roof and standard side vents. Pepper season 2022.

Overall, during the spring–summer crop cycles, the combination of double roofing and increased ventilation in the West sector resulted in lower maximum temperatures and reduced humidity levels compared with the East sector, despite the more extreme external climatic conditions.

3.2. Fungal Diseases

Several fungal diseases developed naturally during the different crop cycles evaluated. In cucumber crops, powdery mildew (*Podosphaera xanthii*), downy mildew (*Pseudoperonospora cubensis*), and gummy stem blight (*Stagonosporopsis* spp.) were observed. In tomato and pepper crops, powdery mildew caused by *Leveillula taurica* was detected in both species, while early blight caused by *Alternaria linariae* was observed only in tomato.

Across all crop cycles, powdery mildew reached the highest disease severity levels among the diseases evaluated, exceeding 30% affected leaf area in all cases and reaching values above 60% in some plots.

For all diseases evaluated, disease severity values differed between greenhouse sectors and irrigation treatments, depending on the crop cycle and pathogen considered. Detailed results for each disease and crop are presented in the following subsections.

Among the diseases evaluated, powdery mildew showed the highest severity and the most consistent response to greenhouse configuration across all crop cycles, whereas downy mildew and gummy stem blight exhibited marked differences between sectors mainly during the cucumber cycles (Figure 9).

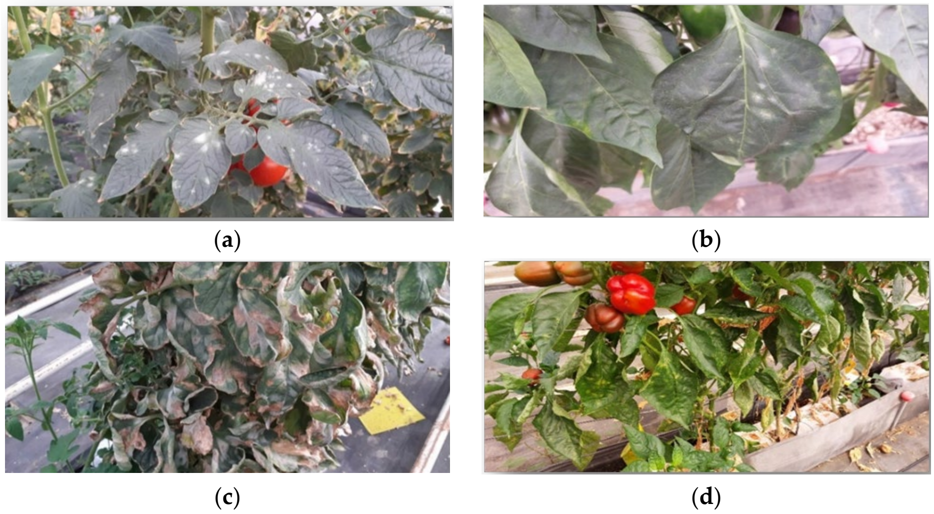

Figure 9. Powdery mildew in tomato (**a**) and pepper (**b**); heavy powdery mildew attack in tomato with single-roof area (**c**); heavy powdery mildew in pepper, with defoliation, in single-roof area (**d**).

3.2.1. Powdery Mildew

Powdery Mildew in Cucurbitaceae

The first symptoms of powdery mildew were observed in October in both cucumber crop cycles. Disease severity increased progressively over time, reaching values above 30% affected leaf area in several plots (Figure 10). Plants grown in the West sector showed lower disease severity values than those grown in the East sector, with statistically significant differences observed on several assessment dates.

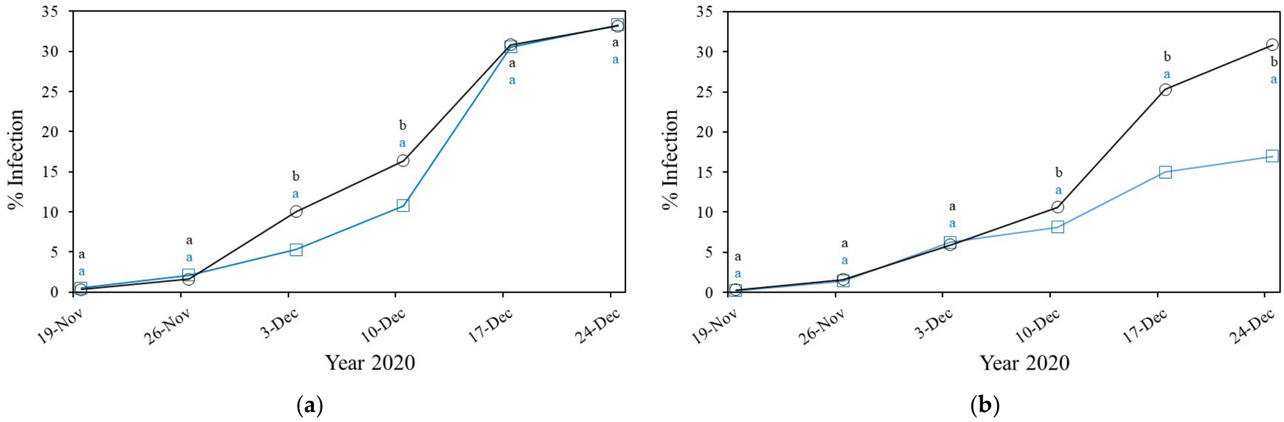

Figure 10. Development of the percentage of powdery mildew infection (*Podosphaera xanthii)* over time during the first crop cycle of cucumber in 2020: Standard irrigation (**a**) and deficit irrigation (**b**). Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents

(□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

Similar trends were observed during the 2021/2022 cucumber cycle, with disease severity remaining lower in the West sector than in the East sector throughout the assessment period (Figure 11). Higher disease severity values were recorded in standard-irrigated plots compared with deficit-irrigated plots in both crop cycles.

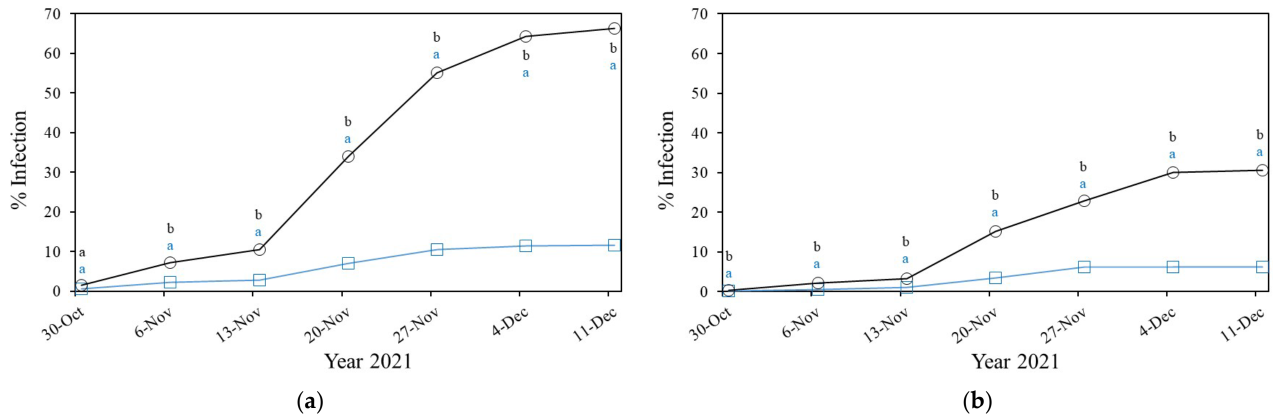

Figure 11. Development of the percentage of powdery mildew infection (*Podosphaera xanthii)* over time of the second crop cycle in 2021: Standard irrigation (**a**) and deficit irrigation (**b**). Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

Powdery Mildew in Solanacea

In tomato, the first symptoms of powdery mildew were detected in early April 2021. Disease severity increased continuously throughout the crop cycle, reaching values close to 60% affected leaf area in the most affected plots by the final assessment (Figure 12). Disease severity was higher in the East sector than in the West sector under both irrigation regimes.

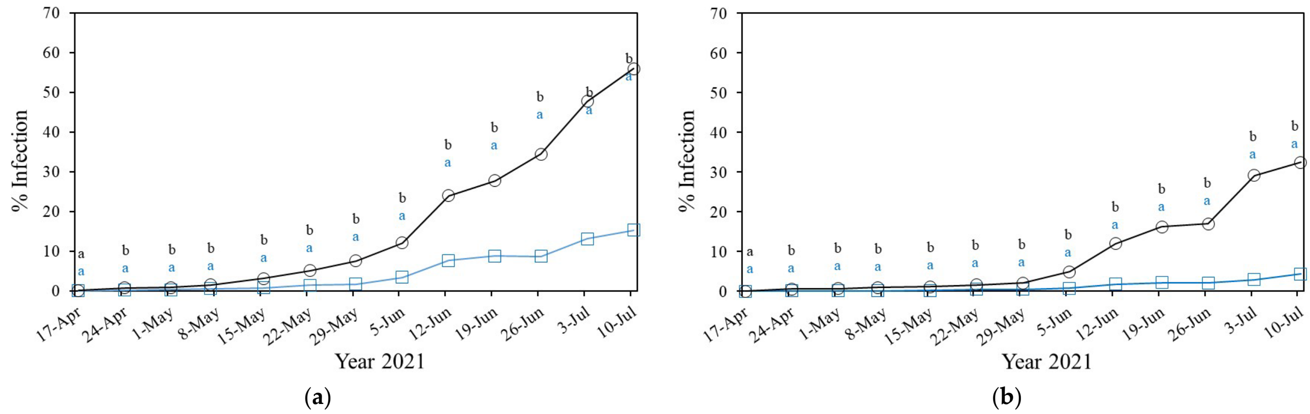

Figure 12. Development of the percentage of powdery mildew infection (*Leveillula taurica)* over time in the tomato crop cycle in 2021: Standard irrigation (**a**) and deficit irrigation (**b**). Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

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In pepper, powdery mildew symptoms were first observed in April 2022. Disease severity increased rapidly during the crop cycle, exceeding 50% affected leaf area in the most affected plots (Figure 13). Disease severity values were consistently lower in the West sector than in the East sector at all assessment dates.

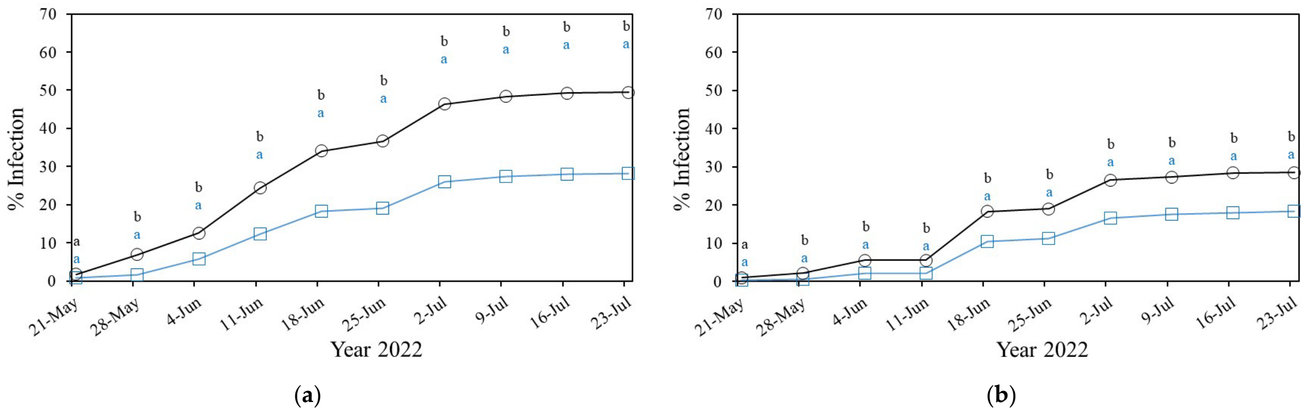

Figure 13. Development of the percentage of powdery mildew (*Leveillula taurica*) infection over time in the pepper crop cycle in 2022: Standard irrigation (**a**) and deficit irrigation (**b**). Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

Overall, powdery mildew severity was consistently lower in the West sector across all crops and irrigation regimes, indicating a strong and reproducible effect of the integrated passive climate management strategy on disease development.

3.2.2. Downey Mildew

Downy mildew developed only during the cucumber crop cycles. During the 2020/2021 season, disease severity exceeded 10% affected leaf area in the East sector, whereas values remained below 1% in the West sector throughout the assessment period (Figure 14).

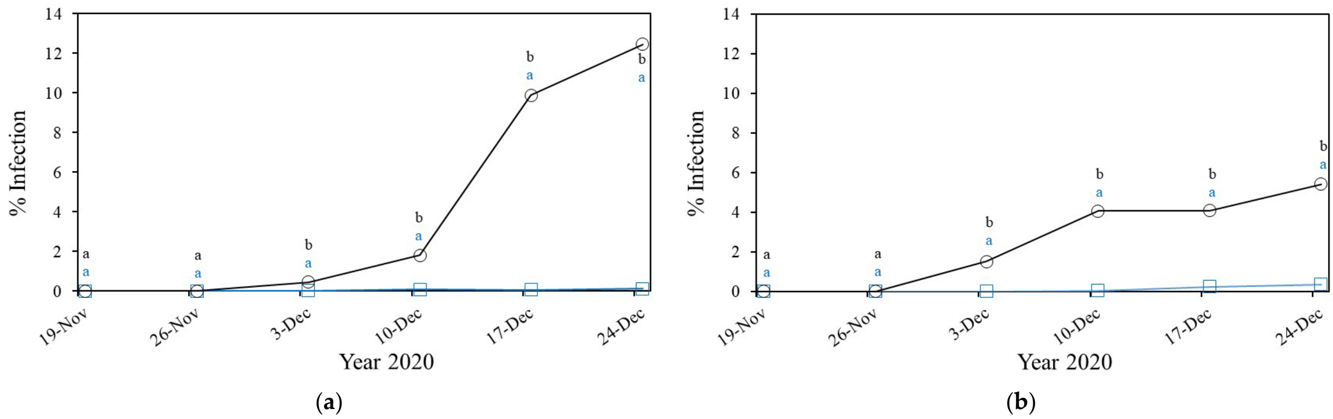

Figure 14. Development of the percentage of downy mildew (*Pseudoperonospora cubensis*) infection over time for first cucumber crop cycle in 2020: Standard irrigation (**a**) and deficit irrigation (**b**). Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

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During the 2021/2022 season, downy mildew severity remained below 3% affected leaf area in all treatments (Figure 15). Lower disease severity values were consistently recorded in the West sector, where values remained below 0.5% throughout the crop cycle.

Differences related to irrigation regime were observed during the 2020/2021 season, with higher disease severity recorded under standard irrigation compared with deficit irrigation. During the 2021/2022 season, no consistent differences related to irrigation regime were observed.

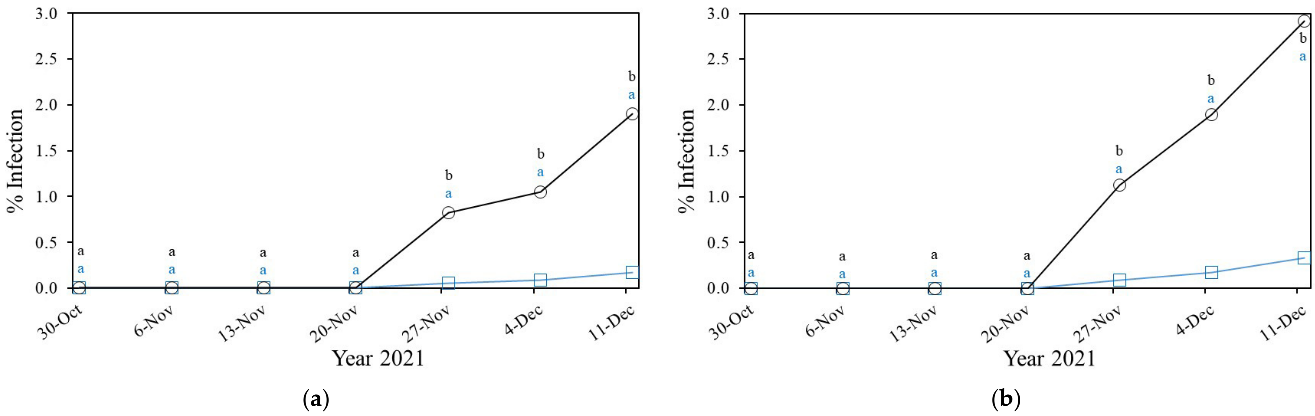


Figure 15. Development of the percentage of downy mildew (*Pseudoperonospora cubensis*) infection over time in the second cucumber crop cycle in 2021: Standard irrigation (**a**) and deficit irrigation (**b**). Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

3.2.3. Gummy Stem Blight

Gummy stem blight was observed during both cucumber crop cycles at generally low disease severity levels. Symptoms appeared approximately three weeks before the final assessment date in both seasons.

During the 2020/2021 crop cycle, disease severity values were higher in the East sector than in the West sector under both irrigation regimes (Figure 16). Disease severity remained below 5% affected leaf area in all treatments.

A similar pattern was observed during the 2021/2022 crop cycle, with higher disease severity recorded in the East sector compared with the West sector (Figure 17). During this second cycle, disease severity values were higher under standard irrigation than under deficit irrigation.

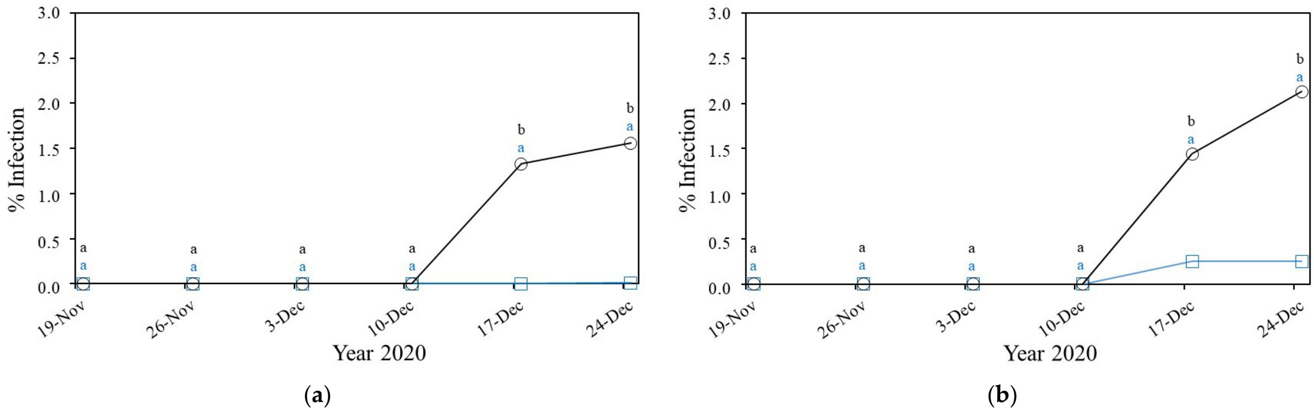
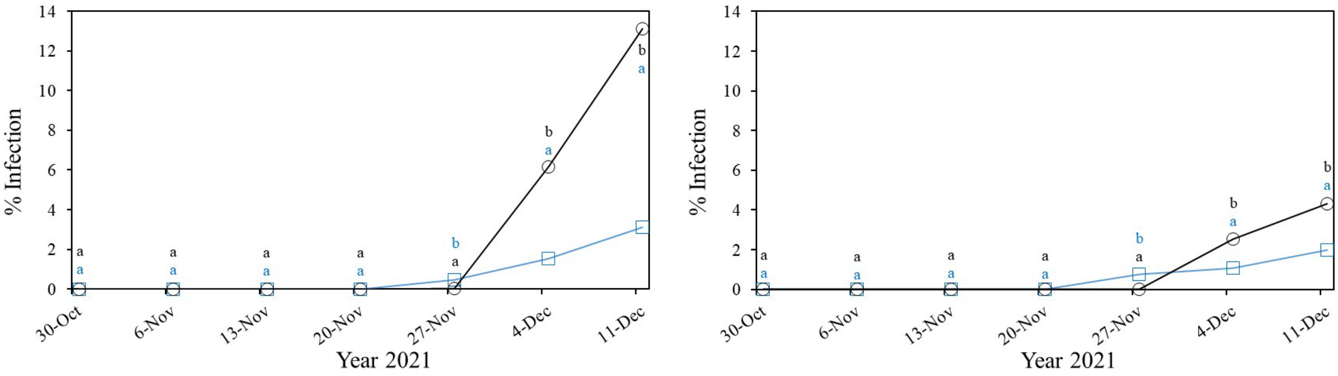


Figure 16. Development of the percentage of gummy stem blight (*Stagonosporopsis cucurbitacearum*) infection over time for the first cucumber crop cycle in 2020: Standard (**a**) and deficit irrigation (**b**).

Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

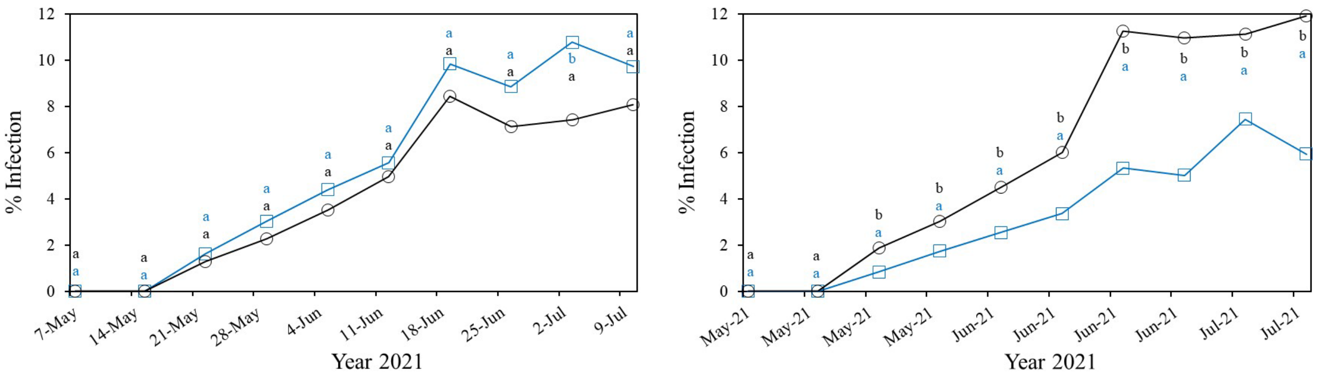


(**a**) (**b**)

Figure 17. Development of the percentage of gummy stem blight (*Stagonosporopsis cucurbitacearum*) infection over time for the second cucumber crop cycle in 2021: Standard (**a**) and deficit irrigation (**b**). Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

3.2.4. Early Blight in Tomato

Early blight was observed only during the tomato crop cycle in 2021. The first symptoms were detected in May, and disease severity increased progressively throughout the assessment period (Figure 18).



(**a**) (**b**)

Figure 18. Development of the percentage of early blight in tomato (*Alternaria solani*) infection over time for the second tomato crop cycle in 2021: Standard irrigation (**a**) and deficit irrigation (**b**) Sector with double roof with sunlight spectrum photoconverter film and increased lateral vents (□). Sector with single roof and standard lateral vents (○). Different letters indicate a statistically significant differences with a confidence level of 95.0% (p-value ≤ 0.05).

By the end of the crop cycle, disease severity reached values close to 10% affected leaf area in some plots. Under standard irrigation, no consistent differences in disease severity were observed between the East and West sectors across assessment dates. Under deficit irrigation, disease severity values tended to be lower in the West sector; however, statistically significant differences between sectors were observed only on specific assessment dates.

Overall, early blight developed at moderate severity levels during the tomato crop cycle and showed limited and inconsistent differences between greenhouse sectors.

In contrast to the other diseases evaluated, early blight did not show a consistent response to greenhouse sector, and differences between treatments were limited to specific assessment dates.

4. Discussion

The combined configuration consisting of a double-roof system and enhanced natural ventilation had a clear influence on the development of the fungal diseases evaluated in both cucurbit crops (cucumber) and solanaceous crops (tomato and pepper). Among the diseases assessed, powdery mildew was the most relevant in terms of incidence and associated damage to plant growth and yield, showing a marked sensitivity to the passive climate management strategies applied in the greenhouse.

The differences observed in disease development between greenhouse sectors can be largely explained by the distinct microclimatic conditions generated by the contrasting structural and management configurations. Variations in air temperature, absolute humidity, and relative humidity recorded between sectors (Figures 5–8) were closely related to the dynamics of fungal disease development throughout the different crop cycles. Despite the use of calcium carbonate whitening on the roof of the East sector to reduce incident solar radiation, this sector, characterised by a single roof and a smaller ventilation surface, exhibited higher temperature peaks, consistently higher absolute humidity levels, and a greater persistence of periods with relative humidity close to saturation, particularly during night-time and early morning hours. These results are consistent with previous studies showing that greenhouse ventilation patterns strongly determine the spatial and temporal distribution of temperature and humidity within the crop canopy [64]. These conditions were especially pronounced during the autumn–winter cucumber cycles and under the more demanding spring–summer conditions of the tomato and pepper crops.

High relative humidity combined with limited ventilation favours condensation and the formation of water films on leaf surfaces, creating a highly favourable environment for spore germination and infection by fungal pathogens. Recent experimental evidence has shown that diurnal humidity fluctuations combined with reduced air movement enhance fungal spore release and dispersal in greenhouse environments [65]. Under such conditions, the development of diseases such as downy mildew (*Pseudoperonospora cubensis*) and gummy stem blight (*Stagonosporopsis* spp.) was enhanced in the East sector [29,31,33,66]. In addition, the coexistence of elevated relative humidity and moderate temperatures may accelerate the progression of powdery mildew under greenhouse conditions, even in the absence of free water, particularly when these conditions persist over extended periods [36,67].

In contrast, the West sector, where the double-roof system was combined with increased lateral ventilation, exhibited a more balanced microclimate, characterised by reduced thermal extremes, lower and more stable absolute humidity levels, and a reduction in both the duration and frequency of periods with high relative humidity. Improved air renewal limited water vapour accumulation and reduced saturation events, particularly during night-time, which are key factors restricting pathogen establishment and spread [6,34]. Consequently, a clear delay and lower intensity in the development of fungal diseases, especially powdery mildew and downy mildew, were consistently observed in this sector.

This effect was particularly evident during crop cycles subjected to higher climatic pressure, such as the 2020/2021 cucumber season and the 2022 pepper season, highlighting the effectiveness of the integrated configuration combining double roofing and enhanced ventilation not only for thermal regulation but also for humidity control, thereby reducing disease risk in greenhouse cropping systems. The strong dependence of fungal disease development on temperature, humidity, and air renewal under protected cultivation has been highlighted in recent reviews addressing plant–pathogen dynamics in greenhouse environments [68].

The presence of the double roof contributed to better insulation from external climatic conditions [10], increasing winter temperatures [13], which was beneficial for crop development. In addition, radiation reaching the crop after passing through the double roof equipped with a sunlight spectrum photoconverter film generated a distinct microclimatic environment that may have influenced plant development, photosynthetic performance [14], and indirectly the interaction between crops and potential pathogens [66].

The use of double roofs in greenhouses has sometimes been associated with increased relative humidity [9], which could potentially favour fungal disease development. However, in the present study, the areas covered by the double roof were also those with the largest ventilation openings (Figure 1). Enhanced passive ventilation effectively counteracted any potential humidity increase associated with the double roof, as natural ventilation is a widely recognised and effective strategy for humidity control in greenhouse crops [6].

Powdery mildew was the disease with the highest infection levels and is endemic in the study area. Its high incidence may also be related to the greenhouse design, as ventilation surfaces and structural configuration allow effective air movement under favourable climatic conditions. While powdery mildew spore production and dispersal are favoured by relatively dry environments, a minimum level of humidity is required for successful infection of plant tissues [69]. During winter, one of the primary objectives of natural ventilation in Almería's greenhouses is to reduce excess humidity [6], which may simultaneously favour the dispersion of powdery mildew spores.

In the present greenhouse, the double-roofed areas coincided with the most ventilated zones, suggesting that the lower levels of fungal disease development observed may be attributed not to a single factor, but to the combined effect of increased ventilation and roof configuration.

Powdery mildew caused significant qualitative and quantitative yield losses in cucumber, pepper, and tomato crops. Reductions in photosynthetic performance and alterations to leaf structure associated with powdery mildew infection have been recently reported in cucurbit crops, confirming its strong impact on plant growth and yield [70]. This disease is widespread in horticultural production in the region and typically requires repeated fungicide applications for effective control, involving additional labour and input costs for growers.

Throughout the trial, powdery mildew developed more rapidly in areas with a single roof and lower ventilation capacity. The use of a sunlight spectrum photoconverter film as part of the double-roof system increased the proportion of useful radiation reaching the crop. Light quality is known to influence the development of powdery mildew in cucumber crops [71,72], as the pathogen develops preferentially under shaded conditions, and its conidia are sensitive to direct and ultraviolet radiation [67,72–77]. Nevertheless, the observed effects cannot be attributed solely to spectral modification, as temperature and humidity conditions also play a decisive role. Overall, the combined use of a double roof and increased ventilation delayed powdery mildew development in this trial, despite the fact that drier environments can stimulate sporulation and dispersal of powdery mildew spores in cucurbits [69].

Higher disease severity was consistently observed under standard irrigation compared with deficit irrigation. The deficit irrigation treatment, which supplied 25% less water, also resulted in lower fertiliser input due to the fertigation system, potentially inducing moderate crop stress. Increased nitrogen availability under standard irrigation may have favoured disease development, as reported in previous studies [78,79]. Moreover, longer irrigation durations may increase local humidity around the crop canopy, favouring spore germination and infection [67,80]. Subsequent daytime ventilation reduces ambient humidity [6], which may further enhance the sporulation and dispersal of powdery mildew spores [81].

The combined use of a double roof with a sunlight spectrum photoconverter film and enhanced ventilation also reduced the presence and severity of downy mildew. One contributing factor may be the reduction in free water on leaf surfaces, as the double roof prevented condensation droplets from falling directly onto the crop. Relative humidity above 90% and the presence of free water strongly favour the development of *Pseudoperonospora cubensis* [67,82], whose zoospores require an aqueous medium for dispersal [64].

In Almería's greenhouses, vents are often kept closed during winter to increase internal temperatures [6], particularly in cucurbit crops that generate high humidity levels conducive to downy mildew development. In this study, increased ventilation in the double-roofed areas likely contributed to limiting downy mildew development by reducing prolonged periods of high humidity. Prolonged low ambient humidity impairs spore viability and dispersal of *Pseudoperonospora cubensis* [67,83], and previous studies have linked spore viability to incident solar radiation [84]. The spectral properties of the photoconverter film may therefore have contributed indirectly to disease suppression, although this effect cannot be isolated from other microclimatic factors.

Gummy stem blight showed the lowest overall severity among the diseases evaluated, but due to its potential to cause yield losses of 15–30% in cucumber crops [85], it was assessed during both cucurbit cycles. Its development requires high humidity and mild temperatures [3], similar to downy mildew. Reduced humidity resulting from enhanced ventilation [6] in the double-roofed areas was a key factor limiting disease development. However, disease reduction was less pronounced than for downy mildew, possibly because the double roof increased winter temperatures [13], which may favour *Stagonosporopsis cucurbitacearum*. Despite this, a substantial reduction in disease severity was observed in areas with a double roof compared with those with a single roof.

Differences in gummy stem blight severity between northern and southern zones during the second cucurbit cycle were associated with irrigation regimes. Reduced irrigation (25%) resulted in lower disease development, likely due to decreased nitrogen fertilisation and lower canopy humidity, both of which are known to influence fungal disease incidence [78].

Early blight appeared in the tomato crop during an atypical period for the study area. This disease requires high humidity and elevated temperatures [85] and is usually associated with regions experiencing significant rainfall. During the trial, unusual rainfall events occurred between May and June, creating favourable conditions for disease onset. Early blight was observed in only one crop cycle and did not show a consistent response to the greenhouse configuration. In some plots, disease severity followed a trend similar to powdery mildew (Figure 12b), but overall differences between sectors were less clear.

Powdery mildew colonised the tomato crop prior to the onset of early blight, reducing the available leaf area for *Alternaria linariae* development. This competitive interaction between pathogens may have been more pronounced in the northern areas with a single roof, where powdery mildew severity was highest. In the southern areas, a lower development of early blight was observed under the double roof, possibly due to greater ventilation capacity reducing ambient humidity [6] and better insulation from external rainfall events [10], which played a key role in disease initiation.

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5. Conclusions

The following conclusions can be drawn from the results obtained using an integrated passive climate management strategy combining a double roof with a sunlight spectrum photoconverter film and an increased ventilation surface in Mediterranean greenhouse conditions:

- The combined configuration of double roofing and enhanced natural ventilation reduced the development and severity of major fungal diseases, particularly powdery mildew (*Podosphaera xanthii* in cucumber and *Leveillula taurica* in tomato and pepper), downy mildew (*Pseudoperonospora cubensis*), and gummy stem blight (*Stagonosporopsis* spp.), in cucumber, tomato, and pepper crops.
- The integrated use of double roofing and increased ventilation contributed to improved humidity control within the greenhouse, reducing the persistence of conditions favourable to leaf wetness and pathogen infection, which was especially relevant for limiting downy mildew development.
- No clear or consistent effect of the greenhouse configuration on early blight (*Alternaria linariae*) was observed. This disease appeared only during one crop cycle under atypical climatic conditions, preventing robust conclusions regarding its response to the passive climate control strategy evaluated.
- Deficit irrigation, supplying 25% less water than standard irrigation, was associated with lower disease severity for powdery mildew, downy mildew, and gummy stem blight, but did not show a consistent effect on early blight development.
- Overall, passive climate control strategies based on structural greenhouse design and ventilation management represent a promising complementary approach for reducing fungal disease pressure in Mediterranean greenhouse crops, potentially decreasing reliance on fungicide applications and contributing to more sustainable disease management.

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