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MASTER'S THESIS-RELATED PAPER

UV-B LIGHT APPLICATION FOR POWDERY MILDEW CONTROL ON CUCUMBER IN GREENHOUSE PRODUCTION

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Abstract

Powdery mildew, primarily caused by *Podosphaera xanthii*, is a major constraint in cucumber (*Cucumis sativus* L.) greenhouse production, causing yield losses up to 50%. Conventional control relies on sulfur and synthetic fungicides, raising concerns about environmental contamination, health risks, and resistance development. This study evaluated an ultraviolet B (UV-B) light-emitting diode (LED) prototype (310 nm) as a sustainable alternative for disease control through direct pathogen inactivation and induction of plant defenses. Two phytotron trials, one experimental greenhouse trial, and one commercial greenhouse trial were conducted to assess efficacy and phytotoxicity. Under controlled conditions, UV-B at Confidential $\text{mJ}\cdot\text{cm}^{-2}$ caused no phytotoxic symptoms, validating this dose (fluence) for subsequent greenhouse trials. In the experimental greenhouse, UV-B irradiation alone provided disease suppression equivalent to conventional sulfur applications (84.6%), while an integrated strategy combining UV-B with a 50% reduction in sulfur maintained full plant protection. In the commercial greenhouse, disease pressure could not be quantified due to absence of inoculation and natural disease pressure. UV-B-treated fruits did not differ from controls in antimicrobial properties and slice healing properties. These findings confirm that UV-B technology can contribute to crop protection without negatively impacting postharvest fruit quality, supporting its integration into sustainable pest management programs in protected cucumber cultivation.

Keywords: UV-B irradiation; UV-B LED; powdery mildew; cucumber; greenhouse production; integrated pest management.

1 Introduction

Cucumber production plays a significant role in Switzerland, ranking as the third largest greenhouse crop in terms of surface area, encompassing 63.01 hectares. In terms of volume, cucumber is the third greenhouse crop, producing 11,825 tonnes, and it ranks sixth in economic value, generating 32.533 million CHF [1].

Powdery mildew (PM) is one of the most common and serious diseases of cucumber worldwide [2]. This disease significantly impacts cucumbers by reducing photosynthesis, which consequently lowers yield. This fungal disease also leads to premature plant death, exhibits rapid propagation, and persists in greenhouse environments [3].

Podosphaera xanthii, the primary causal agent of cucumber powdery mildew, belongs to the *Erysiphaceae* family, which encompasses over 400 species. It overwinters in the form of cleistothecia. The fungus thrives in climates alternating between dry and humid conditions. It reproduces sexually via ascospores and asexually via conidia. These spores infect plants through the cuticle, stomata, or lesions, and develop within the epidermal cells [4].

Current PM control methods utilized in Swiss cucumber cultivation include active ingredients such as sulfur (used in both organic and conventional farming), azoxystrobin, penconazole, and fluopyram [5]. These compounds can adversely affect human health, the environment, and contribute to the development of resistance [6,7]. It is imperative to explore alternative strategies that are environmentally benign, safe for human consumption, and effective in disease control. One potential method is the application of ultraviolet (UV) light. Previous studies have shown that UV light can effectively mitigate the effects of this pathogen [8].

Exploration of UV light applications for pest and pathogen control goes back to the 1990s. Recent years, particularly the last five years, have witnessed a significant revival in research interest in this domain [9].

UV light can control pests and pathogens through two mechanisms [10]. The first is the direct mode of action, in which the UV rays exert a direct lethal effect on pests and pathogens by degrading cellular structures and nucleic acids [11]. The second mechanism triggers defense responses in plants. UV rays activate photoreceptors, notably UV RESISTANCE LOCUS 8 (UVR8), leading to the synthesis of various compounds, including phenolic compounds, alkaloids, glucosinolates, and anthocyanins [11,12]. It is known that exposure to necrotizing pathogens enhances plant resilience against future biotic stresses, a phenomenon known as systemic acquired resistance (SAR) [13]. Previous studies have demonstrated that

UV-B ray exposure induces SAR in tomato calli [14]. We hypothesize that UV-B may also induce SAR in other plants such as cucumber.

On the other hand, exposure to UV may also cause morphological changes such as leaf and cuticle thickness [10] and cause symptoms such as leaf burning or curling, stunted growth, and decreased chlorophyll levels [10,16].

Optimal UV-B fluence efficiently controls pests while minimizing phytotoxicity. A thorough understanding of UV light's varied impacts on different plant species, pest species, and plant-pest interactions could revolutionize crop protection strategies by reducing dependence on chemical fungicides and insecticides.

The aim of this study is to assess the effectiveness and potential phytotoxicity of a UV-B lamp prototype developed by Future of Grow (FOG) for powdery mildew control in cucumber, through a series of trials conducted under controlled phytotron conditions as well as in experimental and commercial greenhouses. This research addresses three key questions: (1) Can the UV lamp prototypes effectively ensure satisfactory plant protection against powdery mildew? (2) Can conventional fungicide treatment doses be reduced when combined with UV-B application as part of an integrated pest management (IPM) approach? (3) Does UV-B treatment impact post-harvest crop quality?

2 Materials and Methods

2.1 Plant Material and Cultivation

2.1.1 Plant Material

The first three experiments employed the powdery mildew-susceptible cucumber (*Cucumis sativus*) cultivar 'Philadelphia' (UFA). Seeds were sown in seed trays containing Capito Organic Universal Potting Soil (Landi) and cultivated in greenhouse conditions at INFORAMA Rütli, Zollikofen, Canton of Bern, Switzerland (46.9690° N, 7.4415° E) for a 22-day establishment period preceding each trial. For the commercial greenhouse experiment, pre-grown plantlets were sourced from the grower's standard commercial supplier.

2.1.2 Seedling Management and Nutrition

During the establishment phase, plants were irrigated with tap water for the first two weeks post-sowing. Subsequently, seedlings received a nutritional supplement with Wuxal® 8-8-6 fertilizer at 0.1% v/v concentration. A second identical fertilization was applied one week after trial initiation to ensure consistent nutrient availability throughout the experimental period. Prophylactic pest management consisted of a single application of Neem Azal® T/S (0.3% v/v) to prevent thrips damage that could interfere with experimental outcomes. In the commercial greenhouse experiment, standard fertilization practices used by the grower were applied. No chemical plant protection treatments were performed; however, biological control agents like *Encarsia formosa*, were released as part of the grower's routine pest management strategy.

2.2 Environmental Conditions

2.2.1 Controlled Environment Trials (PT1, PT2)

Two phytotron experiments were conducted within Fitotron® growth chambers (model HGC 1014-M, Weiss Technik AG, Reiskirchen, Germany) under standardized climatic conditions. In Phytotron Trial 1 (PT1), a UV-B fluence of Confidential $\text{mJ}\cdot\text{cm}^{-2}$ was applied to evaluate its efficacy against powdery mildew and to monitor potential phytotoxic symptoms. In Phytotron Trial 2 (PT2), the fluence was increased by approximately 12% (to Confidential $\text{mJ}\cdot\text{cm}^{-2}$) in order to investigate whether a higher intensity could improve disease control while assessing plant tolerance. For both trials, the temperature regime was maintained at $25 \pm 2\text{ }^{\circ}\text{C}$ during the 16-hour photoperiod and $22 \pm 2\text{ }^{\circ}\text{C}$ during the 8-hour dark cycle. Relative humidity was regulated at 40–50% during daylight hours, increasing to 70% at night to simulate natural diurnal variations.

2.2.2 Experimental and Commercial Greenhouse Conditions (GHT1, GHT2)

The experimental greenhouse trial (GHT1) was conducted under ambient environmental conditions with continuous climate monitoring using a LOG32 TH data logger (Rotronic AG, Bassersdorf, Switzerland). Across the experimental period, the mean temperature was $17.2\text{ }^{\circ}\text{C}$ and the mean relative humidity was 53.0%. The commercial greenhouse trial (GHT2) was likewise conducted under ambient production conditions.

2.3 UV-B Irradiation Technology and Application

2.3.1 UV-B Delivery System

Irradiation treatments utilized custom-designed 310 nm UV-B LED prototypes developed by Future of Grow (F.O.G) Aigle, Switzerland. These specialized fixtures were suspended 30 cm above plant canopies in PT1, PT2, GHT1 and 50 cm above plant canopies for GHT2 to ensure consistent exposure across the treatment zone.

2.3.2 UV-B Dosimetry and Calibration

UV-B irradiance measurements for all trials were performed using an SDL470 UVA/UVC light meter (Extech Instruments®, Nashua, NH, USA) equipped with a UVA probe ($\lambda = 365\text{ nm}$), providing 0.001 mW cm^{-2} resolution and $\pm 4\%$ accuracy. While the probe operates outside the target UV-B range (310 nm), it ensured consistent relative measurements across all experimental conditions.

2.3.3 UV-B Fluence Selection and Rationale

The initial UV-B fluence of Confidential $\text{mJ}\cdot\text{cm}^{-2}$ applied in PT1 was derived from previous optimization research by Kientega et al. (2023), where this fluence demonstrated optimal efficacy against powdery mildew on *Cannabis sativa*, achieving 90% disease-free plants among nine tested intensities. PT2 employed an elevated fluence of Confidential $\text{mJ}\cdot\text{cm}^{-2}$ (approximately 12.2% increase) specifically to investigate potential phytotoxicity thresholds while maintaining disease control efficacy. The UV-B fluences applied in each trial are summarized in Table 1.

Table 1. UV-B fluence for each trial. Trial Fluence ($\text{mJ}\cdot\text{cm}^{-2}$)

PT1 Confidential

PT2 Confidential

GHT 1 Confidential

GHT 2 Confidential

2.3.4 Treatment Timing Protocol

UV-B exposures were scheduled during the 8-hour dark period, following the methodology established by Patel et al. (2020), who demonstrated superior antifungal efficacy under these conditions compared to daylight applications.

2.4 Pathogen Establishment and Inoculation

2.4.1 Natural Infection Protocol (PT1, PT2, GHT2)

Natural powdery mildew infections were established in the INFORAMA Rütli greenhouse during the 22-day seedling development phase. Plants with visible powdery mildew colonies on two to three leaves were selected for both phytotron trials to ensure adequate baseline infection pressure. GHT2 similarly relied on ambient greenhouse pathogen exposure without artificial inoculation.

2.4.2 Standardized Artificial Inoculation (GHT1)

Controlled inoculum pressure was achieved through a dual-approach methodology: placement of three naturally infected spreader plants within each treatment group, supplemented by direct application of prepared spore suspension. The suspension contained 1.875×10^5 spores mL^{-1} formulated in 10% phosphate-buffered saline with 0.03% (v/v) Tween® 20 surfactant, following protocols developed by Basile Veuthey (personal communication, 2025).

2.5 Experimental Design and Treatment Structure

2.5.1 Phytotron Trial Configuration (PT1, PT2)

In the phytotron trials (PT1 and PT2), the phytotron chamber was divided into two compartments: one compartment received UV-B treatment, while the opposite compartment served as a negative control with no treatment and was exposed only to ambient white light. UV treatments were applied from suspension fixtures positioned 30 cm above the plant canopy. Each UV-treated group comprised seven plants in PT1 and eight plants in PT2, randomly allocated to treatment groups.

2.5.2 Greenhouse Trial Design (GHT1, GHT2)

In the experimental greenhouse trial (GHT1), ten plants were assigned to each of four treatment modalities: UV-B alone, wettable sulfur (Soufre Mouillable de Sthuln®) at 0.1% (w/v), a combined UV-B and sulfur regimen with sulfur concentration reduced by 50% (relative to the supplier's recommendation) to 0.05% (w/v) and an untreated control. Fixtures delivering UV-B were suspended 30 cm above the canopy for all UV treatments. Sulfur was applied at the beginning of the experiment and again two weeks later, while UV-B treatments were delivered every night.

In the commercial greenhouse trial (GHT2), six blocks were established across two adjacent cucumber rows, each comprising 7–11 plants. Within each block, half of the plants received UV-B irradiation and the remainder served as untreated controls; the two treatments were separated by buffer plants to minimize UV-B spillover. In addition, a spatial control group (n = 10 plants) was positioned in the same greenhouse but in a row farther from the experimental area to ensure no incidental UV-B exposure.

2.6 Quantification and Disease Metrics

Disease quantification protocols differed between experimental systems to accommodate varying scales and objectives.

2.6.1 Phytotron Assessment (PT1, PT2)

Disease progression was monitored by recording healthy and infected leaf counts for each individual plant at trial initiation and conclusion. The analysis evaluated the change in infection proportion (ratio of diseased to total leaves) from trial initiation to conclusion, compared between UV-treated and control groups.

2.6.2 Greenhouse Assessment (GHT1)

Comprehensive leaf-level evaluation was conducted using a five-point severity scale developed for this study and applied to every leaf of each plant. Scoring criteria assigned: 1 = absence of visible powdery mildew symptoms; 2 = small, localized powdery spots; 3 = larger but contained patches; 4 = multiple patches across most of the leaf surface; and 5 = complete leaf coverage by powdery mildew (Figure 1).



Figure 1. Visual scoring scale for powdery mildew severity on cucumber leaves used in the experimental greenhouse trial (GHT1). Scores: 1 = no visible symptoms; 2 = small, localized spots; 3 = larger but contained patches; 4 = multiple patches across most of the leaf surface; 5 = complete leaf coverage by powdery mildew. (Photo: Author, 2025)

2.6.3 Commercial Greenhouse Assessment (GHT2)

Powdery mildew incidence could not be measured, as no powdery mildew developed under production conditions. Instead, treatment effects were assessed using complementary cucumber quality parameters following the cucumber stress test protocol described by Rembiałkowska et al. (2021), with minor modifications. Whereas the original method involved slicing the cucumber into multiple transverse discs along its length, in this study each cucumber was cut only once at mid-length before reassembly and incubation. After unwrapping samples and photographing them under normal light conditions following a 14-day incubation period, evaluations included : (1) antimicrobial properties (AMP), scored as 1 (no decay), 2 (few traces of decay), or 3 (fully decayed) and (2) slice healing properties (SHP) assessed by hold-

ing the cucumber horizontally by its lower slices and scored as a binary yes/no for whether the slices remain intact when lifted horizontally for 10 seconds.

2.7 Statistical Analysis

Normality and variance homogeneity assumptions were evaluated using Shapiro–Wilk and Levene's tests, respectively. Parametric one-factor ANOVA was applied when assumptions were satisfied, while Kruskal–Wallis tests followed by Dunn's post-hoc comparisons with Bonferroni correction were employed for datasets violating these requirements. For two-group comparisons with unequal variances, Welch's t-test with Satterthwaite degrees of freedom was applied. Binary categorical variables were analyzed using Fisher's exact test. All statistical computations were performed using RStudio (version 2025.05.1+513) and R (version 4.4.1), with the significance threshold set at $\alpha = 0.05$.

2.8 Use of Generative AI

Large Language Models like Anthropic's Claude and OpenIA's ChatGPT were used for targeted terminology checks, syntax refinement and R code generation only. The statistical methodology, experimental design, and data analysis were conducted independently by the author. No AI tools were used to generate data or conduct analysis.

3 Results

3.1 Phytotron Trial 1: Initial UV-B Efficacy Assessment

ANOVA analysis revealed no statistically significant difference in infection progression between UV-treated and control plants ($F_{1,12} = 1.68$, $p = 0.218$) (Table 2).

Table 2. Cucumber leaf infection progression under controlled conditions (PT1)

Treatment	N	Mean (%)	Median (%)	SD	Min	Max
Control	7	-9.4	-17.5	23.2	-56.7	19.2
UV	7	-17.6	-17.9	21.6	-27.7	12.1

Note: Infection progression represents the difference in proportion of infected leaves between trial initiation and conclusion (negative values indicate disease reduction, positive values indicate disease increase). UV-B fluence = Confidential $\text{mJ}\cdot\text{cm}^{-2}$. Statistical analysis: One-way ANOVA, $F_{1,12} = 1.687$, $p = 0.218$.

However, UV-treated plants exhibited an average disease reduction of -17.6%, whereas control plants showed variable responses ranging from substantial improvement to disease progression (mean progression = -9.4%, range: -56.7% to +19.2%). The boxplot showed variation in infection progression between treatments, but with substantial overlap between groups (Figure 2).

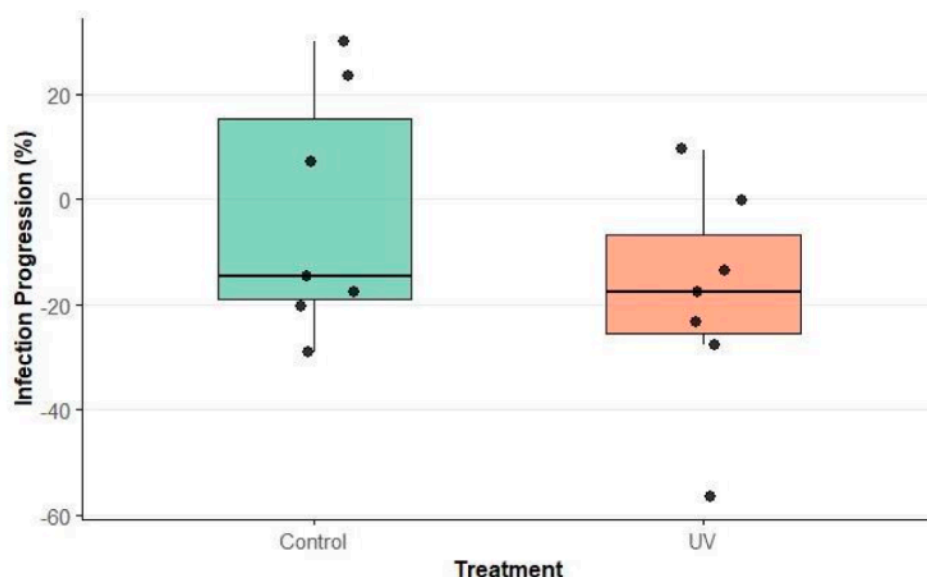


Figure 2. Treatment effect on powdery mildew progression in cucumber leaves. Difference in proportion of infected leaves from trial initiation to conclusion; comparing UV-B treatment (Confidential $\text{mJ}\cdot\text{cm}^{-2}$) with untreated controls in phytotron conditions (PT1). Each point represents an individual plant ($n = 7$ per treatment group).

3.2 Phytotron Trial 2: Elevated Fluence and Phytotoxicity Assessment

No statistically significant difference in infection progression was observed between UV-treated and control plants (Welch's t-test, $t_{4.41} = 1.44$, $p = 0.217$) (Figure 3). UV-treated plants exhibited greater average disease reduction (-37.2%) compared to controls (-24.6%), with all treated plants showing disease reduction ranging from -18.8% to -46.4%. In contrast, control plants showed variable responses ranging from -10.7% to -32.1%. Seven observations were excluded due to plant death, resulting in $n = 4$ control and $n = 5$ UV-treated plants (Table 3).

Table 3. Cucumber leaf infection progression under controlled conditions (PT2)

Treatment	N	Mean (%)	Median (%)	SD	Min (%)	Max (%)
Control	4	-24.6	-26.8	9.8	-32.1	-10.7
UV-B	5	-37.2	-37.5	11.7	-46.4	-18.8

Note: Infection progression represents the difference in proportion of infected leaves between trial initiation and conclusion (negative values indicate disease reduction, positive values indicate disease increase). UV-B fluence = Confidential $\text{mJ}\cdot\text{cm}^{-2}$. Statistical analysis: Welch's t-test, $t_{4.41} = 1.44$, $p = 0.217$.

Although the trial was terminated earlier than planned due to external factors including mite infestation and lighting issues, this duration was sufficient to assess phytotoxicity. No visible phytotoxic symptoms were detected in UV-treated plants at the elevated fluence of Confidential $\text{mJ}\cdot\text{cm}^{-2}$, confirming treatment safety at this level.

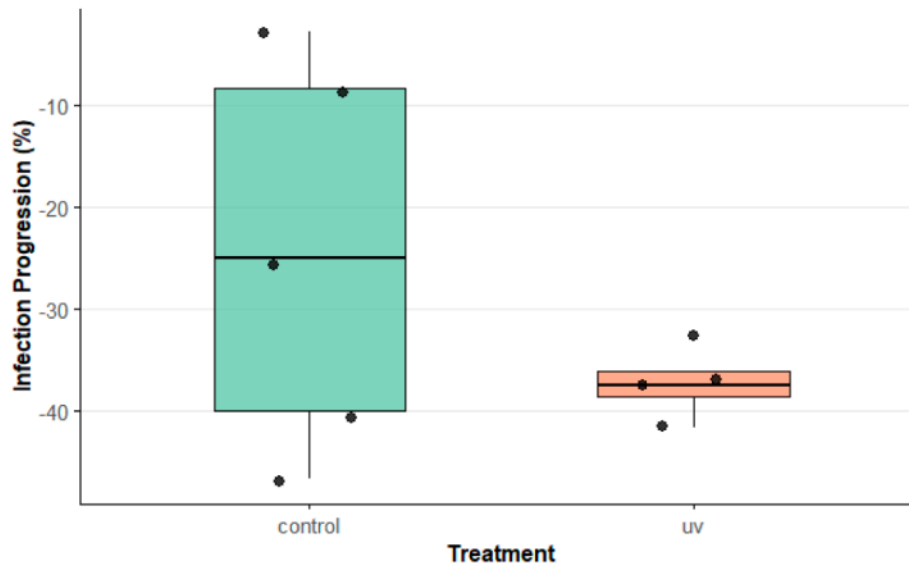


Figure 3. Treatment effect on powdery mildew progression on cucumber leaves. Difference in proportion of infected leaves from trial initiation to conclusion; comparing UV-B treatment (Confidential $\text{mJ}\cdot\text{cm}^{-2}$) with untreated controls in phytotron conditions (PT2). Each point represents an individual plant.

3.3 Experimental Greenhouse Trial

Infection grades differed significantly across treatments (Kruskal-Wallis test, $\chi^2 = 61.13$, $\text{df} = 3$, $p < 0.001$). Post-hoc analysis using Dunn's test with Bonferroni correction revealed that the control group differed significantly from all treatments (Control vs Sulfur: $p < 0.001$; Control vs UV-B: $p < 0.001$; Control vs UV-B + Sulfur: $p < 0.001$), while no significant differences were found between treatment groups (all pairwise comparisons $p > 0.05$).

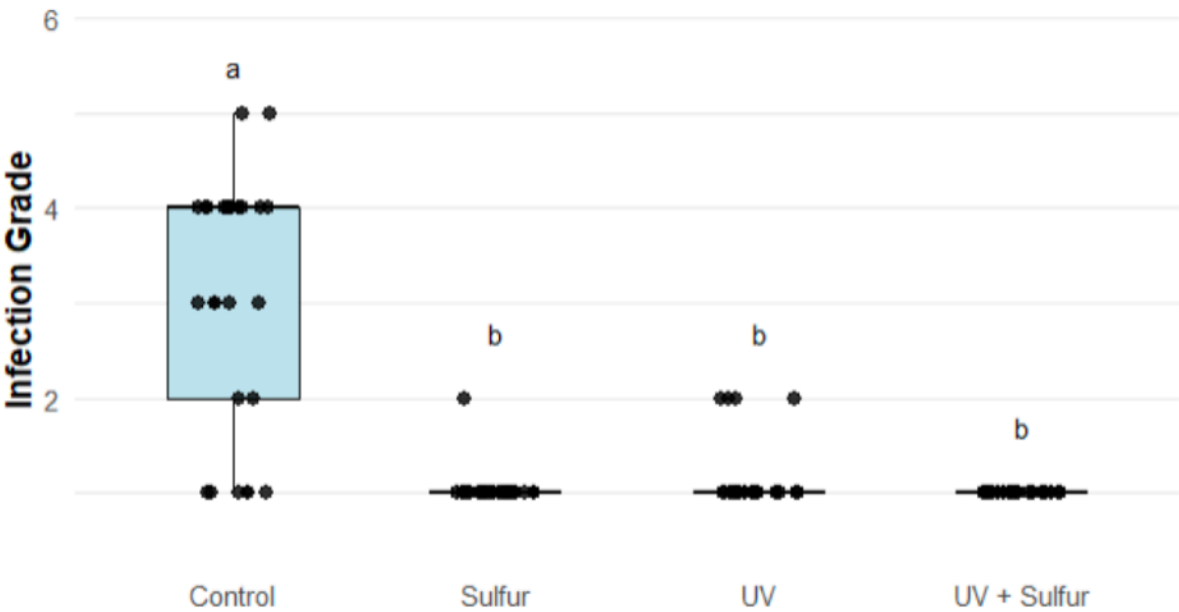
Table 4. Summary statistics of leaf-level infection scores by treatment group (GHT1). Berner Fachhochschule | Haute école spécialisée bernoise | Bern University of Applied Sciences 11

Treatment	N Leaves	N Plants	Mean Score	Median Score	SD	Min	Max	Healthy Leaves (%)
Control	27	7	3.07	4	1.33	1	5	22.2
Sulfur	27	7	1.04	1	0.19	1	2	96.3
UV-B	26	7	1.15	1	0.37	1	2	84.6
UV-B + Sulfur	25	7	1	1	0	1	1	100

Note: Visual scoring scale for powdery mildew severity on cucumber leaves used in the experimental greenhouse trial (GHT1). Scores: 1 = no visible symptoms; 2 = small, localized spots; 3 = larger but contained patches; 4 = multiple infected areas covering the entire leaf surface; 5 = complete leaf coverage by powdery mildew. Healthy leaves were defined as those with a score of 1.

The control group exhibited the highest infection levels, with a mean score of 3.07 (median 4) and only 22.2% of leaves remaining healthy. In contrast, the sulfur and UV-B treatments both achieved low infection levels, with mean scores close to 1 and high proportions of healthy leaves (96.3% for sulfur and 84.6% for UV-B). The combined UV-B + sulfur treatment performed optimally, with a mean score of 1, a median of 1,

Figure 4. Treatment effect on powdery mildew infection severity in cucumber leaves. Final infection grades comparing untreated control, sulfur fungicide, UV-B treatment (Confidential $\text{mJ}\cdot\text{cm}^{-2}$), and integrated UV-B + sulfur (50% reduced) in greenhouse conditions (GHT1). Each point represents an individual leaf assessment (n = 105 observations from 28 plants). Different letters indicate significant differences ($p < 0.05$).



3.4

Commercial Greenhouse Trial:

3.4.1 Antimicrobial Properties (AMP)

UV-B treatment did not affect cucumber post-harvest quality (Table 5). No significant differences were observed in antimicrobial properties (Figure 5) across treatments (Kruskal-Wallis $\chi^2 = 2.61$, $df = 2$, $p = 0.271$), with decay scores remaining low across all groups (means rang-

Table 5 Effect of UV treatment on antimicrobial properties of cucumber slices

Treatment	N	Mean	Median	SD	Min	Max
Control	17	1.41	1	0.80	1	3
Spacial Control	10	1.00	1	0.00	1	1
UV-B	16	1.31	1	0.70	1	3

ing from 1.00 to 1.41 on a 3-point scale).

Note: Antimicrobial properties scored after 14-day incubation: 1 = no decay, 2 = traces of decay, 3 = fully decayed. Kruskal-Wallis test, $p = 0.271$.

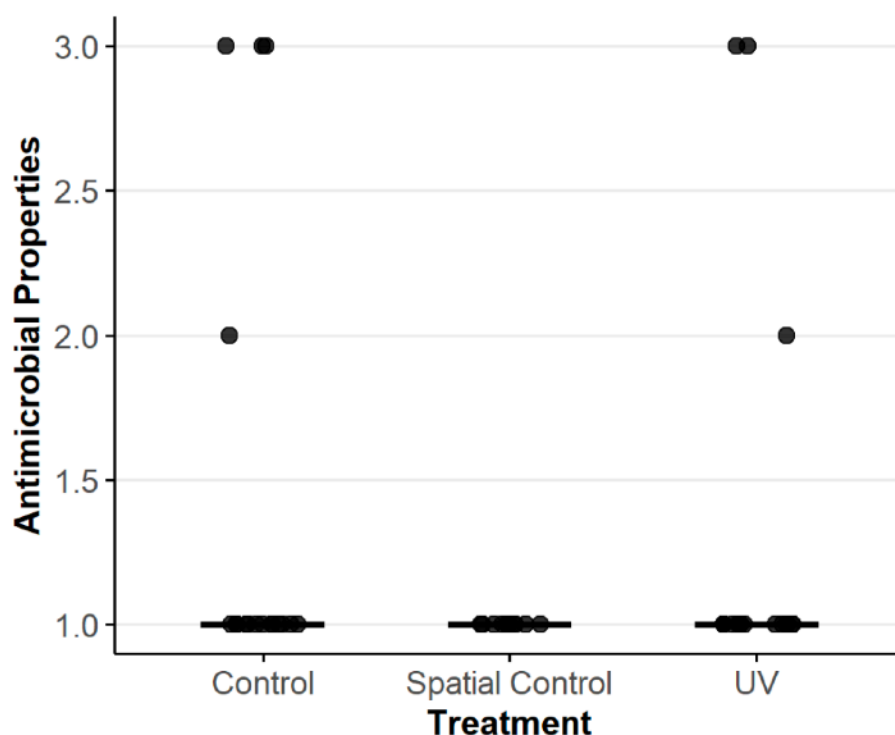


Figure 5 Treatment effect on antimicrobial properties of cucumber slices following 14-day incubation. Decay progression comparing Control, Spatial Control (plants positioned in a distant row from main experimental area), and UV-B treatment in commercial greenhouse conditions (GHT2). Each point represents an individual cucumber assessment (n = 43 observations). Scores: 1 = no decay, 2 = traces of decay, 3 = fully decayed. No significant differences were detected between treatments (Kruskal-Wallis $\chi^2 = 2.61$, df = 2, p = 0.271).

3.4.2 Slice Healing Properties (SHP)

Similarly, slice healing capacity showed no response to UV-B exposure (Table 6). All treatment groups demonstrated comparable proportions of broken slices (Fisher's exact test, p = 1.00), with 23.5% broken in Control, 30.0% in Spatial Control, and 25.0% in UV-B treatment, suggesting treatment had no measurable effect on tissue integrity maintenance (Figure 6Figure 7).

Table 6 Effect of UV treatment on slice healing properties of cucumber

Note: Slice healing assessed by visual inspection: intact = healed tissue, broken = separated tissue. Fisher's exact test, p = 1.00.

Treatment	N	Broken Cucumbers (%)
Control	17	23.5
Control far	10	30.0
UV-B	16	25.0

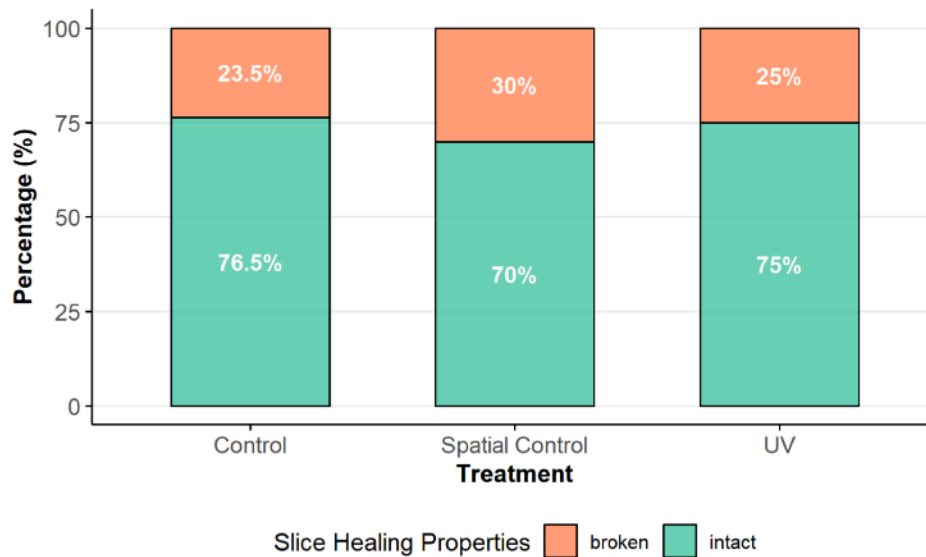


Figure 6 Treatment effect on cucumber slice healing properties following 14-day incubation. Healing capacity comparing Control, Spatial Control (plants positioned in a distant row from main experimental area), and UV-B treatment in commercial greenhouse conditions (GHT2). No significant differences were detected between treatments (Fisher's exact test, $p = 1.00$).

Figure 7 Fused cucumber slices after 14 days of storage.



3.4.3 UV-B Irradiance Measurements

In the commercial greenhouse trial (GHT2), UV-B fluence decreased sharply with increasing distance from the light source. The highest fluence was measured directly beneath the lamp (0 cm, 100 % fluence), but it declined to approximately 19 % fluence at 35 cm and to only about 0.8 % fluence near soil level (~385 cm from the light source), highlighting the strong attenuation of UV-B radiation with distance due to the inverse square law governing light intensity dispersion (Figure 8Figure 9).

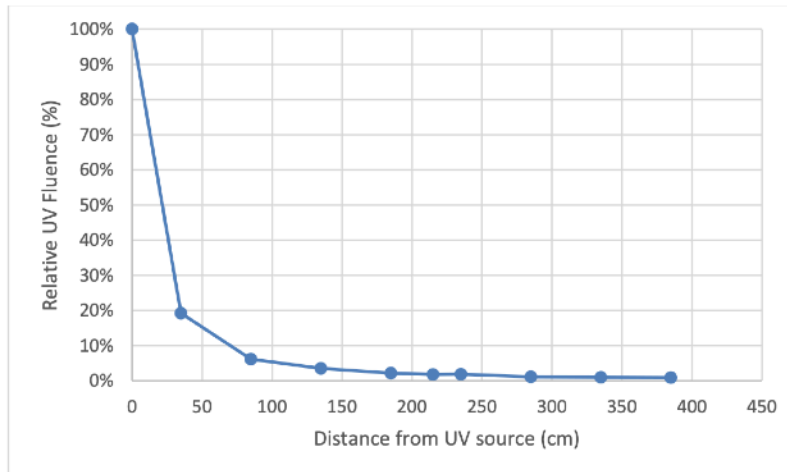


Figure 8. Normalized UV-B fluence (%) as a function of distance from the light source in the commercial greenhouse trial (GHT2).

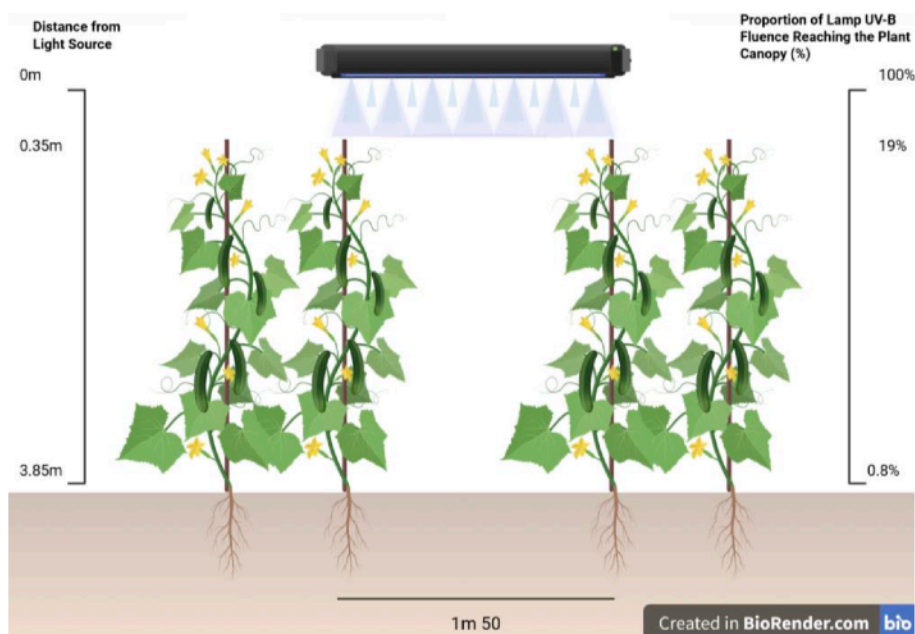


Figure 9. Schematic representation of UV-B irradiance distribution in the commercial greenhouse trial (GHT2). The illustration highlights the sharp decrease in irradiance with increasing distance from the lamps.

4 Discussion

4.1 Phytotron Trial 1: Initial UV-B Efficacy Assessment (PT1)

Although the difference was not statistically significant, graphical inspection suggests a possible trend: in the control group, the proportion of diseased leaves per plant increased in 42.8% of the plants, whereas in the UV-B group, this occurred in only 14.2% of the plants. The graphical representation of the data suggests a potential effect of UV-B treatment on reducing the proportion of diseased leaves per plant, but the sample size does not allow drawing conclusions. Additional trials with larger sample sizes would be necessary to confirm or refute this trend.

4.2 Elevated Fluence Assessment and Safety Validation (PT2)

The elevated UV-B fluence (Confidential $\text{mJ}\cdot\text{cm}^{-2}$) in PT2 provided critical insights into both treatment efficacy trends and phytotoxicity thresholds. Although no statistically significant treatment effect was detected, the narrower interquartile range observed in the UV-B group suggests a more uniform response to treatment compared to controls. All UV-treated plants demonstrated at least a 30% decrease in infected leaf proportion. In contrast, the control group exhibited highly variable disease progression, including cases where infection severity increased during the trial period.

The absence of visible phytotoxic symptoms at Confidential $\text{mJ}\cdot\text{cm}^{-2}$ represents an important safety validation for practical applications of this technology. These observations confirm that the tested fluence falls within cucumber tolerance levels, supporting the feasibility of commercial implementation without apparent crop damage risk. The findings align with previous literature demonstrating that moderate UV-B application can be safely applied without inducing leaf necrosis or growth inhibition [10].

However, PT2 limitations must be acknowledged. The trial was terminated earlier than planned due to external factors including mite infestation and inadequate lighting conditions, resulting in plant losses across both treatment groups. While these constraints limit definitive efficacy conclusions, the safety data obtained remains valuable for establishing UV-B tolerance thresholds in cucumber. Further studies could refine these safety thresholds across different cucumber cultivars and greenhouse production systems.

4.3 Treatment Achieves Sulfur-Equivalent Disease Control: Greenhouse Trial (GHT1)

UV-B treatment and sulfur applications showed no statistically significant differences in disease control efficacy under greenhouse conditions. These findings are consistent with previous studies demonstrating that nocturnal UV exposure provides effective powdery mildew suppression in cucumber [2,8].

Although this study does not determine whether the UV-B effect operates directly on the pathogen or indirectly via activation of plant defenses, the lack of significant differences between treatments indicates that both approaches provide comparable disease suppression. With 84.6% of leaves maintaining healthy status under UV-B treatment alone, this technology could potentially serve as an alternative to other conventional fungicides beyond sulfur, contributing to diversified disease management strategies in protected cultivation systems. However, additional studies across different pathosystems and environmental conditions are needed to validate the broader applicability of UV-B technology in pest management programs.

4.4 Innovative Integrated Strategy: UV-B + Sulfur (GHT1)

The integrated UV-B and reduced sulfur approach represents a significant finding of this study. This combination maintained disease control efficacy while halving fungicide input, demonstrating complementarity between those two control methods. Although the underlying mechanisms require further investigation, this strategy offers potential advantages for resistance management through mode-of-action diversification. The practical implications are considerable: achieving equivalent protection with 50% sulfur reduction reduces environmental residues while potentially delaying resistance development, positioning this integrated approach as a viable pathway toward more sustainable greenhouse production systems.

4.5 Impact of UV-B Treatment on Cucumber Postharvest Quality in Commercial Production (GHT2)

While powdery mildew failed to develop naturally in the commercial greenhouse, preventing assessment of UV-B treatment efficacy against the target pathogen. The absence of negative effects on post-harvest quality parameters like antimicrobial properties and slice healing capacity, demonstrates that UV-B application does not compromise cucumber storage. Although disease suppression efficacy remains undetermined, these findings establish that UV-B treatment at the tested doses does not induce phytotoxic effects or compromise fruit quality, addressing a primary concern for commercial adoption.

4.6 Distance-Dependent UV-B Irradiance Distribution (GHT2)

In the commercial greenhouse trial, UV-B irradiance decreased sharply with distance from the lamps, following the inverse square law of light dispersion. This physical principle explains the pronounced irradiance gradient observed throughout the crop canopy, where the upper leaves received substantially more UV-B exposure than the lower ones. Such spatial heterogeneity highlights the importance of determining whether UV-B effects are confined to directly exposed tissues or can elicit systemic responses. The elicitation of systemic acquired resistance would help counterbalance the uneven distribution of light and ensure more consistent plant protection under commercial greenhouse conditions.

4.7 Potential Mechanisms of Action and Research Perspectives

The observations from this study do not allow defining the precise mode of action. The literature indicates that UV-B exerts both direct fungicidal effects via nucleic acid damage and disruption of pathogen cellular structures and indirect effects through activation of plant defense pathways [11, 12].

The potential for UV-B to induce systemic acquired resistance (SAR) in cucumber remains an open question with conflicting evidence in the literature. While UV-B exposure has been shown to trigger SAR in tomato calli through UVR8-mediated pathways leading to phenolic compound and flavonoid accumulation [14]. Cucumber responses may differ significantly from tomato systems. A recent study by Fardhani et al. (2022) specifically investigated UV-B effects in cucumber and found that while defense-related genes such as *Chi2* and *ETR2* were upregulated in directly exposed leaves, this protective response remained localized without inducing systemic acquired resistance throughout the plant [19]. However, this study examined only a subset of potential SAR-associated pathways, leaving open the possibility that other mechanisms may contribute to UV-B-mediated plant defense responses.

Further research incorporating comprehensive biochemical analyses to quantify defense metabolites, including phenylalanine ammonia-lyase (PAL) activity as a precursor to phenolic compound synthesis, alongside genome-wide gene expression profiling, will be necessary to fully elucidate the mechanistic basis of UV-B protection in cucumber and determine whether systemic responses occur through alternative molecular pathways not yet characterized.

4.8 Post-Infection Treatment Approach and Preventive Potential

This study presents important methodological limitations. The post-infection approach, while validating curative efficacy, likely underestimates the preventive potential of UV-B. The direct and indirect germicidal properties of UV-B suggest that prophylactic application could surpass the observed results, on one hand by neutralizing spores depositing on leaves, and on the other hand by preparing plants for future pathogen attacks.

5 Conclusions

Taken together, the findings address the three guiding questions. Under experimental greenhouse conditions, 310-nm UV-B lamp prototypes developed by F.O.G. ensured satisfactory protection against powdery mildew: disease control with UV-B alone (Confidential $\text{mJ}\cdot\text{cm}^{-2}$) achieved 84.6% healthy leaves, statistically indistinguishable from sulfur treatment (96.3% healthy leaves) and significantly superior to untreated controls (22.2% healthy leaves, $p < 0.001$), with no phytotoxicity observed at fluences up to confidential $\text{mJ}\cdot\text{cm}^{-2}$, whereas the absence of disease in the commercial greenhouse precluded efficacy evaluation in production settings. Integrating UV-B with a reduced fungicide program allowed meaningful input savings: combining UV-B with 50% of the standard sulfur dose (0.05% w/v) achieved 100% healthy leaves, maintaining protection equivalent to the full sulfur dose (0.1% w/v, 96.3% healthy leaves), indicating realistic potential to halve sulfur use within an integrated pest management framework.

No significant differences in postharvest quality were detected at the applied fluences in commercial conditions. Both antimicrobial properties ($p = 0.271$) and tissue integrity ($p = 1.00$) remained comparable between UV-B treated and control fruits.

Overall, the results are encouraging, but additional trials in commercial greenhouse settings are required before recommending routine implementation. Because the present study evaluated curative applications, the next step is to test preventive (pre-infection) protocols, which may improve control efficacy and consistency.

Further priorities include evaluating performance across different crop varieties, botanical families, and target diseases; clarifying the relative contributions of direct pathogen inactivation versus plant-mediated defenses in cucumber; and conducting technical optimization of UV delivery (lamp placement, spacing, etc.) together with economic assessments to weigh deployment and maintenance costs against fungicide savings.

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Annex 1: ANOVA Test Results (PT1)

Annex

Source	df	Sum Sq	Mean Sq	F value	P-value
Treatment	1	836.4	836.4	1.687	0.218
Residuals	12	5948	495.7	-	-

2: Welch's t-test Results (PT2)

Test	df	t	P-value
Welch's t-test	4.41	1.44	0.217

Note: Welch's test used due to unequal variances (Levene's test $p = 0.031$).

Annex 3: Kruskal-Wallis Test Results (GHT1).

Test	df	χ^2	P-value
Kruskal-Wallis	3	61.13	< 0.001

Note: Non-parametric test used due to violations of normality (Shapiro-Wilk $p < 0.001$) and homogeneity (Levene's test $p < 0.001$).

Annex 4: Kruskal-Wallis Test Results for Antimicrobial Properties (GHT2)

Test	df	χ^2	P-value
Kruskal-Wallis	2	2.61	0.271

Note: Non-parametric test used due to violation of normality assumption (Shapiro-Wilk $p < 0.001$).

Annex 5: Fisher's Exact Test Contingency Table for Slice Healing Properties (GHT2)

Treatment	N	Broken	Intact	% Broken	% Intact
Control	17	4	13	23.5	76.5
Spatial Control	10	3	7	30.0	70.0
UV-B	16	4	12	25.0	75.0
Total	43	11	32	25.6	74.4

Note: Fisher's exact test ($p = 1.00$) was applied due to expected cell frequencies below 5 (minimum threshold for chi-square validity). Binary categorical assessment: intact = maintained tissue cohesion, broken = tissue separation.