INVESTIGATING SUPPLEMENTAL UV-B DOSES AND DURATIONS IN TWO HIGH-CANNABINOID CANNABIS SATIVA L. CULTIVARS

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ABSTRACT

This study investigates the effects of supplemental UV-B radiation on two high-cannabinoid Cannabis sativa L. cultivars—CBD-dominant ‘TJs CBD’ and CBG-dominant ‘Janets G’. The experiments examined varying doses and durations of UV-B exposure to assess their impact on plant growth, yield, and cannabinoid concentrations. Despite prior research suggesting potential benefits of UV-B in enhancing secondary metabolite production, the results revealed no significant effects on total cannabinoid content, plant growth metrics, or yield in either cultivar. The study indicates that the chemical profile of the cannabis plant does not substantially influence cannabinoid responses to UV radiation. These findings suggest that UV-B radiation, at the tested levels, does not enhance cannabinoid production in high-CBD and CBG cultivars. Future research could explore different light spectra or cultural management strategies to optimize cannabinoid production and consider UV-B's role in integrated pest management without adverse effects on plant health.

BIOGRAPHICAL SKETCH

Matthew Talan earned his Bachelor of Science in Agriculture and Food Systems, with a minor in Plant Science, from Rutgers University in 2022. After graduating, he joined Bowery Farming, a vertical farming company, where he worked in research and development. It was there that Matthew discovered his passion for research, leading him to pursue a Master of Professional Studies in Integrative Plant Science with a focus on Controlled Environment Agriculture at Cornell University.

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1. Introduction

Cannabis sativa L., a plant recognized for its versatile applications in producing medicinal products, biofuels, building materials, and textiles, stands out as a high-value crop with significant economic and environmental potential (Crini et al., 2020). The New York State Department of Health estimates the market size for adult-use cannabis in New York State is projected to be between $1.7 and $3.5 billion annually, while supporting approximately 30,700 jobs across the state (Schultz, 2019); highlighting the substantial economic benefits of cannabis legalization. While the broad applications and economic impact of cannabis underscores its importance as a high-value crop, indoor cultivation practices in greenhouse and warehouse farms play a critical role in maximizing its potential. Specifically, the flowering of cannabis plants is primarily influenced by photoperiod, where shorter days trigger the transition from vegetative to generative growth in this typically short-day plant, allowing growers to precisely control light (photoperiod, quantity, and spectrum) to optimize both yield and quality (Dowling et al., 2021). Cannabinoids, the primary active secondary metabolites in *Cannabis sativa L.*, are predominantly synthesized in the plant's glandular trichomes (Radwan et al., 2021). The controlled environments of indoor cultivation enable precise regulation of critical factors such as light intensity, temperature, and relative humidity, which are pivotal for cannabinoid biosynthesis (Rodriguez-Morrison et al., 2021a). Such precise environmental management not only ensures the consistent production of high-quality cannabis plants but also enhances the synthesis and stability of cannabinoids. The significant chemical diversity in cannabis, characterized by a wide range of cannabinoid and terpene profiles, necessitates the precise optimization of the compounds (Smith et al., 2022). By fine-tuning cannabinoids and tailoring terpene combinations, cultivators and manufacturers can create highly specialized products that optimize cannabinoid concentrations and profiles, thereby enhancing their applications for both medical and recreational purposes (Hazekamp et al., 2005).

Ultraviolet (UV) radiation is characterized as photon emissions with wavelengths ranging from 100 to 400 nm and can be categorized into three distinct regions: UV-A (315 to 400 nm), UV-B (280 to 315 nm), and UV-C (100 to 280 nm) (Sankari et al., 2017). While sunlight encompasses the complete range of UV radiation, UV-C is predominantly filtered by Earth's atmosphere. Of the sunlight that reaches the Earth's surface, UV-B photon flux density (PFD) accounts for roughly 0.37% of the midday photon flux density (PFD), and UV-A PFD represents approximately 8.5% of midday PFD (Caldwell et al., 1994; Kollias et al., 2011). Plants possess specialized UV photoreceptors, such as UVR8 for UV-B, that detect UV radiation and initiate protective photomorphogenic responses, including the enhanced production of flavonoids which serve as protective molecules against UV damage (Ferreyra et al., 2021; Jenkins, 2014; Tilbrook et al., 2013). This response is regulated by complex signaling pathways involving key molecules like reactive oxygen species (ROS) and ethylene, which integrate UV responses into the plant's overall defense mechanisms (Mackerness, 2000). UV-B and UV-A radiation have distinct effects on plants. UV-B primarily triggers the synthesis of protective secondary metabolites such as flavonoids and glucosinolates, enhancing plant defense against UV stress and herbivores (Czégény et al., 2016; Schreiner et al., 2012). In contrast, UV-A influences broader physiological processes, including photosynthesis and morphogenesis, impacting growth and development (Verdaguer et al., 2017). UV-C radiation has various effects on plants, depending on the dosage and plant species. It can induce stress responses that lead to enhanced production of secondary metabolites like amino acids and antioxidants, which may contribute to increased plant resilience and nutritional quality. However, excessive UV-C exposure can cause visible damage to plant tissues, such as leaf curling and reduced growth (Kobashigawa et al., 2011; Urban et al., 2016). Exposure to UV radiation also enhances the accumulation of medicinal compounds in plants (Zhang & Björn, 2009), highlighting its potential in optimizing the therapeutic properties of plant-derived products and its importance in agriculture and pharmaceutical applications. Recognizing the multifaceted effects of UV radiation on plants underlines its potential to enhance crop resilience and amplify the medicinal value of plants (Krizek, 2004); however, further research is essential to fully harness these benefits for optimizing plant health and productivity under diverse environmental conditions.

UV radiation has been studied for its impacts on yield and cannabinoid production in cannabis plants with mixed results. In an early study (Lydon et al., 1987), drug-type *Cannabis sativa L.* cultivars were exposed to various doses of supplemental UV-B radiation (Table 1.), resulting in no physiological or morphological changes but a significant increase in Δ9-tetrahydrocannabinol (Δ9-THC) concentrations up to 28% in the leaves and inflorescences of drug-type plants. This finding sparked considerable interest in the potential of supplemental UV radiation to enhance secondary metabolite production, prompting calls for more comprehensive research. (Rodriguez-Morrison et al., 2021b) investigated the effects of UV exposure in two indoor-grown cannabis cultivars using several doses of supplemental UV-B radiation (Table 1.). While UV exposure increased the severity of UV-induced morphological and physiological changes (i.e. thicker leaves, shorter stems, changes in leaf coloration), it did not enhance inflorescence yield or the concentration of cannabinoids like Δ9-THC and CBD in the plants. (Llewellyn et al., 2022) tested a high-THC cannabis cultivar under different doses of supplemental UV-A and UV-B radiation (Table 1.). No significant effect on the yield or cannabinoid content of the cannabis plants. In the most recent study (Westmoreland et al., 2023), a high-CBD cannabis cultivar was exposed to supplemental UV-B and UV-A under multiple durations and doses (Table 1). Minimal changes in cannabinoid concentrations and a slight decrease in inflorescence yield and photosynthetic efficiency (Fv/Fm) only at the highest UV treatment levels were observed. Despite multiple studies, the results regarding UV radiation's effects on cannabis yield and quality are inconclusive, emphasizing the variability in its impact based on duration, exposure, time, wavelengths, and cultivars on stress responses and secondary metabolite production without providing a definitive answer on its overall effectiveness. Modern cannabis genotypes now operate near their physiological limits for Δ9-THC production (Dujourdy & Besacier, 2017), reflecting targeted breeding strategies aimed at maximizing Δ9-THC content to cater to both recreational preferences and medical needs.

UV radiation has also been studied for use in controlling crop pests and diseases, which present a significant challenge in the indoor cultivation of cannabis. Insect pests such as spider mites, aphids, and whiteflies, can cause extensive damage by feeding on plant tissues, leading to stunted growth and reduced yield, which also increases plants' vulnerability to other stressors and diseases (Lemay & Scott-Dupree, 2022). Pathogenic infections from *Golovinomyces* (powdery mildew)*, Fusarium* (crown rot)*, Pythium* (root rot)*,* and *Botrytis* (gray mold, bud rot) can trigger a range of detrimental effects in indoor cannabis cultivation, severely impairing plant growth, compromising structural integrity, and diminishing yield, quality, and market value (Punja, 2021; Punja et al., 2019), thereby increasing the complexity and cost of management. As these biological threats continue to impact yield and quality, identifying and applying effective management strategies becomes essential for maintaining the viability and profitability of cannabis production. Optimized and effective management strategies for indoor cannabis cultivation emphasize the integration of advanced greenhouse technologies, such as controlled lighting systems and precision irrigation, alongside biological control agents like predatory mites and beneficial fungicides (Buirs & Punja, 2024). Specific attention to optimizing environmental conditions, including adjustable photoperiods and regulated humidity levels, coupled with enhancing plant resistance through selective breeding, naturally deters pests and pathogens (Lemay et al., 2022).

Table 1. Published values for the known parameters from UV treatment experiments on cannabinoid hemp (Lydon et al., 1987, Rodriguez-Morrison et al., 2021, Llewellyn et al., 2022, and Westmoreland et al., 2023). Exposure periods, distance of fixture from plant (m), waveband delivered, peak wavelength (nm), and instantaneous and daily integrated ultraviolet (UV, 280 – 300 nm) flux densities of treatments at canopy height weighted using the Biological Spectral Weighting Function (BSWF) by ((Flint & Caldwell, 2003); the UV dose reported in (Lydon et al., 1987) was weighted using a previous version of the BSWF, which only incorporated UV wavelengths between ≈ 275 and 315 nm.

Parameter	Units	Lydon et al., 1987	Rodriguez-Morrison et al., 2021	Llewellyn et al., 2022		Westmoreland et al., 2023		
UV Treatment Period	Days	40	60	45	20	≈ 35		
Daily UV Exposure Time	Hours	6	3.5	12	5	1	2.5	5
Photoperiod Timing		Centered on solar noon	End of Day	Full Day	End of Day	Midday		
Distance from Plant	m	0.25, 0.35	0.505	0.9	0.9	Canopy Height		
Waveband Delivered		UV–B	UV-B	UV-A	UV-A + UV-B	UV-A + UV-B		
Peak Wavelength	nm	NS	287	385	ca. 318	ca. 290		
Instantaneous UV PFD [y]	µmol·m^{-2}·s^{-1}	NS	0.032 [z], 0.32 [z], 1.6 [z], 2.6 [z]	0.67 [z]	1.6 [z]	5.6	5.6	6.1
Daily UV PFD [y]	mmol·m^{-2}·d^{-1}	NS	0.403, 4.03, 20.2, 32.8	28.9	28.8	20 [z]	50 [z]	110 [z]
Instantaneous UV Energy Flux	KJ·m^{-2}·s^{-1}	310.2, 620.4	12.7, 126.9, 634.9, 1031.7	210.6	555.6	2833.3	2377.8	2538.9
Daily UV Energy Flux	KJ·m^{-2}·d^{-1}	6.7 [z], 13.4 [z]	0.16 [z], 1.6 [z], 8.0 [z], 13 [z]	9.1 [z]	10 [z]	10.2 [z]	21.4 [z]	45.7

[z] Units originally reported in the publication data.
[y] Photon Flux Density
NS = Not Specified

Exploring strategies that employ UV radiation offers a promising avenue for controlling pest infestations and disease across a variety of plant species. This approach is particularly effective against powdery mildew pathogens such as *Podosphaera pannosa* and *Golovinomyces cichoracearum*. In a study investigating rose (*Rosa rubiginosa*) powdery mildew (Kobayashi et al., 2014), the use of supplemental UV-B radiation effectively suppressed the development of powdery mildew. Low levels of UV-B radiation (Table 2.) applied during the night proved more effective than daytime applications, leading to the inhibition of fungal conidial germination and the activation of plant defense. In a similar study (Suthaparan et al., 2016), doses of supplemental UV-B radiation (Table 2.) applied in various frequencies effectively reduced powdery mildew severity by 90 to 99% in strawberry (*Fragaria ananassa*) and rosemary (*Rosmarinus*) plants, demonstrating that a cumulative dose, rather than the frequency of the application, was critical in achieving significant disease suppression. In a study centered on managing powdery mildew in cannabis (Scott & Punja, 2021), daily exposure to supplemental UV-C radiation (Table 2.) significantly reduced disease development by 45.2%, emphasizing its potential as an effective non-chemical treatment option for controlling fungal infections. Although research has demonstrated the efficacy of supplemental UV radiation as a component of integrative pest management (IPM), additional investigation is required to understand how this radiation source affects plant growth and phototoxicity.

Table 2. Published values for the known parameters from Kobayashi et al., 2014, Suthaparan et al., 2016, and Scott & Punja, 2021. Method of exposure, exposure periods, waveband delivered, peak wavelength (nm), and raw instantaneous and daily integrated ultraviolet (UV, 280 – 300 nm). Original UV doses from Suthaparan et al., 2016 and Scott & Punja, 2021 were converted to photon and energy flux units, which are more acceptable in photobiology research (Flint & Caldwell, 2003).

Parameter	Unit	Kobayashi et al., 2014			Suthaparan et al., 2016						Scott & Punja, 2021
Method of Exposure		Fluorescent Lamp			Automated Boom						Hand-Held CleanLight^{TM} Pro
Frequency of Exposure		3:00am – 5:00am	10:30am – 2:30pm	10:30am – 2:30pm	Every 3 nights	Every night	3x per night	Every 3 nights	Every night	3x per night	Daily
Exposure Length	Hr / Min / Sec	2 hours	4 hours	6 hours	18 min.	6 min.	2 min.	9 min.	3 min.	1 min.	3 – 5 seconds
Photoperiod UV Timing		Night	Day	Day	Night (immediately after dark, followed by darkness)						Day
Waveband Delivered		UV-B			UV-B						UV-C
Peak Wavelength	nm	312			NS						NS
Instantaneous UV Energy Flux	KJ·m^{-2}·d^{-1}	138.9 – 277.8	277.8 – 555.6	416.7 – 833.3	80	80	80	80	80	80	3.861 – 77.167
Daily UV Energy Flux	KJ·m^{-2}·d^{-1}	0.5 - 1.0^{z}	1.0 – 2.0^{z}	1.5 – 3.0^{z}	0.288	0.288	0.288	0.288	0.288	0.288	0.0139 - 0.2778

^{z} Units originally reported in the publication data.
^{y} Photon Flux Density
NS = Not Specified

While previous work has examined he effect of UVB radiation on cannabinoid hemp, more information is needed to understand the impact of intensity and duration of dosage on CBD and CBG cultivars. The objective of this study was to determine the effects of increasing doses and durations of supplemental UV radiation on yield and cannabinoid concentration in two high-cannabinoid hemp cultivars (Chemotype III). This information can also guide future research on the dosage and duration of UV exposure to optimize its effects on plants for IPM studies.

2. Methods

2.1. Experiment 1: Dosage

2.1.1 Plant Culture

Eighty clonal cuttings were taken from stock plants of indoor-grown high cannabinoid hemp cultivars (Chemotype III): cannabidiol (CBD) dominant ‘TJs CBD’ (TJ’s Gardens, Eugene, Oregon, USA) and cannabigerol (CBG) dominant ‘Janets G’ (The Hemp Mine, Fair Play, South Carolina, USA). Cuttings were dipped in an auxin rooting hormone (CloneX Rooting GEL, Hydrodynamics International, Lansing, Michigan, USA) and then rooted for three weeks in an aeroponic cloner (Clone King LLC, Albuquerque, New Mexico, USA) located inside a greenhouse. During the rooting phase, clones were maintained under a vegetative photoperiod (18/6-hour light/dark), provided by 660-watt high-pressure sodium lamps (P.L. Light Systems, Hamilton, Ontario, Canada), which delivered a photosynthetic photon flux density (PPFD, 400 to 700 nm) of ≈ 300 µmol·m^2·s^1 of supplemental lighting at the canopy level. Within the greenhouse, daytime and nighttime temperatures averaged (mean ± SD) 21.5 ± 1.0°C and 18.4 ± 0.3°C, respectively. Environmental conditions were maintained and monitored using an Argus environmental control system (Argus Controls, Surrey, British Columbia, Canada). Supplemental CO^2 was not provided during this trial. The aeroponic reservoir contained municipal tap water with a dilute fertilizer, 37.5 mg·L^1 nitrogen from 21N–2.2P–16.6 K (Jack's Professional LX™ Water Soluble Fertilizer 21-5-20 All-Purpose; JR Peter's Inc., Allentown, Pennsylvania, USA) with 7.5 mg·L^1 magnesium added from MgSO4·7H2O. Rooted cuttings were then transplanted to 7.5 L pots containing a peat-based potting mix (Lambert LM - 111 All Purpose Mix, Lambert, Québec City, Canada). Subsequently, 15 ‘Janets G’ and 15 ‘TJs CBD’ plants were transferred to a controlled environment chamber (3.7 m x 2.4 m x 2.1 m) set to a generative photoperiod (12/12-hour light/dark), where they were grown for six weeks. Full-spectrum LED QB288 V2 Rspec quantum boards (Horticultural Lighting Group, Westerville, Ohio, USA) delivered a PPFD of ≈ 425 µmol·m^2·s^1 at the canopy level, as measured with a LI-190R Quantum Sensor (LI-COR, Lincoln, Nebraska, USA). Daytime temperatures and relative humidity (RH) in the controlled environment chamber averaged (mean ± standard deviation) 24.4 ± 0.7°C and 42.2 ± 9.1%, respectively, while nighttime temperatures and RH measured 23.6 ± 0.7°C and 39.3 ± 8.6%, respectively. Plants were irrigated daily with a two-part nutrient solution where part A consisted of 1001.2 mg·L^1 of Jack's 5N-12P2O5-26K2O (JR Peter's Inc., Allentown, Pennsylvania, USA) and 261.5 mg·L^1 of magnesium-sulfate (Giles Chemical Industries Inc., Waynesville, North Carolina, USA). Part B consisted of 665.7 mg·L^1 of calcium-nitrate (Yara International ASA, Oslo, Norway). The solution was kept at an electrical conductivity (EC) of 2.0 dS·m^1 and pH of 5.5 to 5.8. After six weeks of generative growth, the 12 most uniform plants of each cultivar were selected and UV treatments were conducted (as described below) for an additional two weeks under the generative photoperiod.

2.1.2 Experimental Setup

This experiment was conducted at the Kenneth Post Laboratory (Cornell University, Ithaca, New York, USA). Four compartments (1.8 m x 2.4 m x 2.1 m) were constructed across two controlled environment chambers. These compartments were separated by "panda film" (Vivosun, Ontario, California, USA) with the black side facing inward in order to eliminate external light contamination. Each compartment contained a bench (2.4 m x 0.9 m), accommodating six plants —3 'Janets G' and 3 'TJs CBD'— spaced at a density of 0.36 m^2 per plant. UV exposure in each compartment was provided by two UVB-313EL fluorescent bulbs (Q-PANEL Lab Products, Cleveland, Ohio, USA), delivering an instantaneous UV-B (280 to 315 nm) PFD of 4.32 W/m^2 and UV-A (315 to 400 nm) PFD of 2.84 W/m^2, for a total UV PFD of 7.29 W/m^2 at the canopy level. Spectral measurements were conducted using a BTS2048-UV-S spectroradiometer (Gigahertz-Optik, Munich, Germany) before and after each replication. The experimental design is depicted in (Figure 1.). Treatments commenced six weeks following flower induction and persisted for an additional two weeks until harvest. During the final two weeks of generative growth, UV radiation was applied in the middle of the photoperiod for 0 (control), 15, 30, and 60 minutes resulting in UV dosage treatments of 0 (control), 6.3 (low), 12.6 (medium), and 25.2 (high) KJ·m^{-2}·d^{-1}, respectively. In Table 3., we detailed the treatments as instantaneous and daily integrated UV energy flux densities at the canopy level, based on both raw intensities and values converted using the Biological Spectral Weighting Function (BSWF;

(Flint & Caldwell, 2003). Treatments were provided for three replicate crop cycles with lighting treatment locations randomized before each cycle.

Table 3. Experimental treatments for experiment one (dosage). Time (minutes), dose (KJ·m2·d1), and weighted dose (KJ·m2·d1). Weighting factors from (Flint & Caldwell, 2003) normalized at 300 nm were used to calculate the daily biologically effective UV energy flux$_{(B)}$ (KJ·m^{2}·d^{1}).

Time (minutes)	Daily UV Energy Flux (KJ·m^{-2}·d^{-1})	Daily UV Energy Flux$_{(B)}$ (KJ·m^{-2}·d^{-1})
0	0	0
15	6.3	3.69
30	12.6	7.38
60	25.2	14.75

2.1.3 Yield and Quality Measurements

Plants were harvested 56 days (8 weeks) after the initiation of generative growth for each of three replicate crop cycles. Prior to harvest, plant height (i.e., length of the main stem from the surface of the media to the top of the main stem) was measured in centimeters (cm). To reduce any harvest time effects on fresh biomass, the LEDs were turned off and plants were harvested at random. Apical meristem samples were collected, weighed in grams (g), and set aside for cannabinoid analysis. For each replicate plant, stems were cut at the level of the growing medium, and the plants were manually separated into inflorescence, leaves, and stems. Fresh weight (*FW*) for the inflorescence, leaves, and stems were recorded in grams (g). Once harvested, all fresh biomass was placed into paper bags and returned to the controlled environment chamber with the lights turned off. A 34-pint dehumidifier (Waykar Inc, Gaffney, South Carolina, USA) set to ≈ 30% was positioned inside the controlled environment chamber, accompanied by a fan operating on high, to dry the plants over a two-week period. After two weeks, dry weight (DW) was recorded in grams (g). Inflorescence (DW_f) and non-floral aboveground (DW_{nf}) tissue weights were utilized to calculate the harvest index [$DW_f / (DW_f \text{ x } DW_{nf})$], which determines the ratio of total inflorescence dry weight (DW_f) to the total aboveground dry weight (DW) . Fresh weight (FW) and dry weight (DW) were used to calculate moisture content [$(FW - DW) / FW \text{ x } 100\%$]. Apical meristem samples were ground to ≈ 100 mg of dried inflorescence tissue and mixed with 10 mL of high-performance liquid chromatography

(HPLC) grade methanol for 10 minutes using a VWR Vortexer 2 (VWR International, Radnor, Pennsylvania, USA) at room temperature. Samples were diluted 20-fold with methanol and filtered using a Captiva 0.45 µm regenerated cellulose filter. Samples were then analyzed using an Agilent 1220 Infinity II LC system (Agilent Technologies Inc., Santa Clara, California, USA) using an Agilent Poroshell 120 2.7 µm column (3 × 50 mm, Agilent Technologies Inc., Santa Clara, California, USA). Column temperature was 50 °C throughout the run beginning with an isocratic 1 mL/min -1 ratio of 60:40 methanol + 0.05% formic acid to ultrapure water + 0.1% formic acid for the first minute. This was followed by a six-minute gradient to 77% methanol, followed by an additional 90-second gradient to 95% methanol. UV absorbance was measured at 230 nm. Calibration standards were used for quantification in the range of 1–250 µg mL -1 and included THCA, THC, CBDA, CBD, CBGA, CBG, and CBC (Agilent Technologies Inc., Santa Clara, California, USA). Total potential cannabinoids were calculated by summing the neutral and acidic forms and accounting for decarboxylation by multiplying THCA and CBDA by 0.877 and CBGA by 0.878. Total cannabinoids were measured on a dry-weight basis and analyzed as a percentage. Additionally, we calculated the ratio of total potential CBD and total potential CBG to total potential THC. Last, we calculated the ratio of acidic cannabinoids to neutral cannabinoids to evaluate variation in vivo decarboxylation rates.

2.1.4 Statistical Analysis

All statistical analyses were performed using R version 3.4.4 (R Foundation for Statistical Computing, Vienna, Austria). This study used a completely randomized design using four UV radiation treatments per replicate crop cycle randomly arranged within two controlled environment chambers. The experiment was conducted over three replicated crop cycles. Within each replicate crop cycle, there were three replicated plants per treatment for each of the two cultivars. We employed a one-way analysis of variance (ANOVA) to assess the effects of UV radiation treatments on several harvest and post-harvest parameters across both cultivars. UV radiation treatments were treated as categorical predictor variables and total fresh weight, total dry weight, inflorescence fresh and dry weights, non-floral aboveground biomass (fresh and dry), moisture content, and harvest index were treated as continuous response variables. After conducting the ANOVA, we performed a Tukey's Honestly Significant Difference (Tukey HSD) test to pinpoint specific differences between treatment means. The Tukey HSD test methodically conducts pairwise comparisons across all treatment means, effectively controlling the family-wise error rate to ensure the reliability of our multiple comparisons. Cannabinoid data were analyzed using a linear mixed-effects model (LME) to evaluate the impact of UV radiation treatments on both total and individual cannabinoid concentrations. In this model, UV radiation treatments were treated as fixed effects, while each replicate plant was treated as a random effect to manage variability across experimental trials. After fitting the model, an ANOVA was conducted to determine the statistical significance of the treatment effects. Here, UV radiation treatments were categorized as predictor variables and cannabinoid concentrations were considered continuous response variables. Upon detecting significant effects, further analysis was undertaken using the estimated marginal means (EMM) method. This step included conducting pairwise comparisons with a Tukey HSD test to pinpoint specific differences among treatment levels. Effects were considered significant at $a = 0.05$.

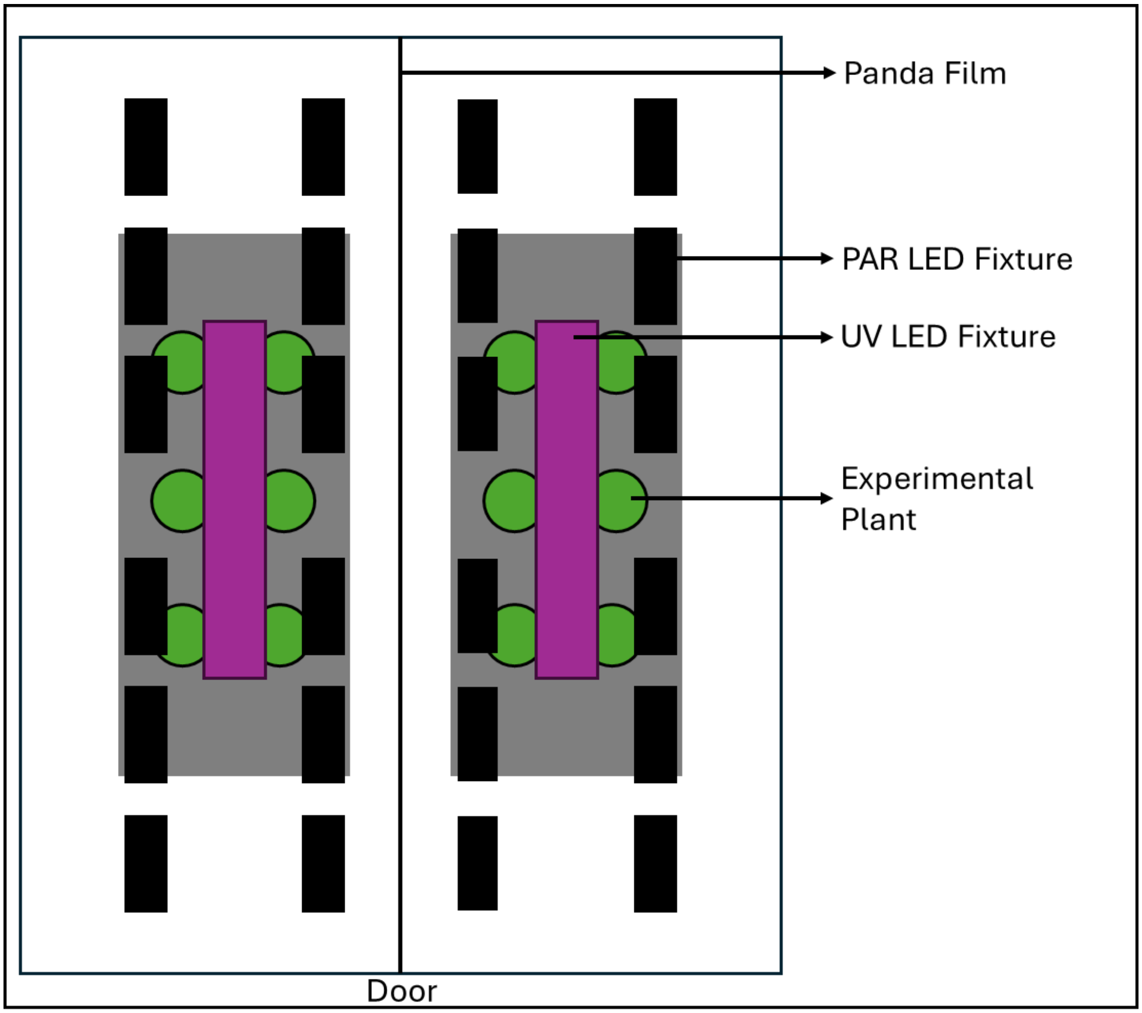

Figure 1. Schematic of the experiment one design featuring 24 PAR LED fixtures (shown in black) positioned above 2 UV LED fixtures (shown in purple). Compartments were divided using Panda Film. This design was replicated across two controlled environment chambers.

2.2 Experiment 2: Duration

2.2.1 Plant Culture

Experiment two employed the same general methods as experiment one, with some modifications noted below. Once cuttings were rooted, they were transplanted to 3.78 L pots containing Lambert LM - 111 All Purpose Mix (Lambert, Québec City, Canada). Subsequently, 15 'Janets G' and 15 'TJs CBD' plants were transferred into a controlled environment chamber (3.7 m x 2.4 m x 2.1 m) set to a vegetative photoperiod (18/6-hour light/dark) for one week. After one week of vegetative growth, the most uniform 12 plants of each cultivar were selected. The photoperiod was then switched to a generative photoperiod (12/12-hour light/dark) for an additional seven weeks, marking the commencement of UV radiation treatments.

2.2.2 Experimental Setup

Four compartments (1.8 m x 1.2 m x 2.1 m) were constructed within one controlled environment chamber. These compartments were separated by “panda film” (Vivosun, Ontario, California, USA) with the black side facing inward in order to eliminate external light contamination. Each compartment contained a bench (1.2 m x 0.9 m), accommodating six plants, 3 ‘Janets G’ and 3 ‘TJs CBD’, spaced at a density of 0.18 m^2 per plant. UV radiation in experiment two (duration) was supplied similarly to experiment one (dosage), using two UVB-313EL fluorescent bulbs (Q-PANEL Lab Products, Cleveland, Ohio, USA), which emitted specific levels of UV-B (280 to 315 nm) and UV-A (315 to 400 nm) photosynthetic photon flux density (PFD) at the canopy level. The consistency of UV exposure was confirmed by spectral measurements taken before and after each experimental replication using a BTS2048-UV-S spectroradiometer (Gigahertz-Optik, Munich, Germany). The experimental design for the duration experiment is depicted in (Figure 2.). For the treatments, plants received 25 $KJ \cdot m^{-2} \cdot d^{-1}$ of UV radiation daily for 60 minutes during the middle of the photoperiod, spanning various durations of the generative cycle. In our longest treatment, UV radiation exposure extended the entire seven-week generative cycle. The one and three-week treatments were applied at the latter stages of the generative cycle (i.e. the last one or three weeks prior to harvest, respectively). In Table 4., we detailed the treatments as instantaneous and daily integrated UV energy flux densities at the canopy level, based on both raw intensities and values converted using the Biological Spectral Weighting Function (BSWF; (Flint & Caldwell, 2003).

Table 4. Experimental treatments for experiment one (dosage). Time (minutes), duration (weeks), dose (KJ·m2·d1), and weighted dose (KJ·m2·d1). Weighting factors from (Flint & Caldwell, 2003) normalized at 300 nm were used to calculate the daily biologically effective UV energy flux$_{(B)}$ ($KJ \cdot m^2 \cdot d^1$).

Time (minutes)	Duration (weeks)	Daily UV Energy Flux ($KJ \cdot m^{-2} \cdot d^{-1}$)
0	0	0
60	1	25
60	3	25
60	7	25

2.2.3 Growth, Yield, and Quality Measurements

Growth measurements were conducted weekly, beginning with the first week of generative growth. Plant height (i.e., length of the main stem from the surface of the media to the top of the main stem) and widths (i.e., maximum width of the plant and its perpendicular width) were recorded in centimeters (cm) for each replicate plant. Plant height and widths were utilized to calculate the growth index [$(height\ x\ width_1\ x\ width_2)/300$] (Ruter, 1992) for each plant, where $width_1$ represents the maximum width of the plant and $width_2$ represents the width directly perpendicular to $width_1$. Weekly measurements of the foliar chlorophyll content index were carried out using a SPAD – 502 Plus Chlorophyll Index Meter (Konica Minolta, Tokyo, Japan). Chlorophyll content index measurements were recorded three times from the newest, fully developed leaf and an average was then calculated. Weekly leaf area measurements were also performed on the same leaf. Leaf length (*LL*) and width (*LW*), measured in centimeters (cm), were used to calculate leaf area [LL x $LW = cm^2$]. Plants were harvested 49 days (7 weeks) after the initiation of generative growth for each replicate crop cycle. At harvest, to reduce any harvest time effects on fresh biomass, the LEDs were turned off and plants were harvested at random. For each replicate plant, the number of branching pairs (*BP*) were counted and stem diameter (*SD*) was measured in centimeters (cm). Subsequently, plant stems were cut at the level of the growing medium, and fresh weight (*FW*) was recorded in grams (g). Apical meristem samples were measured in centimeters (cm), weighed in grams (g), and set aside for cannabinoid analysis. After harvesting, all plants underwent the same drying process as described in experiment one (dosage). After two weeks, the plants were manually divided into inflorescence (DW_f) and non-floral aboveground (DW_{nf}) tissue, and dry weight (*DW*) was recorded in grams (g). Inflorescence and non-floral aboveground tissue weights were utilized to calculate the harvest index [DW_f /(DW_f x DW_{nf})], which determines the ratio of total inflorescence dry weight (DW_f) to the total aboveground dry weight (*DW*) on a per-plant basis. Fresh weight (*FW*) and dry weight (*DW*) were used to calculate moisture content [$(FW - DW) / FW\ x\ 100\%$]. Cannabinoid sample preparation and analysis were conducted using the same methods and materials outlined in experiment one (dosage).

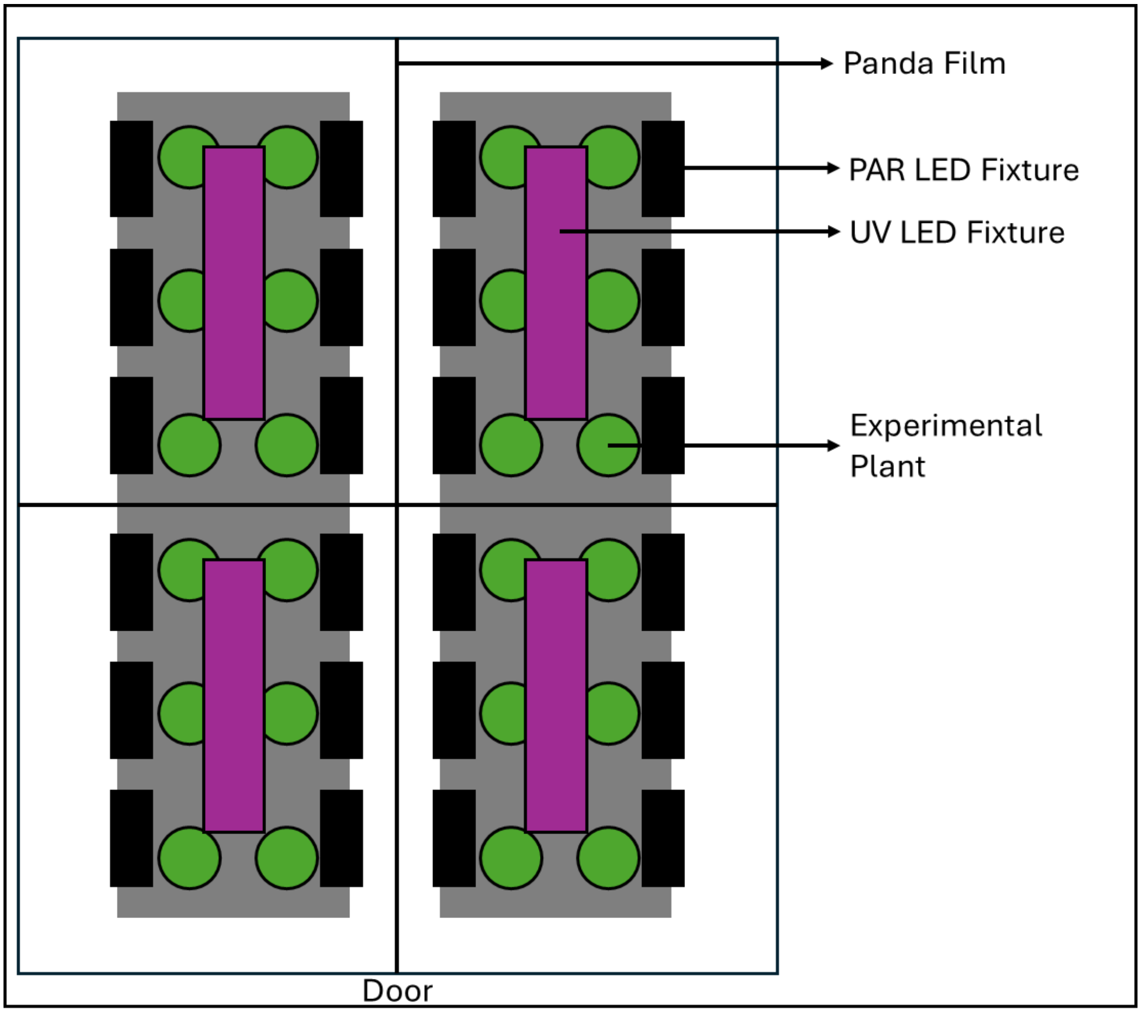

Figure 2. Schematic of experiment 2 design featuring 24 PAR LED fixtures (shown in black) positioned above 4 UV LED fixtures (shown in purple). Compartments were divided using Panda Film.

2.2.4 Statistical Analysis

Experiment two utilized the same fundamental analytical approach as experiment one but incorporated specific modifications detailed below. Growth and physiological measurements recorded throughout the generative growth cycle were analyzed utilizing a linear mixed-effects model (LME) to evaluate the impact of UV radiation treatments on chlorophyll index, growth index, leaf area, and plant height over time. The model was structured to assess the interaction between treatment and the weeks during which they were applied while accounting for individual plant variability. Subsequently, an ANOVA was performed to determine the statistical significance of the main effects and interactions within the model. This test helps in identifying which factors and interactions are statistically meaningful, guiding further in-depth analyses.

Upon detecting significant effects from the LME, further analysis was conducted using the estimated marginal means (EMM) method. This approach calculated the marginal means for each treatment within each week, allowing us to systematically examine how response variables varied according to the treatment across the time points measured. Following the estimation of marginal means, pairwise comparisons were conducted across all treatment levels using the Tukey HSD test to identify specific differences among treatment groups. Effects were considered significant at *a* = 0.05.

3. *Results*

3.1 Experiment 1: Dosage

3.1.1 Yield

UV radiation dosage applied during the last two weeks of the generative stage had no significant effect on total dry weight (g) for both ‘Janets G’ (p = 0.65) and ‘TJs CBD’ (p = 0.98) (Table 5). Subsequent *post-hoc* analysis revealed no significant differences in total dry weight across UV treatments. Similarly, UV radiation treatments had no significant impact on inflorescence dry weights (g) of ‘Janets G’ (p = 0.82) and ‘TJs CBD’ (p = 0.99). *Post-hoc* analysis also indicated no significant differences in inflorescence yield across UV treatments. The harvest index (HI; the ratio of inflorescence to total yield) was not significantly affected by UV treatments in 'Janets G' (p = 0.21) and 'TJs CBD' (p = 0.95). Moisture content in ‘Janets G’ (p = 0.51) and ‘TJs CBD’ (p = 0.93) was also not significantly impacted by radiation treatments.

3.1.2 Cannabinoids

UV radiation treatments had no significant effect on the total cannabinoid content in ‘Janets G’ (p = 0.15) and ‘TJs CBD’ (p = 0.24) (Table 6). Total cannabigerol (CBD) content in ‘TJs CBD’ (p = 0.13) was not significantly impacted by UV radiation treatments. Similarly, total cannabigerol (CBG) content in ‘Janets G’ was unaffected by UV treatments (p = 0.17). UV radiation treatments did not significantly affect total THC content for both ‘Janets G’ (p = 0.16) and ‘TJs CBD’ (p = 0.33). UV radiation treatments did not significantly affect the ratios of acidic to neutral cannabinoid forms (p = 0.68).

Table 5. Harvest parameters for experiment one (dosage) including inflorescence fresh weight (FW$_f$), non-floral aboveground biomass fresh weight (FW$_{nf}$), inflorescence dry weight (DW$_f$), non-floral aboveground biomass dry weight (DW$_{nf}$), and harvest index (HI) for the cultivars 'Janets G' and TJs CBD' exposed to varying intensities of ultraviolet radiation. Harvest index was calculated using the formula: $HI = DW_f/(DW_f + DW_{nf})$. The data presented are means ± standard error (SE).

Biomass Parameter	Cultivar	Treatment				Significance
		0 KJ·m^{-2}·d^{-1}	6.3 KJ·m^{-2}·d^{-1}	12.6 KJ·m^{-2}·d^{-1}	25.2 KJ·m^{-2}·d^{-1}	
FW$_f$ (g)	Janets G	66.0 ± 11.5	64.1 ± 8.4	65.7 ± 10.1	54.7 ± 5.2	NS
	TJs CBD	109.2 ± 29.6	104.8 ± 25.2	103.7 ± 23.8	114.8 ± 25.3	NS
FW$_{nf}$ (g)	Janets G	32.7 ± 7.8	29.4 ± 6.9	37.6 ± 8.2	24.6 ± 3.1	NS
	TJs CBD	40.2 ± 11.0	40.2 ± 11.0	40.4 ± 9.5	46.4 ± 11.2	NS
DW$_f$ (g)	Janets G	12.5 ± 1.6	12.3 ± 1.2	12.9 ± 1.5	11.2 ± 1.0	NS
	TJs CBD	18.3 ± 3.4	17.8 ± 3.0	18.4 ± 3.0	19.2 ± 3.5	NS
DW$_{nf}$ (g)	Janets G	9.3 ± 1.9	8.8 ± 1.4	11.0 ± 2.0	7.7 ± 0.9	NS
	TJs CBD	12.1 ± 2.2	12.0 ± 2.2	12.2 ± 1.9	13.1 ± 2.5	NS
HI	Janets G	0.60 ± 0.02	0.60 ± 0.02	0.56 ± 0.02	0.60 ± 0.01	NS
	TJs CBD	0.61 ± 0.01	0.60 ± 0.01	0.60 ± 0.01	0.60 ± 0.01	NS

NS = Not Significant
* = Significant

Table 6. Per-plant cannabinoid percentages for experiment one (dosage) by weight (g) including cannabidiolic acid (CBDA), cannabidiol (CBD), cannabigerolic acid (CBGA), cannabigerol (CBG), tetrahydrocannabinolic acid (THCA), and cannabichromene (CBC) for the cultivars 'Janets G' and TJs CBD' exposed to varying intensities of ultraviolet radiation. The data presented are means ± standard error (SE).

Cannabinoid Parameter	Cultivar	Treatment				Significance
		0 KJ·m^{-2}·d^{-1}	6.3 KJ·m^{-2}·d^{-1}	12.6 KJ·m^{-2}·d^{-1}	25.2 KJ·m^{-2}·d^{-1}	
CBDA %	Janets G	0.0 ± 0.0	0.01 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	NS
	TJs CBD	12.40 ± 0.63	11.07 ± 0.97	12.94 ± 0.44	13.47 ± 0.81	NS
CBD %	Janets G	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	NS
	TJs CBD	0.30 ± 0.02	0.26 ± 0.03	0.29 ± 0.01	0.28 ± 0.02	NS
CBGA %	Janets G	5.62 ± 0.50	4.63 ± 0.38	5.69 ± 0.51	4.84 ± 0.43	NS
	TJs CBD	0.46 ± 0.03	0.36 ± 0.04	0.46 ± 0.04	0.46 ± 0.04	NS
CBG %	Janets G	0.12 ± 0.02	0.11 ± 0.01	0.13 ± 0.01	0.11 ± 0.02	NS
	TJs CBD	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	NS
THCA%	Janets G	0.13 ± 0.01	0.10 ± 0.01	0.12 ± 0.02	0.11 ± 0.01	NS
	TJs CBD	0.56 ± 0.03	0.49 ± 0.05	0.58 ± 0.02	0.60 ± 0.04	NS
CBC %	Janets G	0.007 ± 0.002	0.005 ± 0.002	0.007 ± 0.001	0.004 ± 0.001	NS
	TJs CBD	0.003 ± 0.001	0.003 ± 0.001	0.002 ± 0.001	0.002 ± 0.001	NS

NS = Not Significant
* = Significant

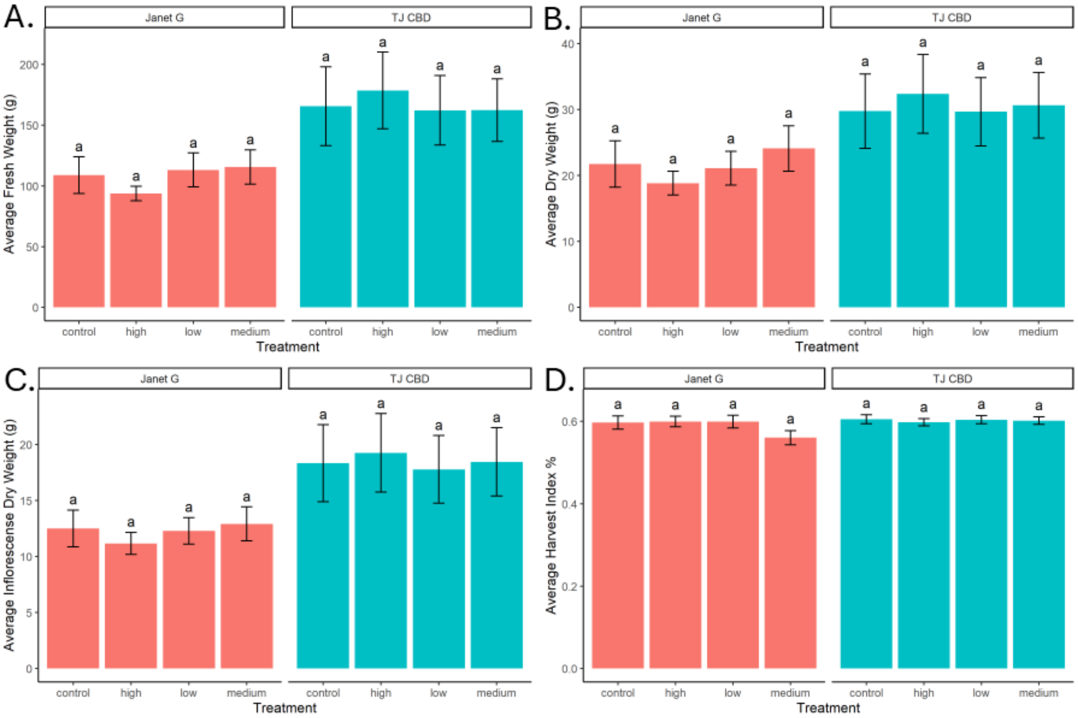

Figure 3. Harvest parameters for cultivars ‘Janets G’ and ‘TJs CBD; from experiment one (dosage), showcasing: **(A)** Average fresh weight (g), **(B)** Average dry weight (g), **(C)** Average inflorescence dry weight (g), **(D)** Average harvest index (the ratio of inflorescence to total yield). The data presented are means ± standard error (SE).

3.2 Experiment 2: Duration

3.2.1 Growth

UV radiation did not significantly affect the growth index [height x width1 x width2)/300] for the cultivar 'Janets G' (p = 0.99) (Table 7). However, a notable impact on the growth index was observed for the cultivar 'TJs CBD' (p = 0.04). Despite this, in the third replicate crop cycle, five 'TJs CBD' plants in the treatment groups: control (one plant), 1-week (three plants), and 7-week (one plant) exhibited abnormally tall growth due to unexplained factors. If the 3rd crop cycle is excluded from the statistical analysis, the p-value becomes 0.27. UV radiation had no significant impact on plant height over time (cm) for both Janets G’ (p = 0.99) and ‘TJs CBD’ (0.63). The foliar chlorophyll content index measurements from the newest, fully developed leaves showed no statistically significant difference resulting from durations of UV radiation treatments for ‘Janets G’ (p = 0.51) and ‘TJs CBD’ (p = 0.45). Leaf area measurements (cm^2) taken from the same newly developed leaves revealed no statistically significant differences for 'Janets G' (p = 0.71). Although UV radiation treatments initially showed significant differences for 'TJs CBD' (p = 0.03), further *post-hoc* analysis indicated no significant differences in leaf area across the various UV treatments. Apical length (cm) was not significantly affected by UV radiation treatments for 'Janets G' (p = 0.20) or 'TJs CBD' (p = 0.19). Subsequent *post-hoc* analysis revealed no significant differences in apical length across UV treatments (Figure 5.). Branching pairs counted at harvest were also unaffected by UV radiation treatments in ‘Janets G’ (p = 0.35) and ‘TJs CBD’ (p = 0.14). Stem diameter (cm), measured at harvest, showed no significant changes in response to UV radiation treatments for 'Janets G' (p = 0.90) and 'TJs CBD' (p = 0.31).

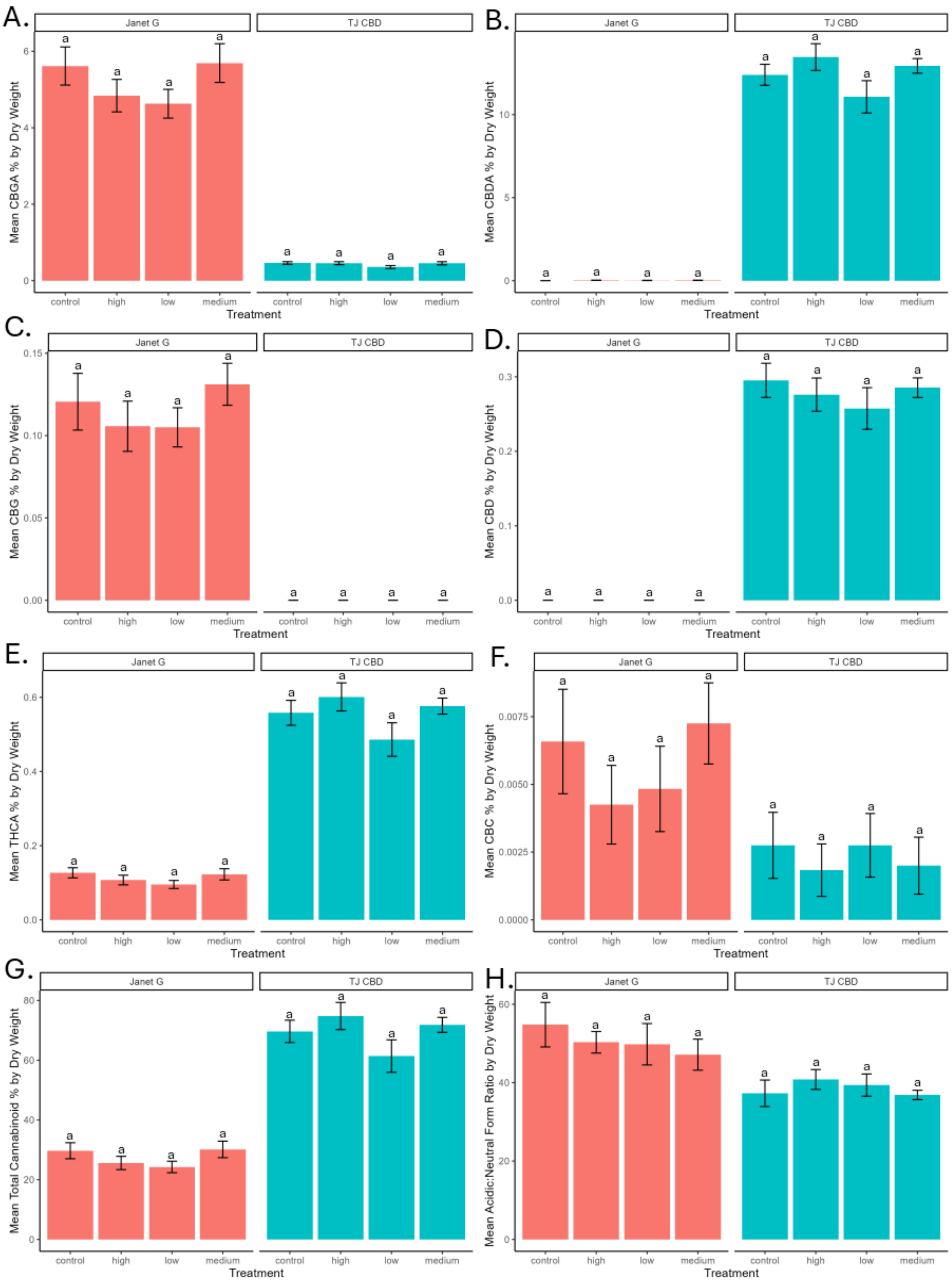

Figure 4. Per-plant cannabinoid percentages by weight (g) for cultivars 'Janets G' and TJs CBD' from experiment one (dosage), including **(A)** Cannabigerolic Acid (CBGA), **(B)** Cannabidiolic Acid (CBDA), **(C)** Cannabigerol (CBG), **(D)** Cannabidiol (CBD), **(E)** Tetrahydrocannabinolic Acid (THCA), **(F)** Cannabichromene (CBC, **(G)** total cannabinoid percentage, and **(H)** mean ratios of acidic to neutral cannabinoid forms. The data presented are means ± standard error (SE).

3.2.2 Yield

Duration of UV radiation treatments did not significantly affect total yields in either cultivar (Table 7.). Specifically, total fresh weight (g) remained unchanged by UV treatments for both 'Janets G' (p = 0.97) and 'TJs CBD' (p = 0.85). Further *post-hoc* analysis confirmed no significant differences in total fresh weight among the UV treatment groups. Duration of UV treatments had no significant effect on the total dry weights (g) of either 'Janets G' (p = 0.96) or 'TJs CBD' (p = 0.81). UV radiation treatments similarly had no significant impact on inflorescence yields (g) for both 'Janets G' (p = 0.91) and 'TJs CBD' (p = 0.82). The harvest index (HI; the ratio of inflorescence to total yield) was not significantly impacted by UV treatments in 'Janets G' (p = 0.53). For control plants, the HI stood at 50.3 ± 1.7 %, and for the 7-week treatment group, it was slightly higher at 50.6 ± 1.9 %. However, HI in 'TJ CBD' was significantly affected by UV treatment durations (p = 0.02). Post-hoc analysis identified significant differences in HI between the 3-week and 7-week treatment groups (p = 0.03). Specifically, the HI was 53.7 ± 0.01 % for the 3-week treatment group, while it was significantly lower at 47.6 ± 0.02 % for the 7-week treatment group. Moisture content in ‘Janets G’ (p = 0.43) and ‘TJs CBD’ (p = 0.10) was not significantly impacted by UV treatments. Moisture content across all treatment groups averaged 77.9 ± 0.3 % per plant for both cultivars.

3.2.3 Cannabinoids

Duration of UV radiation treatments had no significant effect on the total cannabinoid content in ‘Janets G’ (p = 0.35) and ‘TJs CBD’ (p = 0.93) (Table 8). Total CBD content in ‘TJs CBD’ (p = 0.97) was not significantly impacted by UV radiation treatments. Similarly, total CBG content in ‘Janets G’ was unaffected by UV treatments (p = 0.51). UV radiation treatments did not significantly affect total THC content for both 'Janets G' (p = 0.13) and 'TJs CBD' (p = 0.97). UV radiation treatments did not significantly affect the ratios of acidic to neutral cannabinoid forms (p = 0.41).

Figure 5. Apical meristems of cultivars **(A)** 'Janets G' and **(B)** 'TJs CBD', showcasing the effects of control, 1-week, 3-week, and 7-week treatments in Experiment Two (duration).

Table 7. Harvest measurements for experiment two (duration) including total fresh weight (FW), total dry weight (DW), inflorescence dry weight (DW_f), non-floral aboveground biomass dry weight (DW_{nf}), harvest index (HI), apical length, branching pairs, and stem diameter for the cultivars ‘Janets G’ and TJs CBD’ exposed to varying intensities of ultraviolet radiation. Harvest index was calculated using the formula: $HI = DW_f/(DW_f + DW_{nf})$. The data presented are means ± standard error (SE).

Biomass Parameter	Cultivar	Treatment				Significance
		Control	1-week	3-week	7-week	
FW (g)	Janets G	272.3 ± 22.7	273.4 ± 24.6	269.5 ± 16.3	259.3 ± 27.6	NS
	TJs CBD	264.7 ± 26.2	285.1 ± 16.0	283.0 ± 17.1	269.5 ± 18.9	NS
DW_f (g)	Janets G	30.6 ± 3.5	34.0 ± 3.9	33.2 ± 3.3	31.0 ± 5.1	NS
	TJs CBD	33.3 ± 5.1	32.8 ± 3.0	30.7 ± 2.9	28.9 ± 3.2	NS
DW_{nf} (g)	Janets G	29.4 ± 2.5	28.5 ± 2.5	29.9 ± 2.2	28.2 ± 2.7	NS
	TJs CBD	28.1 ± 3.0	32.0 ± 2.2	26.0 ± 1.9	30.8 ± 2.4	NS
HI	Janets G	0.50 ± 0.02	0.54 ± 0.02	0.52 ± 0.02	0.51 ± 0.02	NS
	TJs CBD	0.53 ± 0.02^{ab}	0.51 ± 0.01^{ab}	0.54 ± 0.01^{a}	0.48 ± 0.02^{b}	*
Apical Length (cm)	Janets G	7.0 ± 0.6	7.6 ± 0.4	8.4 ± 1.0	6.5 ± 0.3	NS
	TJs CBD	8.9 ± 0.8	9.9 ± 1.5	7.9 ± 0.8	6.9 ± 0.8	NS
Branching Pairs	Janets G	5.3 ± 0.4	6.1 ± 0.3	5.8 ± 0.3	5.9 ± 0.3	NS
	TJs CBD	5.3 ± 0.2	5.6 ± 0.3	4.8 ± 0.2	5.0 ± 0.2	NS
Stem Diameter (cm)	Janets G	0.98 ± 0.06	1.02 ± 0.06	1.01 ± 0.07	0.97 ± 0.04	NS
	TJs CBD	0.92 ± 0.08	0.94 ± 0.06	0.81 ± 0.04	0.97 ± 0.06	NS

NS = Not Significant
* = Significant

Table 8. Per-plant cannabinoid percentages for experiment two (duration) by weight (g) including cannabidiolic acid (CBDA), cannabidiol (CBD), cannabigerolic acid (CBGA), cannabigerol (CBG), tetrahydrocannabinolic acid (THCA), and cannabichromene (CBC) for the cultivars ‘Janets G’ and TJs CBD’ exposed to varying intensities of ultraviolet radiation. The data presented are means ± standard error (SE).

Cannabinoid Parameter	Cultivar	Treatment				Significance
		Control	1-week	3-week	7-week	
CBDA %	Janets G	0.57 ± 0.17	0.51 ± 0.10	0.83 ± 0.30	0.50 ± 0.19	NS
	TJs CBD	10.94 ± 0.64	10.70 ± 0.60	10.99 ± 0.62	9.49 ± 0.45	NS
CBD %	Janets G	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	NS
	TJs CBD	0.23 ± 0.06	0.26 ± 0.03	0.29 ± 0.03	0.21 ± 0.02	NS
CBGA %	Janets G	4.87 ± 0.37	4.41 ± 0.24	5.08 ± 0.32	4.88 ± 0.41	NS
	TJs CBD	0.98 ± 0.13	1.10 ± 0.16	0.84 ± 0.11	1.18 ± 0.24	NS
CBG %	Janets G	0.16 ± 0.06	0.18 ± 0.03	0.18 ± 0.04	0.18 ± 0.03	NS
	TJs CBD	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	NS
THCA%	Janets G	0.11 ± 0.02	0.09 ± 0.02	0.12 ± 0.01	0.09 ± 0.01	NS
	TJs CBD	0.55 ± 0.04	0.54 ± 0.02	0.51 ± 0.03	0.45 ± 0.03	NS
CBC %	Janets G	0.006 ± 0.004	0.001 ± 0.001	0.004 ± 0.003	0.0009 ± 0.0006	NS
	TJs CBD	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	NS

NS = Not Significant
* = Significant

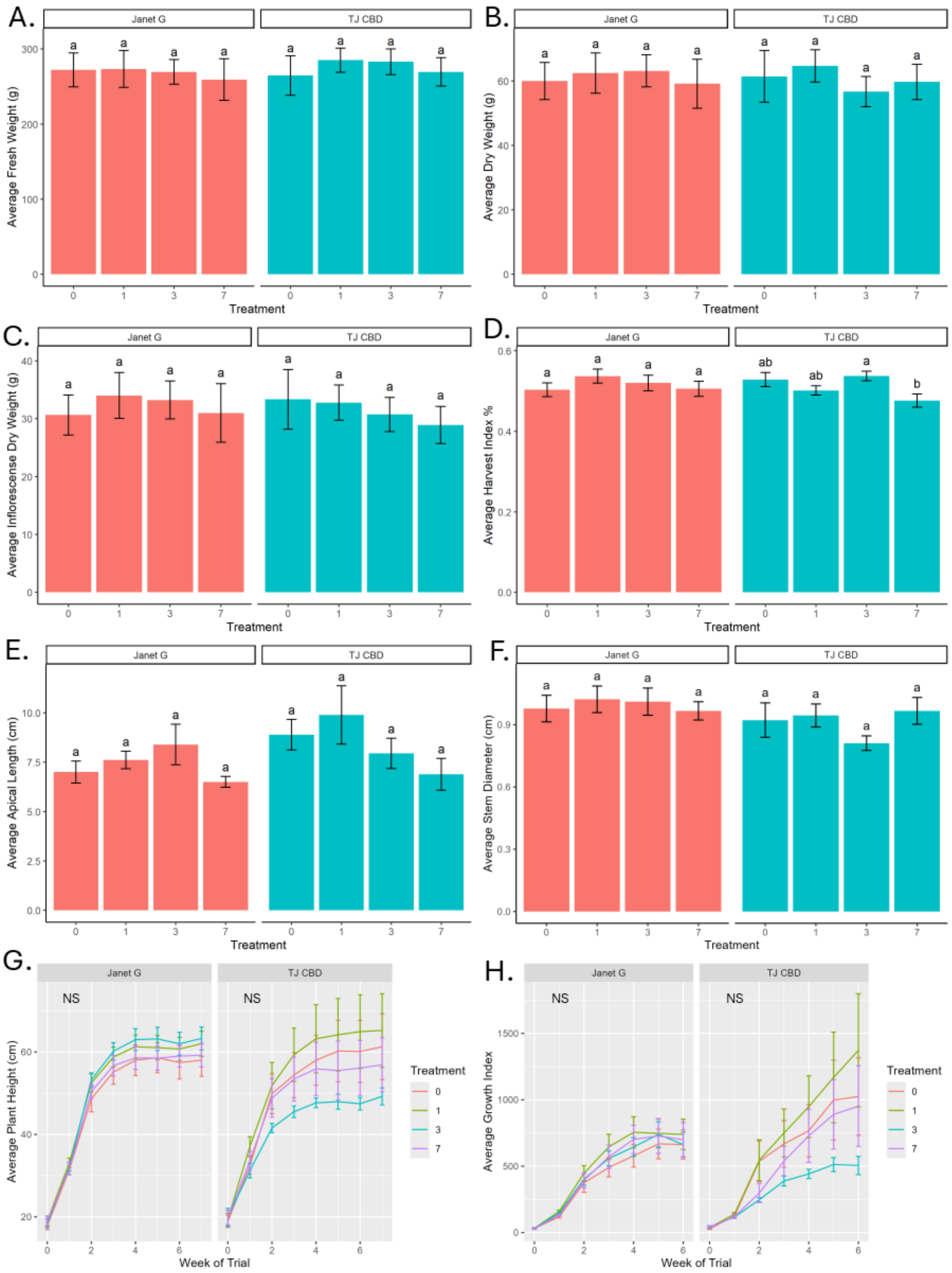

Figure 6. Per-plant metrics for cultivars 'Janets G' and 'TJs CBD' from experiment two (duration), showcasing: **(A)** Average fresh weight (g), **(B)** Average dry weight (g), **(C)** Average inflorescence dry weight (g), **(D)** Average harvest index (the ratio of inflorescence to total yield), **(E)** Average apical length (cm), **(F)** Average stem diameter (cm), **(G)** Average plant height over time (cm), and **(H)** Average growth index. Growth index is calculated using the formula: [*(height x width$_1$ x width$_2$)/300*]. NS = Not Significant. The data presented are means ± standard error (SE).

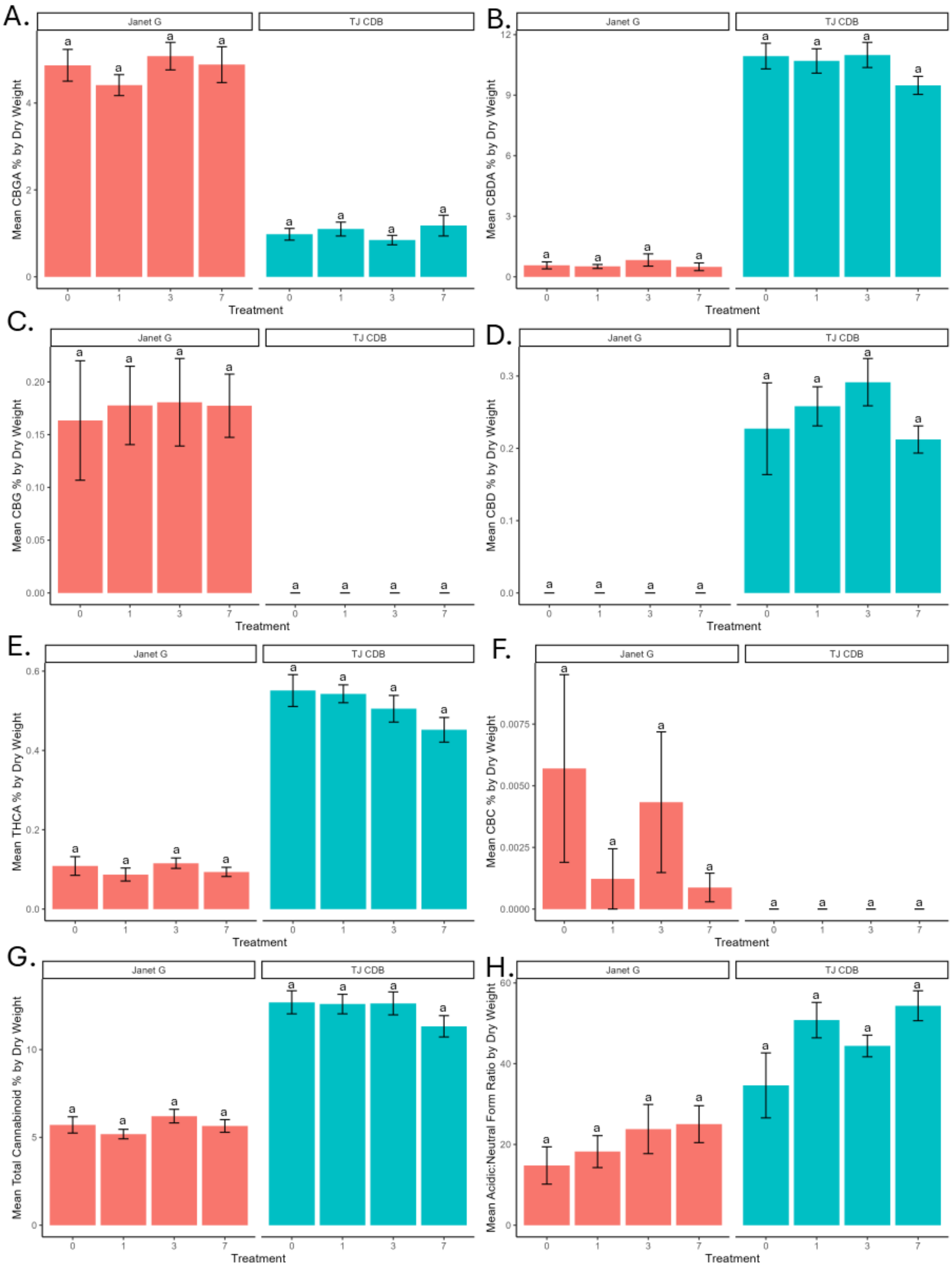

Figure 7. Per-plant cannabinoid percentages by weight (g) for cultivars 'Janets G' and 'TJs CBD' from experiment two (duration), including: **(A)** Cannabigerolic Acid (CBGA), **(B)** Cannabidiolic Acid (CBDA), **(C)** Cannabigerol (CBG), **(D)** Cannabidiol (CBD), **(E)** Tetrahydrocannabinolic Acid (THCA), **(F)** Cannabichromene (CBC), **(G)** total cannabinoid percentage, and **(H)** Mean ratios of acidic to neutral cannabinoid forms for cultivars 'Janets G' and 'TJs CBD'. The data presented are means ± standard error (SE).

Figure 8. Experimental plants prior to harvest for cultivars **(A)** 'Janets G' and **(B)** 'TJs CBD', demonstrating the effects of control, 1-week, 3-week, and 7-week treatments in Experiment Two (duration).

4. Discussion

4.1 Secondary metabolite content was not increased by UV

Increasing ultraviolet radiation did not statistically significantly affect the cannabinoid concentration in the CBG-dominant cultivar 'Janets G' and the CBD-dominant cultivar 'TJs CBD' across both experiments. There were some patterns in cannabinoid concentration, that while not statistically significant, suggesting there may be room to further evaluate UV dosage with a greater number of replicate plants. In Experiment One (dosage), the total cannabinoid content in 'Janets G' was approximately 9.98% higher in the medium treatment (12.6 $KJ\cdot m^2\cdot d^1$) compared to the control. For 'TJs CBD', the total cannabinoid content was about 7.38% higher in the high treatment (25.2 $KJ\cdot m^2\cdot d^1$) relative to the control. In Experiment Two (duration), 'Janets G' exhibited an approximately 8.76% increase in total cannabinoid content in the 3-week duration compared to the control. Conversely, in 'TJs CBD', the total cannabinoid content was less than 1% higher in the control than in the 1-week duration, which had the next highest total cannabinoid content. The study by (Lydon et al., 1987), is frequently cited as evidence that UV radiation can increase cannabinoid concentrations. Similar to our findings, recent studies (Llewellyn et al., 2022; Rodriguez-Morrison et al., 2021b; Westmoreland et al., 2023) demonstrated that UV radiation does not confer any benefits in increasing cannabinoid concentrations. Our study focused on high-CBD and CBG cultivars, while (Rodriguez-Morrison et al., 2021b) focused on two 1:1 CBD:THC cultivars, (Llewellyn et al., 2022) focused on a high-THC cultivar, and (Westmoreland et al., 2023) focused on a high-CBD cultivar. Together, these studies confirm that the chemical profile of a *Cannabis sativa L.* plant does not substantially influence cannabinoid responses to UV photons.

4.2 UV radiation did not affect plant growth or total yield

Overall plant growth and yields were not impacted by ultraviolet radiation treatments. Growth index [(height x width1 x width2)/300], plant height over time (cm), chlorophyll index (SPAD), and leaf area (cm^2) of the newest, fully developed leaf were measured exclusively in Experiment Two (duration). For experiment one (dosage) applied UV treatments only during the final two weeks of generative growth, limiting the time to impact plant growth. As noted in the results, the cultivar 'TJs CBD' showed a significant impact on the growth index, with plants in the third crop cycle exhibiting abnormally tall growth due to unexplained factors. When data from the third crop cycle is excluded from the statistical analysis, the results no longer show significance. UV radiation treatments similarly did not affect plant height over time. Although chlorophyll index and leaf area of the newest, fully developed leaf did not yield statistically significant results, visual differences were observed between the treatments (Figure 9.). Both cultivars displayed similar responses to UV radiation treatments. The initial signs of UV exposure became evident around three weeks after beginning exposure, marked by an accumulation of epicuticular wax and increased leaf thickness. By the time of harvest, the leaves exhibited reduced leaf areas and signs of foliar necrosis. Crop yields were not affected by UV radiation treatments. In both Experiment One (dosage) and Experiment Two (duration), UV exposure had no significant impact on total dry weights or total inflorescence dry weights.

4.3 Implications of UV radiation for indoor cannabis cultivation and directions for future research

Based on our experience and previous studies, there is minimal evidence to suggest that UV-B radiation up to the dosages and durations tested can enhance cannabinoid content. Future research should explore alternative spectra, such as UV-A, UV-C, or visible spectra, or different cultivars, that have not been extensively studied in past research. Additionally, exploring various cultural management strategies could also yield valuable insights into optimizing plant growth and cannabinoid production. Moreover, previous research indicates potential benefits of using UV-B radiation for pest and disease management in cannabis cultivation. The dosages of UV-B applied during midday sessions in our experiments did not result in substantial negative impacts on either yield or cannabinoid content. This suggests that UV-B could be a viable tool for managing crop health without compromising plant development or chemical profiles. Further studies focusing on the application timing, intensity, and frequency of UV-B treatments could enhance our understanding of its efficacy and safety as a pest and disease control strategy in cannabis cultivation.

Figure 9. Signs of UV exposure in 'TJs CBD' in Experiment Two (duration). **A.** First sign of UV exposure three weeks into treatment. **B.** Progression of epicuticular wax accumulation and increased leaf thickness five weeks into exposure. **C.** Reduced leaf area and foliar necrosis at harvest.

5. Conclusion

Our comprehensive research, which uniquely explored both dosage and duration of UV radiation during the generative phase of development, found that UV radiation did not enhance cannabinoid content in the CBG-dominant cultivar 'Janets G' and the CBD-dominant cultivar 'TJs CBD'. Both dosage and duration experiments revealed negligible impacts on total cannabinoid concentrations and plant growth metrics such as growth index, plant height, and leaf area. Despite previous research suggesting potential benefits, our findings align with recent studies indicating that UV radiation does not significantly affect cannabinoid levels or plant yields. This study, is the first to our knowledge to investigate different durations of UV exposure on cannabis. The findings can also be used to guide development of UV-B radiation dosages/durations that might be beneficial for pest and disease management without adverse effects on plant health. These insights pave the way for future research to explore other light spectra and cultivars, enhancing our understanding of UV radiation's role in cannabis cultivation.

6. *References*

Buirs, L., & Punja, Z. K. (2024). Integrated Management of Pathogens and Microbes in Cannabis sativa L. (Cannabis) under Greenhouse Conditions. *Plants*, *13*(6), 786. https://doi.org/10.3390/plants13060786

Caldwell, M. M., Flint, S. D., & Searles, P. S. (1994). Spectral balance and UV-B sensitivity of soybean: A field experiment. *Plant, Cell & Environment*, *17*(3), 267–276. https://doi.org/10.1111/j.1365-3040.1994.tb00292.x

Crini, G., Lichtfouse, E., Chanet, G., & Morin-Crini, N. (2020). Applications of hemp in textiles, paper industry, insulation and building materials, horticulture, animal nutrition, food and beverages, nutraceuticals, cosmetics and hygiene, medicine, agrochemistry, energy production and environment: A review. *Environmental Chemistry Letters*, *18*(5), 1451–1476. https://doi.org/10.1007/s10311-020-01029-2

Czégény, G., Mátai, A., & Hideg, É. (2016). UV-B effects on leaves—Oxidative stress and acclimation in controlled environments. *Plant Science*, *248*, 57–63. https://doi.org/10.1016/j.plantsci.2016.04.013

Dujourdy, L., & Besacier, F. (2017). A study of cannabis potency in France over a 25 years period (1992–2016). *Forensic Science International*, *272*, 72–80. https://doi.org/10.1016/j.forsciint.2017.01.007

Ferreyra, M. L. F., Serra, P., & Casati, P. (2021). Recent advances on the roles of flavonoids as plant protective molecules after UV and high light exposure. *Physiologia Plantarum*, *173*(3), 736–749. https://doi.org/10.1111/ppl.13543

Flint, S. D., & Caldwell, M. M. (2003). A biological spectral weighting function for ozone depletion research with higher plants. *Physiologia Plantarum*, *117*(1), 137–144. https://doi.org/10.1034/j.1399-3054.2003.1170117.x

Hazekamp, A., Peltenburg, A., Verpoorte, R., & Giroud, C. (2005). Chromatographic and Spectroscopic Data of Cannabinoids from *Cannabis sativa* L. *Journal of Liquid Chromatography & Related Technologies*, *28*(15), 2361–2382. https://doi.org/10.1080/10826070500187558

Jenkins, G. I. (2014). The UV-B Photoreceptor UVR8: From Structure to Physiology. *The Plant Cell*, *26*(1), 21–37. https://doi.org/10.1105/tpc.113.119446

Kobashigawa, C., Tamaya, K., & Shimomachi, T. (2011). Effect of UV-C treatment on plant growth and nutrient contents. *Acta Horticulturae*, *907*, 237–242. https://doi.org/10.17660/ActaHortic.2011.907.36

Kobayashi, M., Kanto, T., Fujikawa, T., Yamada, M., Ishiwata, M., Satou, M., & Hisamatsu, T. (2014). Supplemental UV Radiation Controls Rose Powdery Mildew Disease under the Greenhouse Conditions. *Environmental Control in Biology*, *51*(4), 157–163. https://doi.org/10.2525/ecb.51.157

Kollias, N., Ruvolo Jr, E., & Sayre, R. M. (2011). The Value of the Ratio of UVA to UVB in Sunlight. *Photochemistry and Photobiology*, *87*(6), 1474–1475. https://doi.org/10.1111/j.1751-1097.2011.00980.x

Krizek, D. T. (2004). Influence of PAR and UV-A in Determining Plant Sensitivity and Photomorphogenic Responses to UV-B Radiation ¶ †. *Photochemistry and Photobiology*, *79*(4), 307–315. https://doi.org/10.1111/j.1751-1097.2004.tb00013.x

Lemay, J., & Scott-Dupree, C. (2022). Management of Insect Pests on Cannabis in Controlled Environment Production. In Y. Zheng, *Handbook of Cannabis Production in Controlled Environments* (1st ed., pp. 253–290). CRC Press. https://doi.org/10.1201/9781003150442-9

Lemay, J., Zheng, Y., & Scott-Dupree, C. (2022). Factors Influencing the Efficacy of Biological Control Agents Used to Manage Insect Pests in Indoor Cannabis (Cannabis sativa) Cultivation. *Frontiers in Agronomy*, *4*, 795989. https://doi.org/10.3389/fagro.2022.795989

Llewellyn, D., Golem, S., Foley, E., Dinka, S., Jones, A. M. P., & Zheng, Y. (2022). Indoor grown cannabis yield increased proportionally with light intensity, but ultraviolet radiation did not affect yield or cannabinoid content. *Frontiers in Plant Science*, *13*, 974018. https://doi.org/10.3389/fpls.2022.974018

Lydon, J., Teramura, A. H., & Coffman, C. B. (1987). UV-B radiation effects on photosynthesis, growth and cannabinoid production of two Cannabis sativa chemotypes. *Photochem Photobiol.*, *46*(2), 201–206. https://doi.org/10.1111/j.1751-1097.1987.tb04757.x

Mackerness, S. A. H. (2000). Plant responses to ultraviolet-B (UV-B: 280–320 nm) stress: What are the key regulators? *Plant Growth Regulation*, *32*, 27–39. https://doi.org/10.1023/A:1006314001430

Punja, Z. K. (2021). Emerging diseases of *Cannabis sativa* and sustainable management. *Pest Management Science*, *77*(9), 3857–3870. https://doi.org/10.1002/ps.6307

Punja, Z. K., Collyer, D., Scott, C., Lung, S., Holmes, J., & Sutton, D. (2019). Pathogens and Molds Affecting Production and Quality of Cannabis sativa L. *Frontiers in Plant Science*, *10*, 1120. https://doi.org/10.3389/fpls.2019.01120

Radwan, M. M., Chandra, S., Gul, S., & ElSohly, M. A. (2021). Cannabinoids, Phenolics, Terpenes and Alkaloids of Cannabis. *Molecules*, *26*(9), 2774. https://doi.org/10.3390/molecules26092774

Rodriguez-Morrison, V., Llewellyn, D., & Zheng, Y. (2021b). Cannabis Inflorescence Yield and Cannabinoid Concentration Are Not Increased With Exposure to Short-Wavelength Ultraviolet-B Radiation. *Frontiers in Plant Science*, *12*, 725078. https://doi.org/10.3389/fpls.2021.725078

Rodriguez-Morrison, V., Llewellyn, D., & Zheng, Y. (2021a). Cannabis Yield, Potency, and Leaf Photosynthesis Respond Differently to Increasing Light Levels in an Indoor Environment. *Frontiers in Plant Science*, *12*, 646020. https://doi.org/10.3389/fpls.2021.646020

Ruter, J. M. (1992). Influence of source, rate, and method of applicating controlled release fertilizer on nutrient release and growth of ?Savannah? Holly. *Fertilizer Research*, *32*(1), 101–106. https://doi.org/10.1007/BF01054399

Sankari, M., Hridya, H., Sneha, P., George Priya Doss, C., & Ramamoorthy, S. (2017). Effect of UV radiation and its implications on carotenoid pathway in Bixa orellana L. *Journal of Photochemistry and Photobiology B: Biology*, *176*, 136–144. https://doi.org/10.1016/j.jphotobiol.2017.10.002

Schreiner, M., Mewis, I., Huyskens-Keil, S., Jansen, M. A. K., Zrenner, R., Winkler, J. B., O'Brien, N., & Krumbein, A. (2012). UV-B-Induced Secondary Plant Metabolites—Potential Benefits for Plant and Human Health. *Critical Reviews in Plant Sciences*, *31*(3), 229–240. https://doi.org/10.1080/07352689.2012.664979

Schultz, L. (2019). *The Economic Impact of Developing the Adult-Use Cannabis Industry in New York*.

Scott, C., & Punja, Z. K. (2021). Evaluation of disease management approaches for powdery mildew on *Cannabis sativa* L. (marijuana) plants. *Canadian Journal of Plant Pathology*, *43*(3), 394–412. https://doi.org/10.1080/07060661.2020.1836026

Smith, C. J., Vergara, D., Keegan, B., & Jikomes, N. (2022). The phytochemical diversity of commercial Cannabis in the United States. *PLOS ONE*, *17*(5), e0267498. https://doi.org/10.1371/journal.pone.0267498

Suthaparan, A., Solhaug, K. A., Bjugstad, N., Gislerød, H. R., Gadoury, D. M., & Stensvand, A. (2016). Suppression of Powdery Mildews by UV-B: Application Frequency and Timing, Dose, Reflectance, and Automation. *Plant Disease*, *100*(8), 1643–1650. https://doi.org/10.1094/PDIS-12-15-1440-RE

Tilbrook, K., Arongaus, A. B., Binkert, M., Heijde, M., Yin, R., & Ulm, R. (2013). The UVR8 UV-B Photoreceptor: Perception, Signaling and Response. *The Arabidopsis Book*, *11*, e0164. https://doi.org/10.1199/tab.0164

Urban, L., Charles, F., De Miranda, M. R. A., & Aarrouf, J. (2016). Understanding the physiological effects of UV-C light and exploiting its agronomic potential before and after harvest. *Plant Physiology and Biochemistry*, *105*, 1–11. https://doi.org/10.1016/j.plaphy.2016.04.004

Verdaguer, D., Jansen, M. A. K., Llorens, L., Morales, L. O., & Neugart, S. (2017). UV-A radiation effects on higher plants: Exploring the known unknown. *Plant Science*, *255*, 72–81. https://doi.org/10.1016/j.plantsci.2016.11.014

Westmoreland, F. M., Kusuma, P., & Bugbee, B. (2023). Elevated UV photon fluxes minimally affected cannabinoid concentration in a high-CBD cultivar. *Frontiers in Plant Science*, *14*, 1220585. https://doi.org/10.3389/fpls.2023.1220585

Zhang, W. J., & Björn, L. O. (2009). The effect of ultraviolet radiation on the accumulation of medicinal compounds in plants. *Fitoterapia*, *80*(4), 207–218. https://doi.org/10.1016/j.fitote.2009.02.006