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# Exploring the effects of UV-A and UV-C light on *Catharanthus roseus* cultivars: insights into plant growth and physiology

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## Abstract

*Catharanthus roseus* is a medicinal and ornamental plant that has a short cultivation cycle and high commercial value, making it an ideal candidate for vertical farming production. This study explored the influence of UV-A (365 nm) and UV-C (250 nm) radiation on plant growth and physiology, and their impact in the synthesis of anticancer alkaloid in three *C. roseus* cultivars ('Sunstorm Apricot' (S-APR), 'Cora-Red' (C-Red), and 'Cora-XDR Polka Dot' (C-XDR Polka)). To this end, plants were exposed in the last five days of a 35 days trial to 10.8 kJ m<sup>-2</sup> day<sup>-1</sup> of UV-A and UV-C radiation, following a 12-h red:blue (2:1) photoperiod with 150 μmol m<sup>-2</sup> s<sup>-1</sup>. UV-C markedly decreased total dry matter (TDM) by 59%, significantly reduced leaf area and photosynthetic rates by 75 and 80% respectively, indicating a pronounced stress impact. Conversely, UV-A maintained growth parameters near control levels, suggesting a milder influence. Importantly, UV-C exposure significantly enhanced the production of anticancer alkaloids by up to 125%, achieving a yield of approximately 0.07 mg plant<sup>-1</sup>. However, the increase in alkaloid production came at the cost of significant biomass reduction. These results underscore the potential of UV-C to enhance alkaloid yields but highlight the need for fine-tuning exposure to optimize alkaloid production without detrimental effects on biomass. Further research on optimizing UV-C exposure could lead to more effective cultivation strategies in vertical farming.

**Keywords:** medicinal plants, periwinkle, plant stress response, UV radiation, vertical farming, vinblastine, vincristine

## INTRODUCTION

The World Health Organization (WHO) recognizes approximately 21,000 plant species used for medicinal purposes, reflecting the vast biodiversity harnessed for human health. The global production of medicinal and aromatic plants (MAPs) is substantial, with an estimated 330 million t cultivated over 77 million ha as reported by the Food and Agriculture Organization of the United Nations (FAO, 2015). Despite this extensive cultivation, the medicinal plant sector faces significant challenges, including variability in yield, quality, and the efficacy of plant extracts (Bafort and Jijakli, 2024). These challenges need innovative cultivation techniques to meet the growing demand for MAPs.

Plant factories, utilizing multilayer indoor systems, offer a promising solution by providing precise control over growth conditions, thereby optimizing output m<sup>-2</sup>. However, these systems come with high initial investment costs and substantial energy requirements (SharathKumar et al., 2020). Thus, selecting high-value crops is crucial for economic sustainability.

*Catharanthus roseus*, a plant from the *Apocynaceae* family native to Madagascar, is an excellent candidate for such systems. Known for its potent anti-cancer alkaloids, vinblastine and vincristine, as well as their precursors, catharanthine and vindoline (Zhang et al., 2017; Howes, 2018), it represents a high-value plant with significant therapeutic potential. In plant factories, every parameter can be tailored to maximize the production of these targeted



alkaloids.

Ultraviolet (UV) radiation has been shown to enhance the production of valuable specialized metabolites in plants. While UV-B (280-315 nm) effects on plants are well-documented, there is comparatively limited research on the roles of UV-A (315-400 nm) and UV-C (200-280 nm) in influencing plant growth and secondary metabolite production (Vanhaelewyn et al., 2020; Samal et al., 2023). UV-B has been widely studied in *Catharanthus roseus*, particularly for its influence on morphogenesis and phototropism (Thakur et al., 2023); thus, we focused on the less-explored UV-A and UV-C wavelengths to evaluate their effects on secondary metabolite synthesis and growth. UV-A primarily impacts photoreception, while UV-C has been shown to significantly enhance secondary metabolite synthesis.

This study evaluates the impact of equivalent energy levels of UV-A (365 nm) and UV-C (250 nm) on three *Catharanthus roseus* cultivars. Our aim is to delineate the responses of these cultivars in terms of growth and alkaloid yield, contributing to optimized production strategies in plant factory settings.

## MATERIALS AND METHODS

### Plant materials and cultivation methods

Seedlings of three *Catharanthus roseus* (L.) cultivars, obtained from Syngenta four weeks after sowing, were produced by Group Roig - Viveros Pereira (Valencia, Spain). These included: 'Cora Red' (C-RD), 'Cora XDR Polka dot' (C-XDR-PK) and 'Sunstorm Apricot' (S-APR) (Syngenta cultivars). A growing mix of 50% humus, 17% peat (0-40mm), 17% perlite, and 15% coco peat enriched with fertilizer (16N-11P-10K + 2Mg + micronutrients) was used to plant the seedlings in 8 cm diameter pots. Plants were grown in climate chambers at a temperature of  $24.0 \pm 0.8^\circ\text{C}$  and 80% relative humidity (RH). Light emitting diodes (LEDs) lamps where three distinct light treatments were applied: 1) Control where dichromatic light spectrum of Red (667 nm) + Blue (450 nm) (model RX-TP12050-F5, 200W - Koray light; Seoul, Korea) in a photon flux density ratio 2:1 and photoperiod of 12 h with a total of  $150 \mu\text{mol m}^{-2} \text{s}^{-1}$  photosynthetic photon flux density (PPFD) at the plant level was used; 2) UV-A: which was the same as Control but with a supplementary UV-A (350-380 nm with a peak in 365 nm,  $10.8 \text{ kJ m}^{-2} \text{ d}^{-1}$ , model: VL-215-L, 15 W - Vilber Lourmat, Germany) on the final five days of production; and 3) UV-C: which was the same as Control but with a supplementary UV-C (248-252 nm, with a peak in 250 nm,  $10.8 \text{ kJ m}^{-2} \text{ d}^{-1}$ , model: VL-215-C, 15 W - Vilber Lourmat, Germany) on the final five days of production (both UV-A and UV-C corresponding to approximately 6 h exposure per day after the 12-h photoperiod). Temperature and RH were recorded every 2 min using a temperature logger (LogTag® TRIX-8, Auckland, New Zealand). Light intensity and quality – spectrum – were weekly checked with a spectrophotometer Optimum SRI-2000 (wavelength range 250-850 nm; Hsinchu, Taiwan) and adjusted when necessary. Plants were grown for 35 days, which represents the commercial growing period as an ornamental plant at Viveiros Vitor Lourenço (Maia, Portugal). The experiment was conducted three times, growing five plants for each cultivar and light treatment combination in each of the three replicates. Plants were moved every three days so a border effect could be discarded.

At harvest stage, plants were collected to record morphological parameters as plant height (cm), total number of internodes, average internode length (cm) and to study physiological parameters as chlorophyll content (SPAD) and photosynthetic performance – photosynthesis ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and stomatal conductance ( $\mu\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) – which were measured on fully expanded and well exposed leaves for optimal accuracy, using a Portable Photosynthesis System (IRGA, LI-6400XT, LI-COR inc). Later, total leaf area (LA,  $\text{cm}^2$ ) was measured using a LI-3100C Leaf area meter (LI-COR, Lincoln, Nebraska, USA) and specific leaf area (SLA,  $\text{cm}^2 \text{ g}^{-1}$ ) was calculated. After drying the plants at  $90^\circ\text{C}$  for 72 h in a ventilated oven (GreenUPorto, Vairão, Portugal) leaf dry matter (LDM), stems dry matter (SDM) and flowers dry matter (FDM) were determined.

### Alkaloid extraction and LC-MS methods

Alkaloid extraction followed the protocol described by Carqueijeiro et al. (2016). Fresh *C. roseus* leaves were flash-frozen in liquid nitrogen (-70°C) and ground into a fine powder using a mortar and pestle. Approximately 150 mg of the powdered sample was transferred into a 2-mL Eppendorf tube, and 1 mL of methanol (MeOH) was added. The sample was vortexed for 2 min, followed by sonication for 30 min. Afterwards, the microtubes were centrifuged at 12,000 rpm for 10 min, and the supernatant was collected and filtered through a 0.45- $\mu$ m membrane filter before injection into the liquid chromatography-mass spectrometer. The samples were analyzed by LC-ESI-SIM in a Finnigan Surveyor Plus HPLC (Thermo Scientific) coupled to Finnigan LCQ Deca XP Plus mass detector with an electrospray ionization source (ESI) operating at room temperature and a quadrupole ion trap. The system was controlled, and the information recorded by the software Xcalibur (Thermo Fisher Scientific). The separation was carried out under the same conditions described by Jeong and Lim (2018) with some modifications. The column and the solvents are the same, but the contents of mobile phase were varied from 35% and not 40% of B from 5 to 10 min.

The mass spectra were acquired in positive mode in the range between 300 m/z and 1000 m/z from ESI source with the conditions set to capillary temperature of 325°C, capillary exit offset of 5 KV, capillary voltage of 15 V and tube lens of 50 V. Nitrogen was used as nebulizing and drying gas at 40 and 15 (arbitrary units), respectively.

The LC-MS output chromatograms were analyzed using XCalibur™ software, with each alkaloid identified by its observed ionic mass (m/z): catharanthine (CAT: 337), vindoline (VDL: 457), vincristine (VCR: 825), anhydrovinblastine (AVLB: 793), and vinblastine (VLB: 811). The alkaloid concentrations in the samples were quantified in mg g<sup>-1</sup> dry weight (DW) using calibration curves based on five known concentrations of each standard alkaloid.

### Statistical analysis

For all studied parameters, the resulting matrix contained 27 averaged measurements (3 cultivars  $\times$  3 light treatments  $\times$  3 replicates) corresponding to 135 samples (5 plants per cultivar). A two-way ANOVA in blocks was used to test for significant differences between the three cultivars (S-APR, C-Red and C-XDR-Polka) and light levels (Control, UV-A and UV-C), using post-hoc Tukey's test with a 95% confidence interval. This analysis was conducted using GraphPad Prism 9.3.1 edition.

## RESULTS AND DISCUSSION

### High UV-C exposure significantly impacts plant morphology and physiology

Previous research suggested that plants respond to stressors such as UV radiation by increasing the production of therapeutically relevant specialized metabolites, including flavonoids, terpenoids, and phenolic acids (Alyas et al., 2023). Notably, the effects induced by UV radiation typically depend on the intensity of the radiation and the developmental stages of the plants (Moreira-Rodríguez et al., 2017). In our study, the exposure of *Catharanthus roseus* to ultraviolet-C (UV-C) radiation (250 nm, 10.8 kJ m<sup>-2</sup> d<sup>-1</sup>) during the final five days of the experiment led to a significant reduction in total dry matter (TDM), averaging a 59% decrease compared to the control and UV-A treated plants. This trend was consistent across different plant organs; leaf dry matter was reduced by 58%, and stem dry matter decreased by 70%. These changes were visibly evident in the images captured at the end of the trial, where all three cultivars exhibited markedly reduced biomass under UV-C treatment (Table 1) with leaves showing slight burn marks (Figure 1).

Table 1. Morphophysiological parameters measured after 35 days of cultivation of three *Catharanthus roseus* cultivars ('Sunstorm Apricot' (S-APR), 'Cora Red' (C-RD) and 'Cora XDR Polka Dot' (C-XDR-PK)) grown under three light levels: Control (12 h photoperiod with red-blue light); UV light supplementation (10.8 kJ m<sup>-2</sup> day<sup>-1</sup> in the last five days during the photoperiod) with 365 nm light (UV-A) and 250 nm light (UV-C). Values are presented as mean ± SEM (*n*=3; with each independent replicate composed of five plants).

Measured parameter	S-APR			C-Red			C-XDR-Polka			
	Control	UV-A	UV-C	Control	UV-A	UV-C	Control	UV-A	UV-C	
Total dry matter (g)	0.46 <sup>a</sup>	0.39 <sup>a</sup>	0.16 <sup>b</sup>	0.55 <sup>a</sup>	0.51 <sup>a</sup>	0.22 <sup>b</sup>	0.44 <sup>a</sup>	0.52 <sup>a</sup>	0.22 <sup>b</sup>	n.s.i. <i>p</i> =0.06 <i>I</i> * <i>p</i> <0.0001
Leaf dry matter (g)	0.28 <sup>a</sup>	0.25 <sup>a</sup>	0.10 <sup>b</sup>	0.31 <sup>a</sup>	0.30 <sup>a</sup>	0.12 <sup>b</sup>	0.28 <sup>a</sup>	0.33 <sup>a</sup>	0.14 <sup>b</sup>	n.s.i. <i>p</i> =0.51 <i>I</i> * <i>p</i> <0.0001
Stem dry matter (g)	0.12 <sup>a</sup>	0.10 <sup>a</sup>	0.07 <sup>b</sup>	0.14 <sup>a</sup>	0.14 <sup>a</sup>	0.11 <sup>b</sup>	0.10 <sup>a</sup>	0.11 <sup>a</sup>	0.08 <sup>b</sup>	n.s.i. <i>p</i> =0.37 <i>I</i> * <i>p</i> <0.0001
Flower dry matter (g)	0.04 <sup>c</sup>	0.03 <sup>c</sup>	0.02 <sup>c</sup>	0.04 <sup>b</sup>	0.05 <sup>b</sup>	0.04 <sup>b</sup>	0.07 <sup>a</sup>	0.10 <sup>a</sup>	0.06 <sup>a</sup>	n.s.i. <i>p</i> =0.48 <i>c</i> * <i>p</i> =0.0058 <i>I</i> <i>p</i> =0.406
Leaf area (cm <sup>2</sup> )	85.96 <sup>a</sup>	86.27 <sup>a</sup>	18.08 <sup>b</sup>	111.12 <sup>a</sup>	108.01 <sup>a</sup>	23.51 <sup>b</sup>	82.10 <sup>a</sup>	104.92 <sup>a</sup>	30.77 <sup>b</sup>	n.s.i. <i>p</i> =0.0943 <i>I</i> * <i>p</i> <0.0001
Specific leaf area (cm <sup>2</sup> g <sup>-1</sup> )	286.36 <sup>a</sup>	354.14 <sup>a</sup>	236.71 <sup>b</sup>	325.86 <sup>a</sup>	364.39 <sup>a</sup>	280.73 <sup>b</sup>	294.01 <sup>a</sup>	319.26 <sup>a</sup>	248.30 <sup>b</sup>	n.s.i. <i>p</i> =0.824 <i>I</i> * <i>p</i> =0.0003
Plant height (cm)	5.05 <sup>a</sup>	5.19 <sup>a</sup>	3.44 <sup>b</sup>	6.61 <sup>a</sup>	5.70 <sup>a</sup>	4.40 <sup>b</sup>	5.43 <sup>a</sup>	5.75 <sup>a</sup>	4.41 <sup>b</sup>	n.s.i. <i>p</i> =0.07 <i>I</i> * <i>p</i> <0.0001
Number of internodes	4.60 <sup>a</sup>	4.07 <sup>a</sup>	3.07 <sup>b</sup>	5.00 <sup>a</sup>	4.71 <sup>a</sup>	4.13 <sup>b</sup>	4.30 <sup>a</sup>	4.80 <sup>a</sup>	3.47 <sup>b</sup>	n.s.i. <i>p</i> =0.16 <i>I</i> * <i>p</i> <0.0001
Average internode length (cm)	1.12 <sup>ab</sup>	1.29 <sup>ab</sup>	1.25 <sup>ab</sup>	1.37 <sup>a</sup>	1.22 <sup>ab</sup>	0.95 <sup>b</sup>	1.31 <sup>ab</sup>	1.21 <sup>ab</sup>	1.30 <sup>ab</sup>	s.i. <i>p</i> =0.0243
SPAD value	59.32 <sup>a</sup>	58.71 <sup>a</sup>	48.30 <sup>b</sup>	60.49 <sup>a</sup>	60.28 <sup>a</sup>	48.69 <sup>b</sup>	58.27 <sup>a</sup>	58.88 <sup>a</sup>	51.20 <sup>b</sup>	n.s.i. <i>p</i> =0.19 <i>I</i> * <i>p</i> <0.0001
Photosynthetic rate (μmol CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup> )	5.67 <sup>a</sup>	6.15 <sup>a</sup>	0.24 <sup>b</sup>	5.19 <sup>a</sup>	5.73 <sup>a</sup>	1.52 <sup>b</sup>	4.55 <sup>a</sup>	6.11 <sup>a</sup>	1.66 <sup>b</sup>	s.i. <i>p</i> =0.0201
Stomatal conductance (μmol H <sub>2</sub> O m <sup>-2</sup> s <sup>-1</sup> )	0.39 <sup>a</sup>	0.36 <sup>a</sup>	0.03 <sup>b</sup>	0.40 <sup>a</sup>	0.31 <sup>a</sup>	0.04 <sup>b</sup>	0.23 <sup>a</sup>	0.38 <sup>a</sup>	0.10 <sup>b</sup>	s.i. <i>p</i> =0.023

Different letters indicate significant differences according to Tukey's HSD test at *p*=0.05. n.s.i means no significant interaction, s.i. means significant interaction presented statistical differences are represented using a \*, for instance, when light dependent (*I*\*).

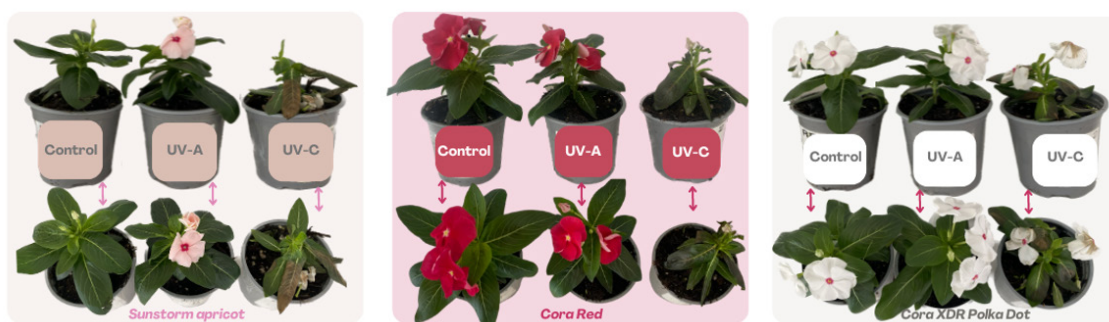


Figure 1. Visual aspect of three *Catharanthus roseus* cultivars after 35 days of cultivation under the three light conditions. Details on the treatments are given in Table 1.

Interestingly, flower dry matter was the only parameter not influenced by the light treatments. 'C-XDR Polka' produced the highest flower biomass at 0.075 g, followed by 'C-Red' at 0.045 g, and 'S-APR' at 0.032 g (Table 1). Leaf area (LA) and specific leaf area (SLA) were also affected by UV-C treatment. Plants exposed to UV-C exhibited a significant reduction in total leaf area, measuring approximately 24 cm<sup>2</sup>, which is 75% smaller than those subjected to other light treatments. Furthermore, UV-C exposure resulted in thicker leaves, with a 21% decrease in SLA compared to control and UV-A treatments. Plant height and internode number were similarly impacted by UV-C. Plants under UV-C treatment were on average 0.5 cm shorter, representing a 27% reduction compared to the control and UV-A treated plants. There was also a 22% reduction in the number of internodes in UV-C treated plants compared to other treatments. The average internode length (AIL) varied not only by light treatment but also by cultivar, with only 'C-Red' showing a statistically significant difference; UV-C treated 'C-Red' plants exhibited a 30% reduction in AIL compared to the control (Table 1).

Similarly, the SPAD index – an indirect measure of chlorophyll content – also showed a substantial reduction, with a significant 17% decrease in plants exposed to UV-C at the end of the day during the last five days of the experiment. This decline in chlorophyll content parallels drastic reductions in photosynthetic rate and stomatal conductance, which dropped by 80 and 84%, respectively, when compared to control and UV-A treated plants (Table 1). These pronounced effects under UV-C stress are indicative of the plants activating their secondary metabolism as a defense mechanism, potentially enhancing their resilience against stressors (Samal et al., 2023). This activation triggers a cascade of signals that regulate a range of light-induced biological processes, allowing for increased conversion of catharanthine (CAT) and vindoline (VDL) into the anticancer alkaloid vinblastine (VLB).

### UV-C exposure enhances anti-cancer alkaloid production

The response to light treatments varied among different alkaloids. Catharanthine (CAT) levels were notably higher under UV-A, showing a 1.17-fold increase across all three studied cultivars compared to the Control and UV-C treatments (Figure 2A). Although no significant differences were observed in vindoline (VDL) levels across treatments or cultivars, UV-A treatment tended to increase VDL in 'C-XDR-Polka' compared to other treatments. Interestingly, 'S-APR' consistently showed lower VDL production, even though these differences were not statistically significant (Figure 2B). 3',4'-anhydrovinblastine (AVLB) production was significantly reduced by 85% in plants exposed to UV-C during the final five days of the trial compared to those under UV-A or control conditions (Figure 2C).

The two relevant anti-neoplastic alkaloids, vinblastine (VLB) and vincristine (VCR), were significantly enhanced by UV-C treatment, which resulted in increases of 85 and 363% for VLB and VCR, respectively (Figure 2D, E). This suggests a potential therapeutic benefit in the targeted use of UV-C for enhancing alkaloid yields.

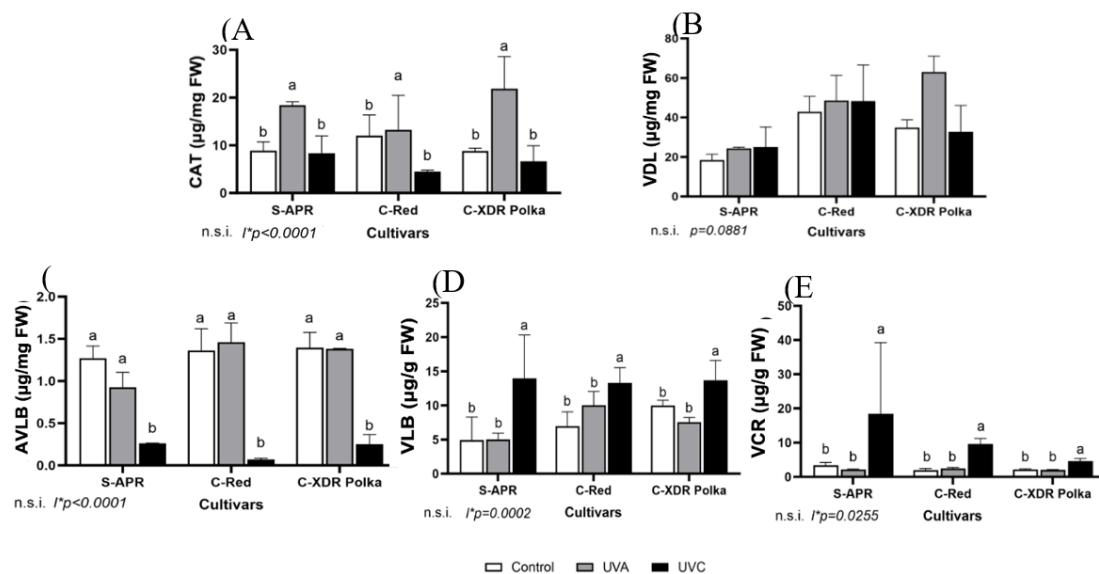


Figure 2. Concentration of different alkaloids (catharanthine (CAT) (A), vindoline (VDL) (B), anhydrovinblastine (AVLB) (C), vinblastine (VLB) (D), and vincristine (VCR) (E)) per mg leaf fresh weight (FW) of three *Catharanthus roseus* cultivars ('Sunstorm Apricot' (S-APR), 'Cora Red' (C-RD) and 'Cora XDR Polka Dot' (C-XDR-PK)) under three light conditions. Details on the treatments are given in Table 1. Values are presented as mean  $\pm$  SEM for three independent replicates ( $n=3$ ; with each independent replicate composed of five plants). Different letters above the bars indicate significant differences among the means of each cultivar, as determined by Tukey's HSD test at  $p=0.05$ . n.s.i means no significant interaction, statistical differences are only light dependent ( $I^*$ ).

While these findings highlight light-induced variation in alkaloid production, it is also essential to consider the overall yield of these compounds, in grams per total leaf fresh weight. By integrating leaf biomass data with alkaloid concentrations, from our results, we estimate that the total alkaloid yield per plant had no significant differences between treatments. However, UV-A appeared to enhance the total alkaloid yield, a response particularly notable in the 'C-XDR-Polka' cultivar, which exhibited a 113% increase compared to the other treatments (Figure 3A). In contrast, focusing specifically on the anticancer alkaloids, vinblastine (VBL) and vincristine (VCR), revealed that UV-C treatment led to a 125% increase in these critical compounds relative to the Control and UV-A treatments (Figure 3B).

The differential response of plants to UV-A and UV-C suggest that photoreceptors respond not to the total energy amount, but rather to the energy per photon, which varies with wavelength. UV-A and UV-C photons have different energy levels due to their respective wavelengths, leading to distinct interactions with plant photoreceptors. Plants possess a broad array of photoreceptors: cryptochromes (CRY1 and CRY2) primarily absorb UV-A (Ahmad et al., 2002), while UV-B is mainly sensed by UVB-RESISTANCE 8 (UVR8) (Heijde and Ulm, 2012). Although plant responses to UV-A and UV-B are well documented, there is no known photoreceptor specifically for UV-C (Vanhaelewyn et al., 2020), which may account for the varied plant responses to these wavelengths.

Further investigations into how UV-C influences plant morphology, physiology, and alkaloid production, including the role of reactive oxygen species (ROS) generated under UV-C exposure, are necessary. Such research will help unravel the mechanisms by which plants manage UV-C absorption and optimize their defense strategies, offering insights into enhancing medicinal alkaloid yields in controlled environments.

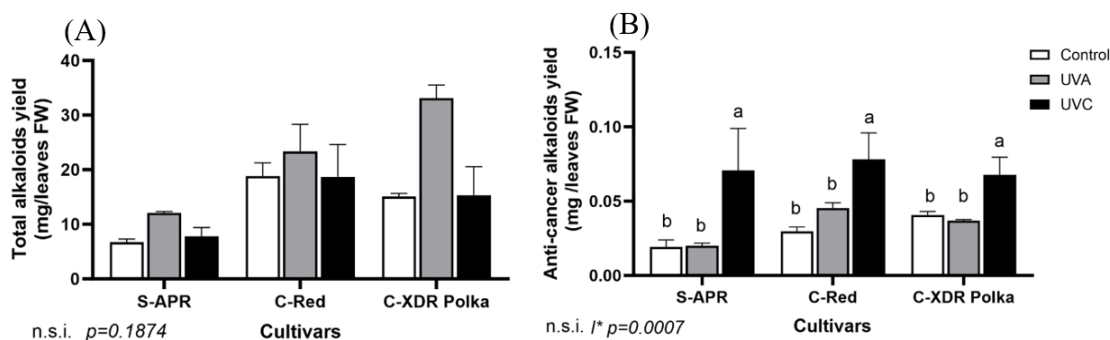


Figure 3. Total alkaloid yielded from the leaves (including catharanthine (CAT), vindoline (VDL), anhydrovinblastine (AVLB), vinblastine (VLB), and vincristine (VCR)) (A), and the yield of anti-cancer alkaloids (vinblastine (VLB) and vincristine (VCR)) specifically (B), quantified in the total leaf fresh weight at the conclusion of the 35-day experimental period for three studied *Catharanthus roseus* cultivars: ‘Sunstorm Apricot’ (S-APR), ‘Cora Red’ (C-RD) and ‘Cora XDR Polka Dot’ (C-XDR-PK) under three light conditions: 12 h RB (control), 12 h RB with UV-A  $10.8 \text{ kJ m}^{-2} \text{ day}^{-1}$  in the last five days (UV-A) and 12 h RB with UV-C  $10.8 \text{ kJ m}^{-2} \text{ day}^{-1}$  in the last five days (UV-C). Values are presented as mean  $\pm$  SEM for three independent replicates ( $n=3$ ), with each replicate consisting of five plants. Different letters above the bars indicate significant differences among the means of each cultivar, as determined by Tukey’s HSD test at  $p=0.05$ . n.s.i means no significant interaction, statistical differences are only light dependent ( $I^*$ ).

## CONCLUSIONS

High-intensity ultraviolet light significantly impacts plant morphology, physiology, and metabolite production. Applying  $10.8 \text{ kJ m}^{-2} \text{ day}^{-1}$  of UV-C over the last five days in a *Catharanthus roseus* plant factory resulted in notable changes, including a 27% reduction in plant height and a 59% decrease in final biomass. This substantial decline was primarily due to an 80% reduction in photosynthetic activity and a 75% decrease in leaf area. Despite these drawbacks, UV-C treatment markedly enhanced the production of anti-neoplastic alkaloids, yielding 125% more than other treatments. This increase was consistent across all three studied cultivars, indicating a uniform response to the light treatments concerning alkaloid production. These findings suggest potential avenues for further research to optimize the intensity and timing of UV-C exposure. Proper calibration could maximize the production of vital anti-cancer alkaloids, which are currently produced in limited quantities in *Catharanthus roseus*, while minimizing negative impacts on plant growth and resilience. Additionally, the neutral effect of UV-A on plant performance invites exploration into its broader application in plant factories, potentially offering a less detrimental alternative for enhancing plant growth and metabolites accumulation.

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