



OPEN Effects of UV-B radiation distance on morphological and biochemical traits of chicory (*Cichorium intybus* L.) in an aeroponic system

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Chicory (*Cichorium intybus* L.) exhibits significant phytochemical variations in response to environmental stressors. This study investigated the distance-dependent effects of UV-B exposure on the morpho-biochemical traits of chicory using a specialized aeroponic system. Seedlings were transplanted into the system and subjected to varying UV-B distances: a non-irradiated control (RD-0) and three treatment distances (40, 80, and 120 cm; 290–315 nm) in a completely randomized design with three replicates. Results indicated that proximity to the UV-B source induced significant reductions in biomass, leaf area, root volume, and chlorophyll levels, reflecting stress-induced growth inhibition. Conversely, UV-B exposure (particularly at 40 and 80 cm) significantly enhanced anthocyanins, total phenolics, proline accumulation, and antioxidant enzyme activities (CAT, POD, and APX), indicating a robust compensatory defense against oxidative stress. Radar plot analysis revealed that while the control (RD-0) and 120 cm distance optimized vegetative growth, the 40 cm and 80 cm distances maximized antioxidant capacity and secondary metabolite concentrations. These findings demonstrate a clear trade-off between morphological development and stress-induced metabolic elicitation. The study underscores the utility of aeroponic systems for the precise manipulation of environmental factors to balance growth and bioactive compound accumulation. Overall, these results provide critical insights for optimizing cultivation strategies, allowing for the targeted use of UV-B to enhance the medicinal quality of chicory while managing the associated growth-biomass trade-offs.

Keywords Aeroponic system, Secondary metabolites, Oxidative stress, Phenolic compounds, Morpho-physiological responses

Chicory (*Cichorium intybus* L.), a typical Mediterranean erect perennial herb, is widely recognized for its multifaceted applications in culinary and medicinal domains. Its roots are particularly valued for their high content of bioactive compounds such as inulin, a prebiotic dietary fiber, as well as flavonoids and phenolic acids that contribute to antioxidant, anti-inflammatory, and hepatoprotective properties^{1,2}. With the increasing global demand for functional foods and natural therapeutics, understanding the factors that influence both growth and bioactive compound accumulation in chicory has become critical.

Ultraviolet-B (UV-B) radiation, a component of the solar spectrum with wavelengths between 280 and 320 nm, is a key environmental factor influencing plant physiology. UV-B can modulate photosynthesis, morphology, and secondary metabolite production, exerting both beneficial and detrimental effects depending on the exposure intensity and duration^{3,4}. Moderate UV-B exposure often enhances the accumulation of protective secondary metabolites, whereas excessive exposure triggers oxidative stress, reduces photosynthetic efficiency, and impairs plant growth⁵. In chicory, UV-B stress has been reported to stimulate the biosynthesis of phenolic compounds and other antioxidants, likely as a protective mechanism against reactive oxygen species (ROS) generated under high UV conditions^{6,7}. However, these protective responses can be accompanied by

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growth inhibition, particularly affecting root and shoot development, highlighting the complex trade-off between medicinal quality and biomass accumulation⁸.

Previous studies have demonstrated that UV-B radiation can significantly alter plant morphology and physiology across multiple species. Laurencikova⁹ reported that UV-B influences light absorption and photochemical responses, particularly in photosystem II, leading to photomorphogenic changes such as reduced plant height and biomass. Kataria et al.¹⁰ highlighted similar effects, while Chen et al.¹¹ observed reductions in shoot height, total leaf area, net photosynthetic rate, and chlorophyll content in *Morus alba* under enhanced UV-B exposure. UV-B stress also causes distorted morphological features, including reduced seedling length and dry biomass, increased auxiliary branch formation, and leaf deformities, as demonstrated by León-Chan et al.¹². Studies by Zuk-Golaszewska et al.¹³ on *Avena sativa* and *Setaria viridis* revealed significant alterations in plant height and fresh weights of leaves, shoots, and roots, alongside leaf curling as a response to UV-B. Similarly, Bernal et al.¹⁴ reported that UV-A and UV-B modulate biomass, relative water content, and water use efficiency in *Laurus nobilis* L., particularly under drought stress conditions.

Chicory (*Cichorium intybus* L.), a perennial herbaceous plant native to Europe, North Africa, and Western Asia, has gained global importance due to its medicinal and functional properties. Research by Mariz-Ponte et al.¹⁵ found that even low UV-B levels can enhance reactive oxygen species (ROS) production and stimulate productive capacity in *Solanum lycopersicum*, suggesting its potential as a cultivation tool. Furthermore, studies on *Anabaena doliolum* and *Trigonella foenum-graecum* demonstrated significant increases in enzymatic antioxidants—including superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and peroxidase (POD) as well as non-enzymatic antioxidants such as carotenoids, anthocyanins, flavonoids, and phenolics under UV-B radiation, highlighting its role in triggering defense mechanisms^{16–19}.

Cultivating plants in controlled environments offers opportunities to improve the quality, consistency, bioactivity, and biomass production of medicinally important crops²⁰. Aeroponic systems, a subset of soil-less cultivation, involve enclosing underground organs in a dark chamber and supplying them with a fine mist of nutrient solution. This approach enhances root aeration, nutrient absorption, and overall biomass accumulation compared to traditional hydroponics²¹. Despite these advantages, investigations on the effects of UV-B radiation specifically on roots—particularly in aeroponic systems—remain scarce. Given the accessibility of roots in aeroponics, studying their morpho-physiological and biochemical responses to UV-B represents a unique opportunity to optimize both growth and bioactive compound accumulation in chicory.

Understanding the interplay between UV-B stress and chicory physiology is crucial for developing targeted cultivation strategies that maximize medicinal value while minimizing adverse growth effects. Therefore, this study aimed to evaluate the impact of UV-B application at varying radiation distances on the morpho-physiological traits and biochemical properties of chicory roots under an aeroponic system, providing insights into optimizing its cultivation for functional food and herbal medicine applications.

Materials and methods

Plant material and growth conditions

Chicory seeds (PakanBazr Co., Isfahan, Iran) were initially sown in small pots within a greenhouse. Following a 30-day growth period, seedlings of uniform height (20 cm) were transplanted into a specialized aeroponic system (phytorhizotron). The greenhouse environment was maintained with a 16 L:8D photoperiod (06:00 to 22:00), a temperature of 25 °C, and 55% relative humidity.

Aeroponic system configuration

The phytorhizotron consisted of two sections: an overhead section for shoot development and a sealed “down section” (180 × 120 × 120 cm) maintained in darkness for root proliferation (Fig. 1). Seedlings were planted on the overhead surface at 13 × 13 cm intervals, with one-third of the plant height extending into the lower chamber. Roots were intermittently nourished every 20 min for 20 s using Hoagland solution (pH 5.8 ± 0.2; EC 1.6 ± 0.2 dS/m) dispensed through 15 fog nozzles. The phytorhizotron’s “down section” was engineered with a depth of 180 cm to accommodate the natural growth habit of the chicory taproot. In aeroponic systems, the lack of physical soil impedance allows herbaceous taproots to achieve maximum elongation and prolific lateral branching, which may appear more extensive than those grown in high-density soil.

Experimental design and UV-B treatments

The study employed a completely randomized design (CRD) with three replicates. To investigate the physiological response of root tissues to direct oxidative stress, two UV-B lamps (Philips TL40W/12/RS; 290–315 nm) were installed side-by-side within the root chamber of the aeroponic system.

While roots are typically shielded from light in soil-based environments, this aeroponic setup was intentionally designed to study the direct impact of artificial UV-B exposure on root secondary metabolism and stress-response mechanisms. Plants were positioned at three distances from the lamps: 40 cm (RD-40), 80 cm (RD-80), and 120 cm (RD-120). A separate group of plants, maintained in a distinct room within an identical phytorhizotron unit without UV-B exposure, served as the control (RD-0).

Ten days post-transplantation, roots were subjected to continuous UV-B radiation (24 h per day) for a duration of 20 days. This uninterrupted exposure regime was chosen to provide a constant elicitive stimulus to the root system, independent of the shoot’s 16 L:8D photoperiod. For all physiological and biochemical measurements, ten plants were randomly selected from each replicate ($n = 30$ per treatment) to ensure statistical robustness. Internal thermometers monitored for heat stress; however, no significant thermal fluctuations were recorded. As direct measurement of UV-B irradiance (W/m^2) was unavailable, treatment levels were defined by physical distance, a limitation addressed in the discussion.



Fig. 1. Schematic and operational view of the phytorhizotron system. (A) Overhead section showing shoot development under controlled photoperiod. (B) Sealed down-Sect. (180 cm depth) where roots are exposed to 24-h UV-B radiation via side-by-side Philips TL40W/12/RS lamps.

Morphological and biochemical assessments

Sixty days after transplantation, plants were harvested to evaluate growth and physiological status. Morphological parameters, including plant height, leaf number, leaf area, root length, root volume, and the fresh and dry weights of both shoots and roots, were recorded. Root volume was determined via the water displacement method using a graduated cylinder. These measurements were performed on ten randomly selected plants per replicate ($n=30$ per treatment) to ensure statistical validity.

Biochemical and enzymatic analyses

Photosynthetic pigments (chlorophyll *a* and *b*) were determined according to Lichtenthaler and Wellburn¹⁷. Total carbohydrates¹⁸, anthocyanin content¹⁹, and proline content (at 520 nm)²⁰ were quantified. Total phenolic content was extracted using Folin-Ciocalteu reagent and measured at 760 nm against a gallic acid calibration curve²¹. Electrolyte leakage was assessed following Ben-Hamed²², and soluble protein content was determined by the Bradford method²³.

Antioxidant enzyme extraction followed the protocol of²⁴: 0.5 g of fresh tissue was homogenized in 1 ml of extraction buffer and centrifuged (14,000 rpm at 4 °C for 15 min, followed by 10,000 rpm at 4 °C for 10 min). Catalase (CAT) activity was assessed by monitoring the decomposition of H₂O₂ at 240 nm²⁶, peroxidase (POD) activity was recorded via the guaiacol method at 470 nm²⁵, and ascorbate peroxidase (APX) was measured per Nakano and Asada²⁷. All physiological and biochemical assays were performed using middle leaf samples. This specific leaf age was selected to minimize experimental noise; middle leaves are fully expanded and metabolically

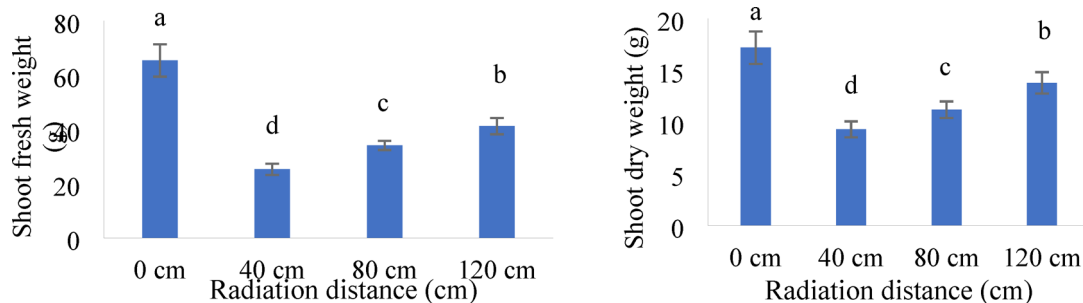


Fig. 2. Graphic mean (\pm standard deviation) comparison of shoot fresh weight, and shoot dry weight of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

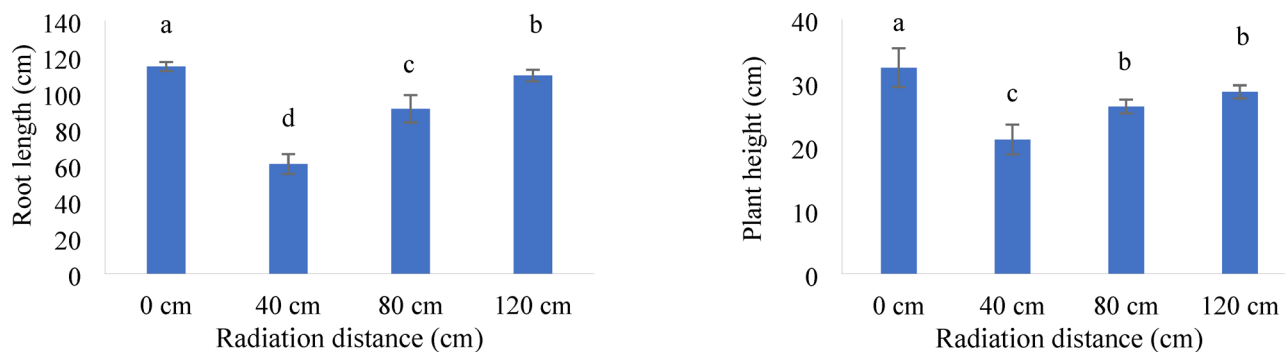


Fig. 3. Graphic mean (\pm standard deviation) comparison of (A, up left side) root length and plant height of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

stable, representing the functional maturity of the plant's canopy, unlike the highly variable developing apical leaves or senescing basal leaves.

Tissue selection and unit standardization

While the roots were the primary site of UV-B exposure, biochemical analyses were conducted on the middle leaves to evaluate the systemic physiological response and distal signaling effects triggered by root-zone stress. All enzyme activities are reported as specific activity in Units per milligram of protein (U/mg protein). One unit (U) of enzyme activity is defined as the amount of enzyme required to cause a 0.01 change in absorbance per minute under the specified assay conditions.

Statistical analysis

The initial analysis was the application of the Ryan-Joiner test for normality and the Levene test to assess the homogeneity of variances. Subsequently, an analysis of variance (ANOVA) was conducted and the means of radiation treatments were evaluated via Duncan's Multi Range Test (DMRT) at $P < 0.05$. SPSS 21.0 was employed for the execution of all statistical analyses.

Results and discussions

Mean comparisons revealed that UV-B radiation significantly modulated the morphological and biochemical profile of chicory in a distance-dependent manner. As the distance from the radiation source decreased, the intensity of stress symptoms increased, while the induction of protective secondary metabolites was concurrently upregulated.

Morphological responses and biomass accumulation

A significant ($P < 0.05$) reduction in shoot and root biomass was observed under high-intensity UV-B exposure. Specifically, shoot fresh and dry weights decreased by 61% and 46%, respectively, at the RD-40 treatment compared to the control (Fig. 2). This reduction in biomass is likely mediated by the UVR8 photoreceptor, which triggers photomorphogenic changes and growth inhibition under UV-B stress⁵.

Root development was similarly affected; root length at RD-40 (60.6 cm) was significantly lower than the control (114.6 cm), representing a reduction of approximately 47% (Fig. 3). Root fresh and dry weight also followed similar patterns (Fig. 4). Furthermore, a 62% decrease in root volume was recorded at the closest radiation distance (Fig. 5). These morphological shifts, including a 50% reduction in leaf number and a 35%

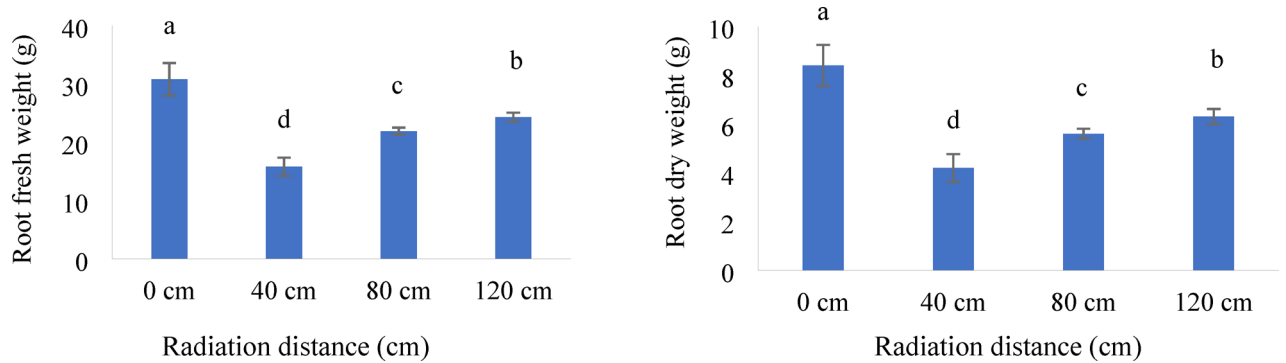


Fig. 4. Graphic mean (\pm standard deviation) comparison of root fresh weight, and root dry weight of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

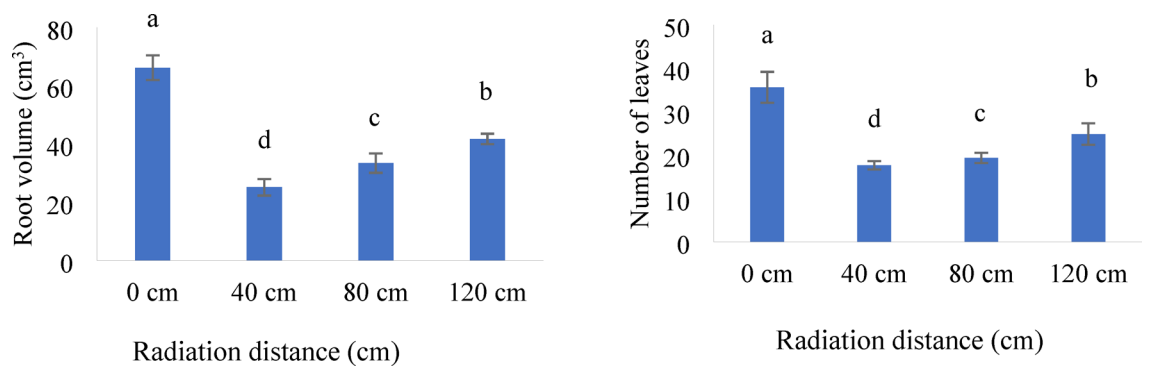


Fig. 5. Graphic mean (\pm standard deviation) comparison of root volume and number of leaves of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

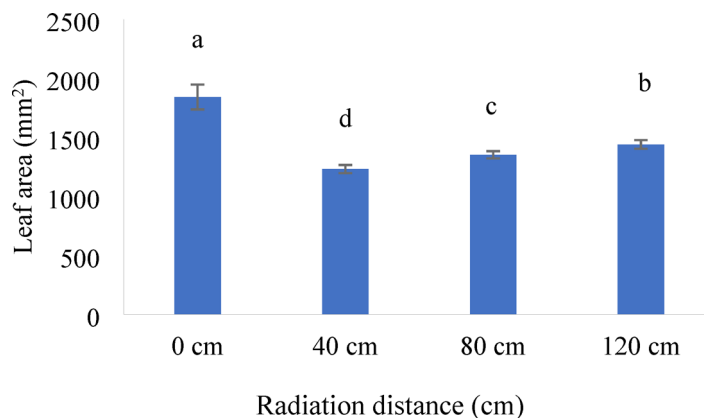


Fig. 6. Graphic mean (\pm standard deviation) comparison of leaf area of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

decrease in plant height are attributed to the suppression of cell division and DNA replication, a documented consequence of UV-B-induced oxidative damage to tubulins and microtubules^{28,29}. The reduction in leaf area by 33% (Fig. 6) further suggests a trade-off between biomass production and the synthesis of UV-screening compounds, such as flavonoids, which influence auxin transport via efflux carriers³⁰.

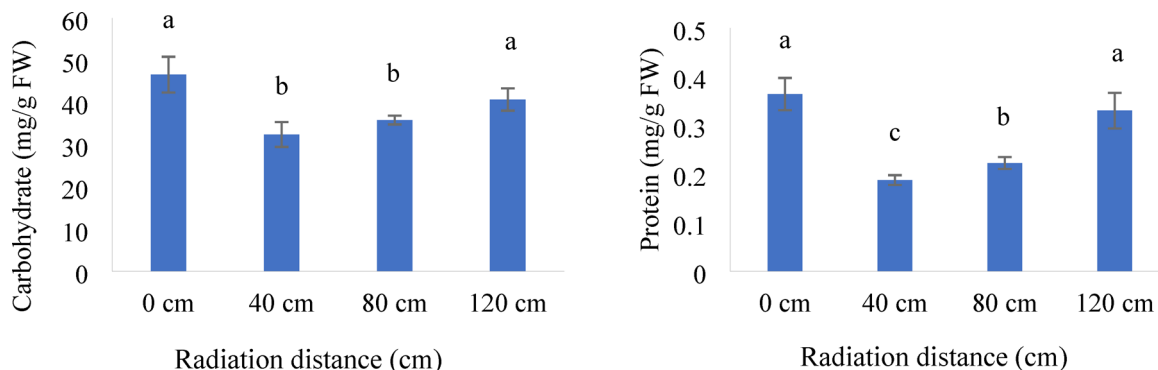


Fig. 7. Graphic mean (\pm standard deviation) comparison of (A, left side) carbohydrates, and (B, right side) proteins of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

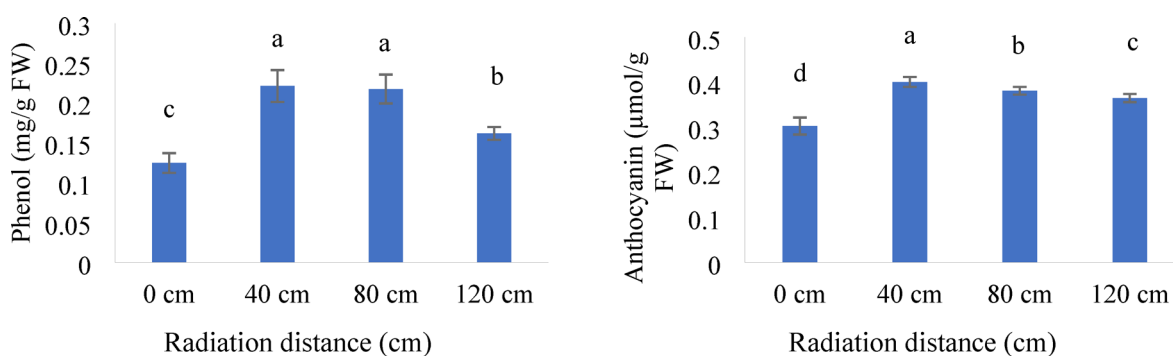


Fig. 8. Graphic mean (\pm standard deviation) comparison of (A, left side) total phenol, and (B, right side) anthocyanins of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

Primary metabolites and secondary signaling

Primary metabolism showed a threshold response to radiation distance. While carbohydrate and soluble protein levels in the RD-120 treatment did not differ significantly from the control, substantial declines were recorded at RD-40 and RD-80 (Fig. 7). The decrease in soluble proteins may stem from the inhibition of protein synthesis or the acceleration of protein degradation under acute oxidative stress³¹.

In contrast, secondary metabolites associated with defense were significantly upregulated. Total phenolic content at RD-40 and RD-80 increased by 78% and 75%, respectively, compared to the control (Fig. 8). This accumulation likely serves a dual purpose: acting as a biochemical shield against UV penetration and initiating lignification as a structural defensive barrier^{32,33}. Similarly, anthocyanin levels increased by 32% at the closest distance (RD-40), consistent with the role of light-induced gene expression in activating the phenylpropanoid pathway³⁴.

Antioxidant defense and physiological stress

To mitigate UV-B-induced reactive oxygen species (ROS), chicory plants deployed a robust antioxidant defense system. Proline content, a key osmoprotectant and ROS scavenger showed a dramatic 210% increase at RD-40 compared to the control (Fig. 9). This was accompanied by a significant rise in electrolyte leakage at RD-40 and RD-80, indicating that while defense mechanisms were active, some level of membrane lipid peroxidation occurred.

Antioxidant enzyme activities followed a similar trend. Catalase (CAT) activity increased 3.5-fold at RD-40, while peroxidase (POD) and ascorbate peroxidase (APX) also showed significant peak ($P < 0.05$) activities at the closest radiation distances (Figs. 10 and 11). These results confirm that the plant activates a systemic enzymatic defense to neutralize H_2O_2 and other free radicals generated by the distal UV-B stress applied to the root zone^{36,38}.

Photosynthetic pigments

Chlorophyll *a* and *b* concentrations were significantly lower in the RD-40 and RD-80 treatments compared to the control (Fig. 12). This degradation is likely due to the non-enzymatic photo-oxidation of pigments and the disruption of the photosynthetic apparatus (Photosystem II)^{3,40}. Interestingly, at the maximum distance (RD-

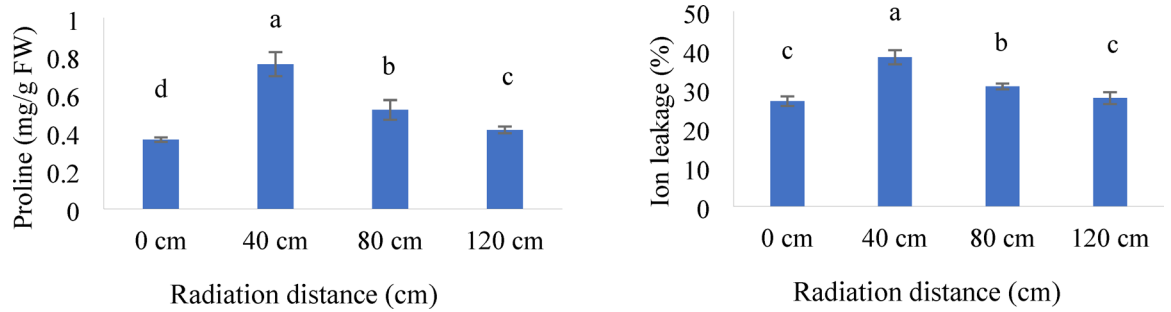


Fig. 9. Graphic mean (\pm standard deviation) comparison of (A, left side) proline, and (B, right side) ionic leakage of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

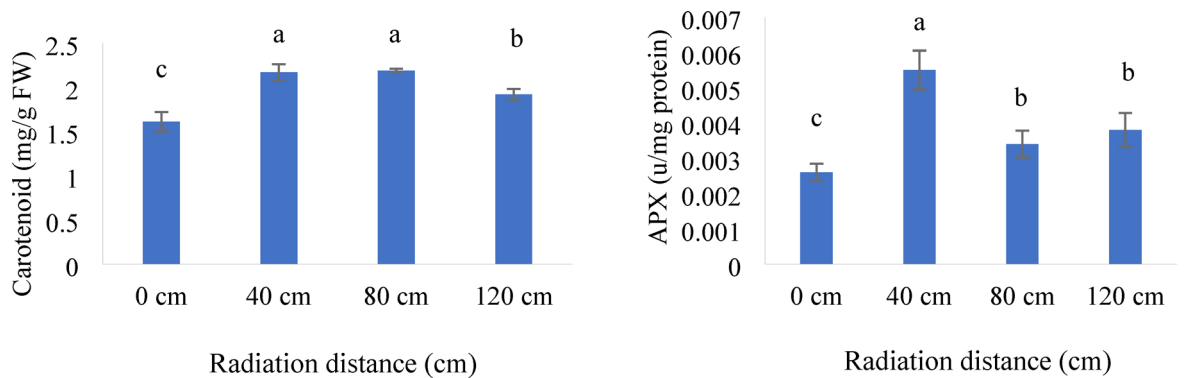


Fig. 10. Graphic mean (\pm standard deviation) comparison of (A, left side) carotenoid, and (B, right side) APX of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

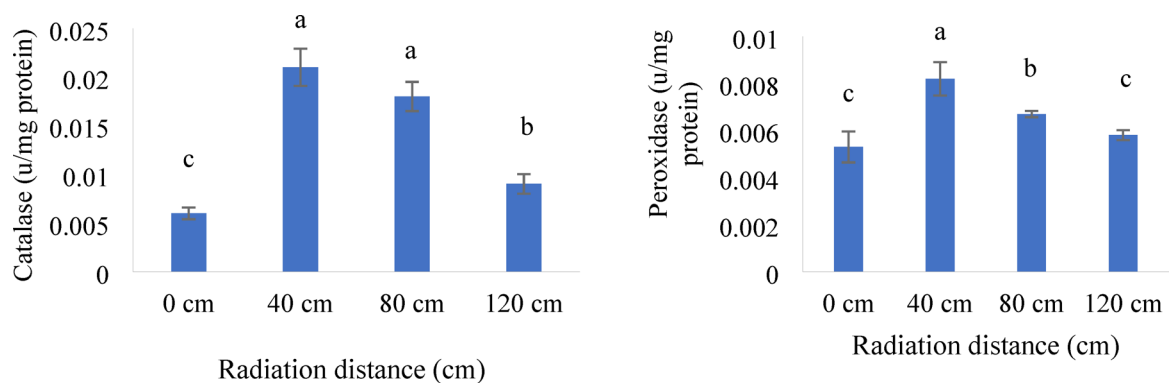


Fig. 11. Graphic mean (\pm standard deviation) comparison of (A, left side) catalase, and (B, right side) peroxidase of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

120), chlorophyll *a* levels remained statistically comparable to the control, suggesting that lower UV-B intensities may be tolerated without compromising the primary photosynthetic machinery.

Multivariate analysis of UV-B impact

To provide a comprehensive overview of the distance-dependent effects on chicory, a Radar Plot was generated based on standardized mean values of all 21 measured traits (Fig. 13). This multivariate visualization highlights a clear physiological divergence:

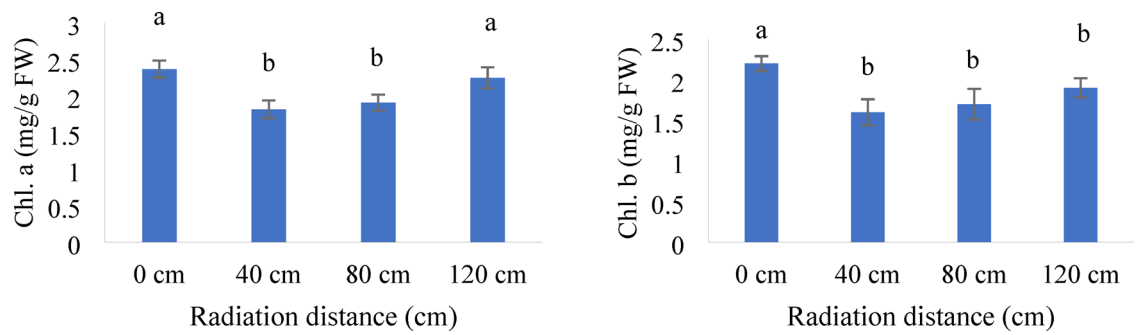


Fig. 12. Graphic mean (\pm standard deviation) comparison of (A, left side, left side) chlorophyll a, and (B, right side) chlorophyll b of chicory at various UV-B radiation distances. Different letters indicate significant differences ($P < 0.05$) using ANOVA followed by Duncan's Multi Range Test.

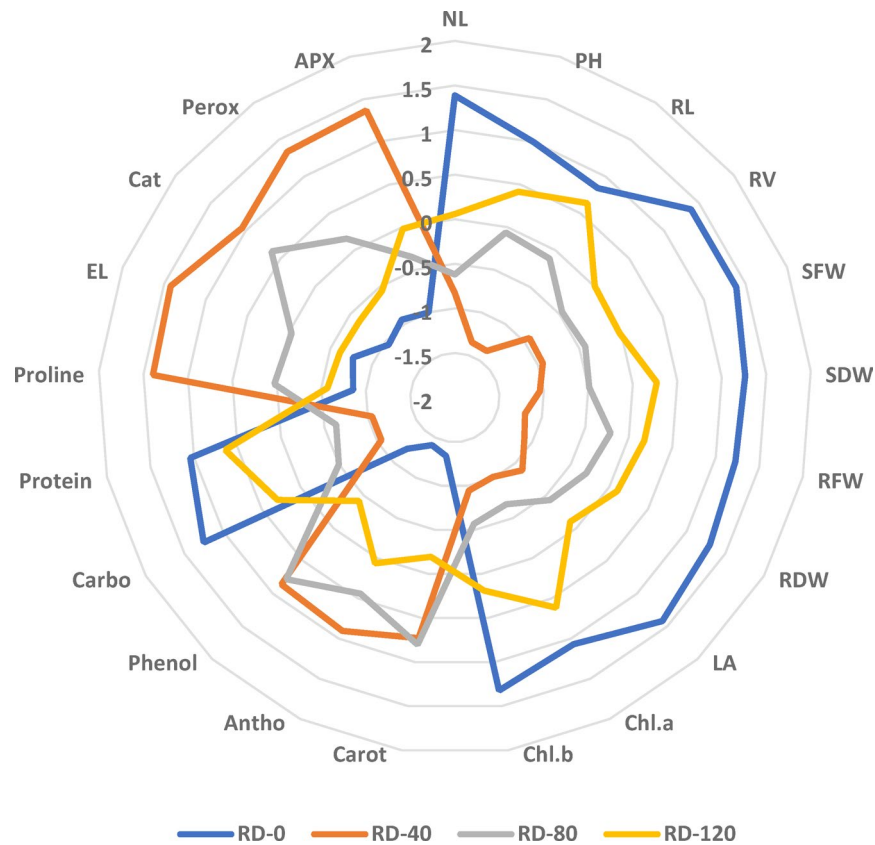


Fig. 13. Radar plot of all measured traits of chicory at four UV-B radiation distances (0,40, 80 and 120 cm). Traits are: NL, number of leaves; PH, plant height; RL, root length; RV, root volume; SFW, shoot fresh weight; SDW, shoot dry weight; RFW, root fresh weight; RDW, root dry weight; LA, leaf area; Chl.a, Chlorophyll type a; Chl.b, Chlorophyll type b; Carot, carotenoids; Antho, anthocyanins; Phenol, phenol content; Carbo, carbohydrates; Protein, soluble proteins content; Proline, proline content; EL, Electrolyte leakage; Cat, catalase; Perox, peroxidase; and APX, ascorbate peroxidase.

- **The control (RD-0) and RD-120:** These treatments clustered together on the right-hand side of the plot, showing superior performance in growth-related parameters such as plant height (PH), leaf number (NL), and soluble protein content.
- **RD-40 and RD-80:** These treatments dominated the left-hand side of the plot, exhibiting the highest values for stress-response markers, including antioxidant enzymes (CAT, POD, APX), proline, electrolyte leakage (EL), and protective pigments (anthocyanins and carotenoids).

This separation confirms that while proximity to the UV-B source significantly impairs vegetative development, it simultaneously acts as a powerful elicitor for the plant's secondary metabolism and antioxidant machinery.

| Control | Growth parameters | Phenotype characteristics |
|-------------------------------|---|--|
| Root growth | Moderate root elongation, good lateral growth | Roots well-developed, dense, no visible stress symptoms |
| Root length | About 120 cm | Long, robust primary root |
| Root diameter | 2–3 cm | Uniform thickness throughout |
| Lateral root density | High | Well-distributed lateral roots, no abnormalities |
| Root color | White to light brown | Healthy, no signs of oxidative damage or discoloration |
| <i>UV-B stress</i> | | |
| Root growth | Reduced root elongation, fewer lateral roots | Root growth suppressed, shorter primary roots, less branching |
| Root length | About 70 cm | Roots significantly shorter than control, reduced overall biomass |
| Root diameter | 1–2 cm | Thinner roots, sometimes uneven diameter due to cellular damage |
| Lateral root density | Low to moderate | Reduced number of lateral roots, fewer branches, sparse development |
| Root color | Brownish to dark brown | Signs of oxidative stress, possible root tip necrosis |
| Reactive Oxygen Species (ROS) | High | Accumulation of ROS, leading to cell damage and root discoloration |
| Root Hair Formation | Reduced | Decreased root hair density, impacting nutrient uptake |
| Antioxidant Defense Response | Increased | Production of flavonoids, phenolic compounds to counter oxidative damage |

Table 1. Phenotype chart of root growth in chicory under normal and UV-B stress conditions.

Comparative root phenotypes

The phenotypic variations observed between the control and UV-B stressed roots are summarized in Table 1. Under stress conditions (particularly at RD-40), chicory roots underwent profound morphological and qualitative shifts. Primary root elongation was suppressed by approximately 41% compared to the control, accompanied by a noticeable reduction in lateral root density and root hair formation.

Furthermore, a distinct color transition from healthy white/light brown to a darker brownish hue was observed in irradiated roots. This discoloration is a classic symptom of oxidative damage and the accumulation of protective phenolic compounds in the rhizospheric tissues. These phenotypic markers illustrate the plant's attempt to prioritize defense over expansion, resulting in a significantly reduced, yet biochemically enriched root biomass.

Conclusions and way forward

This study demonstrates that UV-B radiation exerts distance-dependent effects on chicory within an aeroponic system. While high-intensity exposure (RD-40) significantly inhibits growth and reduces biomass, it serves as a potent elicitor for secondary metabolites, including phenolics, anthocyanins, and antioxidant enzymes.

For commercial application, these results suggest that controlled UV-B “pulsing” or specific distance management can be used in vertical farming or aeroponic facilities to enhance the medicinal quality of chicory without causing total biomass collapse. Specifically, intermediate distances (e.g., RD-80) may offer a balance between secondary metabolite induction and growth maintenance. Future research should investigate the molecular signaling pathways, particularly the root-to-shoot long-distance signaling, to fully elucidate how localized root-zone UV-B exposure modulates whole-plant physiology.

Data availability

The dataset is available from the corresponding author on reasonable request.

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Additional information

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