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RESEARCH ARTICLE

Morpho-physiological, water productivity and hyperspectral responses of lettuce to regulated deficit irrigation and mulching: Plastic mulch sustains yield under a 14-day pre-harvest deficit at 70% ETc

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Abstract

Regulated deficit irrigation (RDI) combined with soil mulching may reduce irrigation requirements while limiting yield losses in leafy vegetables. This study evaluated the morpho-physiological, productive, and hyperspectral responses of lettuce subjected to pre-harvest RDI under different mulching conditions. The experiment was conducted in a protected environment using a randomized block design with three soil cover conditions (no mulch, double-sided black-and-white plastic mulch, and rice straw mulch), four periods of RDI imposed before harvest (0, 7, 14, and 21 days), and four replications. During the deficit periods, irrigation was reduced to 70% of crop evapotranspiration (ETc), which was determined daily using constant water-table lysimeters. A 14-day RDI period reduced the irrigation depth from 131.6 to 110.9 mm without mulch and from 47.2 to 39.4 mm with plastic mulch, corresponding to water savings of 15.8 and 16.5%, respectively. Plastic mulch resulted in the highest overall yield (2.05 kg/m²) and water productivity (49.91 g/L), compared with 1.90 kg/m² and 16.49 g/L without mulch. Lettuce maintained shoot fresh mass and yield under plastic mulch when irrigation at 70% ETc was imposed during the 14 days preceding harvest, whereas extending the deficit to 21 days reduced plant growth and yield and increased electrolyte leakage. These responses were also reflected in the spectral behavior of the plants. Therefore, combining plastic mulch with irrigation at 70% ETc during the final 14 days before harvest reduced irrigation water use by 16.5% while maintaining lettuce yield, indicating a defined pre-harvest window for reducing water application without a significant productive penalty.

Keywords: Crop production; *Lactuca sativa* L.; productive efficiency; yield.

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1. Introduction

Efficient water management is essential in lettuce (*Lactuca sativa* L.) production because crop growth and marketable yield are highly responsive to water availability. Reduced water availability can restrict leaf expansion, biomass accumulation, and yield (Menezes et al., 2022). These morphological and productive responses may be accompanied by reductions in stomatal conductance, transpiration, and carbon assimilation under deficit irrigation (Villa e Vila et al., 2024). However, appropriate deficit-irrigation strategies can reduce water consumption and improve water productivity, if water restriction does not exceed the crop's tolerance (Terassi et al., 2021; Villa e Vila et al., 2024).

Regulated deficit irrigation (RDI) involves intentionally reducing water supply during selected periods of crop development to conserve water while minimizing yield losses (Romero-Trigueros et al., 2020; Terassi et al., 2021). Plant responses to water restriction involve physiological and biochemical adjustments, including stomatal regulation, abscisic acid (ABA)-mediated signaling, osmotic regulation, and antioxidant responses (Urbutis et al., 2024). These mechanisms may contribute to plant acclimation under moderate stress, whereas prolonged or severe water deficit can impair carbon assimilation, membrane integrity, growth, and yield (Urbutis et al., 2024; Villa e Vila et al., 2024). Therefore, the effectiveness of RDI

depends not only on deficit intensity but also on its duration and timing.

Soil mulching can modify crop responses to water restriction by reducing soil evaporation and improving water conservation in the root zone (Vialle et al., 2024; Helmy et al., 2025). Plastic and organic mulches differ in their physical properties and persistence and may therefore result in different crop responses under reduced irrigation. Studies have shown that irrigation management and mulch type can substantially affect irrigation requirements, crop growth, yield, and water productivity (Helmy et al., 2025; Pacetti et al., 2025). Thus, combining RDI with appropriate soil mulching may provide an opportunity to reduce irrigation requirements while buffering the effects of moderate water deficit.

Integrating morphological and productive traits with plant water status, membrane integrity, biochemical attributes, hyperspectral responses, and organic mulch decomposition may provide a more comprehensive characterization of crop responses to water restriction. Hyperspectral sensing is particularly promising because stress-induced changes in plant water status, pigments, biochemical composition, and tissue structure can alter spectral reflectance, providing complementary information to conventional plant measurements (Adhikari et al., 2025).

Therefore, this study aimed to determine how the duration of pre-harvest regulated deficit irrigation and mulch type affect the morpho-physiological, productive, water-productivity, and hyperspectral responses of lettuce subjected to irrigation at 70% of crop evapotranspiration (ETc) for 0, 7, 14, or 21 days before harvest under no mulch, double-sided black-and-white plastic mulch, or rice-straw mulch conditions.

2. Methodology

Study site

The study was conducted at the Technical Irrigation Center (CTI), an integral part of the State University of Maringá (UEM), located in the municipality of Maringá – PR (23º25'S, 51º57'W, and 542 m altitude). The protected environment was 25 m long, 7 m wide, and 3.5 m high, with sides covered by white anti-aphid netting and arched roof covered with 150-µm low-density polyethylene film.

Experimental design

The experiment was arranged in a randomized complete block design in a 3×4 factorial schemes, with four replications. The first factor consisted of three soil-cover conditions: no mulch (NM), double-sided black-and-white plastic mulch (PM), and rice-straw mulch (RM). The second factor consisted of four periods of regulated deficit irrigation (RDI) imposed before harvest: 0, 7, 14, and 21 days. During the RDI periods, irrigation was applied at 70% of crop evapotranspiration (ETc), whereas plants outside the deficit period received 100% ETc. Each experimental unit consisted of a 3.0×0.5 m bed (1.5 m^2), 0.5 m deep, containing 10 lettuce plants spaced 0.30 m apart. Six central plants per experimental unit were used for evaluations, while border plants were excluded. Therefore, each treatment combination comprised 40 plants distributed among four replicate plots, of which 24 plants were evaluated. The entire experiment comprised 480 plants, with 288 plants constituting the effective experimental sample.

Crop management

Commercial seedlings of hybrid lettuce (BS-068) were used for crop establishment, transplanted into pre-fertilized beds following soil chemical analysis and specific crop recommendations, as described by Pauletti & Motta (2019). The lettuce plants were spaced 0.30 m apart within the beds.

During the first seven days after transplanting (DAT), all plants received full irrigation (100% ETc) to ensure seedling establishment. Thereafter, irrigation was maintained at 100% ETc until the beginning of the respective RDI period. Water restriction was progressively initiated according to each treatment so that plants were subjected to 70% ETc during the final 7, 14, or 21 days before harvest, whereas the control treatment remained at 100% ETc throughout the crop cycle. All treatments were harvested at 35 DAT.During the experiment, no diseases were observed. Pest control was carried out as needed, considering the incidence in the experimental area. When identified, neem oil was applied following the manufacturer's recommendations.

Irrigation management

Irrigation was performed using a drip system. Each experimental plot was equipped with 10 pressure-compensating emitters with a nominal flow rate of 4 L/h, spaced 0.25 m apart and operated at a pressure of 10 m water column (approximately 98 kPa). An individual valve installed at the beginning of each lateral line allowed independent irrigation management among experimental plots.

Crop evapotranspiration (ETc) was determined using constant water-table lysimeters installed inside the protected environment, following the methodology described by Andrian et al. (2022). Three lysimeters were used for each soil-cover

condition (NM, PM, and RM), totaling nine lysimeters. Each lysimeter had a capacity of 1000 L and an upper diameter of 1.52 m. Water consumption was determined using a graduated scale with a resolution of 0.1 mm.

Crop water consumption was monitored daily, with readings performed at 08:00 h. Thus, irrigation replacement was based on daily ETc measurements rather than averaged ETc values. During the first seven DAT, all treatments received 100% ETc. Thereafter, irrigation was maintained at 100% ETc until the beginning of each RDI period.

During the deficit periods, irrigation replacement was determined as $I_{RDI} = 0.7 \times ETc$. where I_{RDI} is the irrigation depth applied under regulated deficit irrigation and ETc is the daily crop evapotranspiration determined using the constant water-table lysimeters. The RDI treatments were progressively initiated to provide 7, 14, or 21 consecutive days at 70% ETc immediately before harvest, while the control remained at 100% ETc.

Evaluations

Border plants were discarded to ensure the evaluation was based only on plants within the effective experimental area. Of the 10 plants in each experimental unit, six central plants were used for the evaluations. The lettuce crop was harvested 35 days after transplanting (DAT). For the final evaluation, plant height and diameter in the experimental area were measured using a graduated ruler. Then, the lettuce plants from the effective experimental area were removed by cutting the stems at the soil level. After harvest, the plants were taken to the laboratory, where the following characteristics were evaluated: number of leaves, fresh shoot and stem mass (measured using a digital scale), dry shoot and stem mass (measured using a forced-air oven at 65 °C until constant weight), and leaf area per plant (measured using a LI-COR® LI-3100 leaf area meter).

Based on crop yield data and the volume of water used for irrigation, water productivity was calculated using Equation 1, in which WP: water productivity (g/L); CP: crop productivity (g/plant); VWA: volume of water applied (L/plant).

$$WP = \frac{\mathrm{CP}}{\mathrm{VWA}} \qquad (1)$$

To determine electrolyte leakage (EL), a hole punch was used to obtain three leaf discs per treatment. These discs were washed and placed in test tubes containing 10 mL of deionized water. The tubes were sealed and left to stand for 24 hours. The initial conductivity (Ci) of the medium was then measured using a benchtop conductivity meter. The tubes were subsequently subjected to a temperature of 100 °C for 60 minutes in a water bath. After cooling, the final conductivity (Cf) was measured. Electrolyte leakage was expressed as the percentage of conductivity relative to total conductivity, as calculated using Equation 2, detailed by Campos and Pham Thi (1997), in which EL: electrolyte leakage (%); IC: initial conductivity (S/m); FC: final conductivity (S/m).

$$EL\ (\%) = \frac{\mathrm{IC}}{FC}\mathrm{x}100 \qquad (2)$$

To determine relative water content in the aerial portion (RWC), three leaf discs per plant were collected using a hole punch. These discs were weighed on an analytical balance to obtain the fresh mass (FM_{RWC}). They were then immersed in distilled water for 24 hours to measure the turgid mass (TM_{RWC}). Subsequently, the material was dried in a forced-air oven at 80 °C for 24 hours to determine the dry mass (DM_{RWC}). Based on these data, RWC (%) was calculated using Equation 3, as described by Smart & Bingham (1974), in which RWC: relative water content (%); FM_{rwc}: fresh mass (g); DM_{rwc}: dry mass (g); TM_{rwc}: turgid mass (g).

$$RWC = \frac{FMrwc - DMrwc}{TMrwc - DMrwc}\ x\ 100 \qquad (3)$$

Nitrate concentration and total polyphenol content were also determined in lettuce leaves. Nitrate concentration was determined spectrophotometrically using the salicylic acid colorimetric method described by Cataldo et al. (1975), and the results were expressed as mg/kg fresh mass. Total polyphenol content was determined spectrophotometrically using the Folin–Ciocalteu method, with gallic acid as the reference standard, and the results were expressed as mg gallic acid equivalents (GAE)/g fresh mass.

Rice straw samples were collected and sent to the laboratory at the State University of Maringá. In the laboratory, the samples underwent drying in a forced-air oven at 65 °C for 72 hours to determine biomass yield. The dried rice straw was divided into 5 g portions and placed in decomposition bags made of tulle, a hexagonal transparent fabric measuring 10×15 cm. The exact quantity was measured using an analytical balance (± 0.001 g). On the day of lettuce transplanting, five decomposition bags were distributed in each bed.

The collected samples were returned to the UEM laboratory, where they were processed to remove foreign materials such as soil, insects, and debris. The remaining straw in the bags underwent a second drying stage in a forced-air oven at 105 °C for 24 hours. After drying, the residual straw mass

was measured using an analytical balance (± 0.001 g). Regression analysis was conducted based on the remaining straw content in the decomposition bags to estimate the decomposition rate throughout the lettuce growth cycle.

At 28 DAT, the ASD Fieldspec 3 spectroradiometer (ASD Inc.TM) connected to a Plant Probe was used to obtain the spectral response of lettuce in the wavelength range of 350 to 2500 nm. Spectral readings were taken from an intermediate leaf of the plants.

Data analysis

The collected data were subjected to analysis of variance (ANOVA) using the F-test, verifying the assumptions of ANOVA, and means were compared using Tukey's test at a 5% significance level, employing the SISVAR statistical software (Ferreira, 2019). Hierarchical cluster analysis was performed for fresh shoot mass and water productivity using the paired-group algorithm (UPGMA) based on Euclidean distance. Dendrograms were generated using PAST software, version 4.03.

3. Results and discussion

Water deficit and lettuce morphological responses

The practice of regulated deficit irrigation (RDI) plays a crucial role in the efficient management of water resources in contemporary agriculture, influencing not only crop growth and development but also resource use efficiency (Yang et al., 2017). The interaction between the application of RDI and the appropriate choice of soil cover can be essential for maximizing agronomic benefits under water scarcity conditions.

Previous studies have shown that the strategic combination of RDI with different types of soil cover can not only mitigate the negative effects of water deficit but also promote significant improvements in crop productivity and quality (Li et al., 2023). In this context, this study explored how different water deficit conditions and soil cover types affect morphological variables, yield, and hyperspectral behavior of lettuce crops. This integrated approach is essential for understanding the practical impacts of these interactions on sustainable water management and agricultural productivity.

The application of regulated deficit irrigation resulted in substantial water savings throughout the crop cycle. When 70% ETc was applied during the last 14 days before harvest, total irrigation depth was reduced from 131.6 to 110.9 mm under no soil cover, representing a water saving of 15.8%. Under plastic mulch, irrigation depth decreased from 47.2 to 39.4 mm, corresponding to a water saving of 16.5%, while under vegetative mulch the reduction was 15.7% (from 111.8 to 94.3 mm) (Table 1). These results indicate that the pre-harvest RDI strategy effectively reduced irrigation water input, although the absolute irrigation requirement differed among soil-cover conditions.

Table 1
Presents the amount of water supplied to the plants during the cultivation cycle for each treatment, including plastic cover, vegetative cover, and no cover

Water deficit period	Water depth (mm)		
	Without cover	Plastic cover	Vegetation cover
0	131.63	47.15	111.76
7	120.67	43.14	101.56
14	110.86	39.37	94.26
21	101.43	36.10	86.10

The variables fresh and dry aerial mass, fresh and dry stem mass, height, number of leaves, diameter, relative water content (RWC), electrolyte leakage, water productivity, leaf area, polyphenols, and nitrate were significantly influenced ($p < 0.05$) by the imposed water deficit period. Regression models were fitted to describe the responses of these variables to the duration of water deficit, as presented in Figure 1.

Fresh and dry aerial mass, fresh and dry stem mass, plant height, number of leaves, diameter, leaf area, and relative water content showed relatively small changes between 0, 7, and 14 days of water deficit, whereas a more pronounced reduction was observed after 21 days. This pattern indicates that lettuce tolerated a moderate pre-harvest water restriction, but extending the deficit period increased the negative effects on vegetative growth. Similar responses were reported by Menezes et al. (2022), who observed reductions in lettuce growth as water availability decreased. More recently, Li et al. (2023) demonstrated that water deficit affects several morphological and physiological traits of lettuce, including aboveground biomass and relative water content, although the magnitude of the response varies among genotypes. Reduced water availability can restrict leaf expansion and biomass accumulation through changes in plant water status and stomatal regulation. Under increasing water deficit, stomatal closure reduces water loss but also limits CO_2 assimilation, which can ultimately decrease biomass accumulation when the stress becomes sufficiently prolonged or severe. This interpretation is consistent with recent lettuce studies showing that water-deficit responses involve coordinated changes in morphological and physiological traits (Li et al., 2023) and that the magnitude of yield reduction depends on the intensity of irrigation restriction (Villa e Vila et al., 2024).

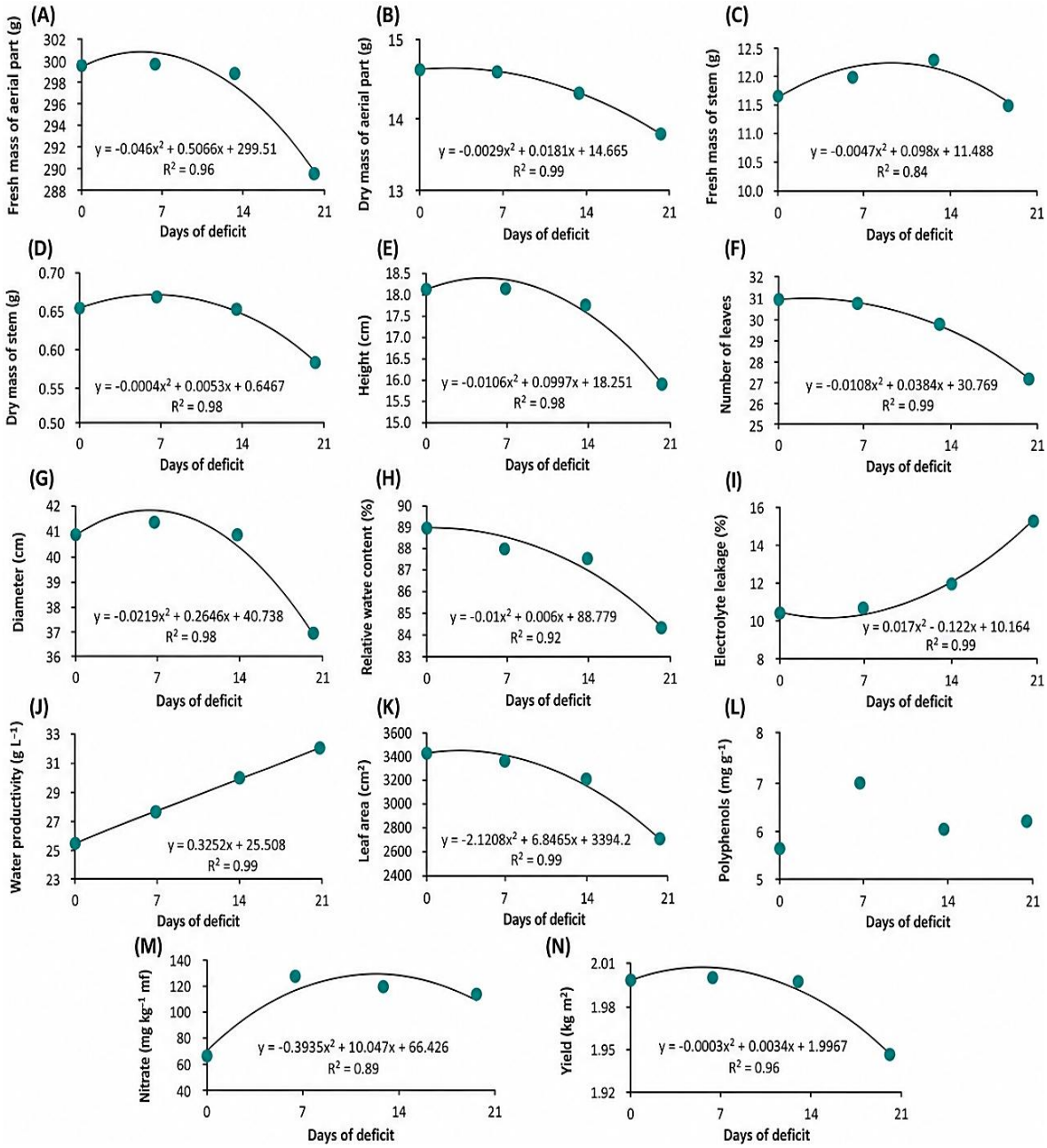

Figure 1. Characteristics of lettuce crops: Fresh mass of part aerial (A), dry mass of part aerial (B), fresh mass of stem (C), dry mass of stem (D), height (E), number of leaves (F), diameter (G), relative water content (H), electrolyte leakage (I), water productivity (J), leaf area (K), polyphenols (L), nitrate (M), and yield (N) as a function of water deficit days.

In Figure 1N, the highest estimated yield occurred under full irrigation (2.05 kg/m²), followed by a progressive reduction as the pre-harvest deficit period increased. Recent evidence similarly indicates that lettuce yield responses depend strongly on deficit intensity; moderate reductions in water supply may preserve production under appropriate management, whereas more severe water restriction progressively reduces biomass and yield (Li et al., 2019, Villa e Vila et al., 2024).

Physiological responses to regulated deficit irrigation

Electrolyte leakage is often used as an indicator of cell membrane integrity, reflecting the plant's ability to maintain its cellular structure under adverse conditions (Kovaleski & Grossman, 2021). The analysis of electrolyte leakage shows a positive quadratic behavior, indicating that the percentage of electrolyte leakage increased with prolonged water deficit periods, being most pronounced in the 21-day treatment (Figure 1I).

As the intensity and duration of water stress increases, membrane permeability rises, resulting in greater electrolyte leakage. This phenomenon is a common physiological response of plants to stress, reflecting potential damage to cell membranes caused by water scarcity (Martins et al., 2018). Regarding polyphenols, it was not possible to adequately fit a quadratic model to the relationship between their concentration and the intensity of water deficit, indicating that their response was not proportional to the duration of water restriction.

Biophysical water productivity increased linearly with the duration of water deficit. While plants under full irrigation presented an average water productivity of approximately 16.5 g/L, values increased to nearly 50 g/L under the plastic mulch treatment, representing an increase of more than 200% compared to the no-cover condition (Figure 1J; Table 2). Soil cover significantly influenced crop performance. Plastic mulch increased fresh shoot mass to 307.3 g/plant, compared to 298.3 g/plant under vegetative mulch and 285.2 g/plant in the no-cover treatment. Yield followed the same pattern, reaching 2.05 kg/m² under plastic mulch, which was 7.9% higher than the no-cover treatment (1.90 kg/m²) (Table 2).

Lettuce plants showed an ability to adapt to periods of water stress, suggesting the activation of internal mechanisms that positively influence water productivity (Figure 1J), highlighting the crop's favorable response to moderate water scarcity (70% of ETc). This relationship suggests specific adaptive strategies in lettuce to optimize water use at critical moments, possibly involving physiological and biochemical adjustments that maintain plant growth and development even under unfavorable water availability conditions.

When exploring the relationship between polyphenol content and water deficit intensity, no clear trend was observed (Figure 1L). This response highlights the complexity of phenolic metabolism under water deficit, since the accumulation of these compounds may depend on stress intensity and duration, plant developmental stage, and interactions with other environmental factors. Water deficit can stimulate phenolic metabolism as part of the antioxidant response to oxidative stress; however, this response is not necessarily linear, which may explain the variability observed among deficit periods.

Beyond cellular integrity, water deficiency in crops can cause variations in the accumulation of compounds such as nitrate, which is directly related to the plant's ability to assimilate nutrients under different water conditions. The lowest accumulated nitrate value was recorded in the treatment without water deficit, indicating an inverse relationship between water availability and nitrate accumulation in lettuce plants (Figure 1M). Changes in nitrate concentration under water deficit may be associated with alterations in nitrate uptake, transport, reduction, and assimilation, since water limitation affects both nutrient transport and nitrogen metabolism.

From a food-safety perspective, nitrate accumulation in lettuce deserves attention because excessive concentrations in leafy vegetables are regulated due to potential risks to human health. Commission Regulation (EU) 2023/915 establishes maximum nitrate levels for fresh lettuce that vary according to cultivation conditions and harvest period. The nitrate concentrations observed in the present study were substantially below these regulatory limits, indicating that, although water deficit increased nitrate accumulation, the concentrations recorded under the experimental conditions did not represent a concern when compared with current European regulatory thresholds.

The analysis of electrolyte leakage showed that the percentage of leakage increased with prolonged water deficit periods, being most significant in the 21-day deficit condition. This indicates that the intensity and duration of water stress increase cell membrane permeability, resulting in greater electrolyte leakage (Figure 1I).

Table 2

Mean values of lettuce morphological, physiological, productive, and water productivity variables as affected by soil cover

	FMPA (g)	MSPA (g)	MFR (g)	MSR (g)	Height (cm)	D (cm)	NF	RWC (%)
No cover	285.19 c	13.87 c	9.04 b	0.51 c	14.76 c	37.75 b	26 c	84.93 b
Plastic cover	307.33 a	14.75 a	13.06 a	0.70 a	20.29 a	45.79 a	34 a	88.55 a
Vegetal cover	298.32 b	14.45 b	13.02 a	0.69 b	17.37 b	36.08 b	28 b	87.91 a
CV (%)	0.58	2.20	4.37	2.83	6.10	4.08	5.57	1.97

	EE (%)	Water productivity (g/L)	Leaf area (cm²)	Nitrate (mg/kg mf)	Polyphenols (mg/g)	Yield (kg/m²)
No cover	13.57 a	16.49 c	2846.27 c	53.44 c	2.59 c	1.90 c
Plastic cover	10.29 c	49.91 a	3381.97 a	87.57 b	7.76 b	2.05 a
Vegetal cover	11.52 b	20.38 b	3078.74 b	172.28 a	8.29 a	1.99 b
CV (%)	3.71	0.53	1.41	8.55	8.12	0.54

Legend: FMPA: Fresh mass of aerial part; MSPA: Dry mass of aerial part; MFR: Fresh mass of stem; MSR: Dry mass of stem; Height: Plant height; D: Diameter; NF: Number of leaves; RWC: Relative water content; EE: electrolyte leakage.

In addition to the intrinsic adaptive strategies of lettuce, another agricultural practice that significantly influenced cultivation conditions was the use of double-sided black-and-white plastic mulch (Table 2). This type of cover is effective in regulating soil temperature, conserving moisture, and reducing weed incidence (Kader et al., 2017). The black side facing downward helps absorb and retain heat, keeping the soil warm, while the white side facing upward reflects sunlight, preventing excessive plant heating and reducing injuries (Queiroga et al., 2015). These combined factors can create a favorable microclimate for lettuce development. In the present study, yield under plastic mulch averaged 2.05 kg/m², compared with 1.99 kg/m² under vegetative mulch and 1.90 kg/m² without soil cover (Table 2).

Interaction between soil cover and regulated deficit irrigation

The interaction between factors (deficit days and soil cover) was significant for the variables shoot fresh weight, leaf area, stem dry weight, electrolyte leakage, yield, water productivity, nitrate, and polyphenols, indicating that deficit days and soil cover act interdependently. Figure 2 presents the quadratic regression, significant at a 5% probability level, showing the behavior of deficit periods under each cover type for the significant variables.

In Figure 2F, it can be observed that the treatment with 21 days of water deficit showed the highest increase in electrolyte leakage, especially under the no-cover condition. This highlights the critical importance of proper selection and management of soil cover in protecting against cell damage induced by water deficit, emphasizing the need for agronomic practices that promote plant health and resilience under adverse conditions.

While lettuce demonstrates high water use efficiency in terms of productivity, the increase in electrolyte leakage with prolonged water deficit indicates a more pronounced physiological response, highlighting the adverse effects of water stress on cell integrity.

The interaction responses further indicate that the effects of water deficit depended on the soil-cover condition. The response of plastic mulch combined with water management can be attributed to several beneficial factors that positively impact lettuce growth and development. Plastic mulch acts as a physical barrier that reduces direct soil water evaporation, helping to maintain adequate moisture levels in the plant root zone (Kader et al., 2017).

This specific water management practice, combined with plastic mulch, demonstrates synergy in efficient water use, ensuring an adequate supply to the crop without drastically compromising lettuce fresh mass (Figures 2A and 2C). In particular, the 70% ETc treatment imposed during the final 14 days before harvest under plastic mulch-maintained yield close to the fully irrigated condition while reducing the irrigation water applied, indicating that a moderate and temporally restricted deficit can be combined with plastic mulch without a marked productive penalty. When analyzing factor interactions, plastic mulch showed higher fitted responses for five variables (shoot fresh weight, stem dry weight, leaf area, yield, and water productivity), followed by organic mulch and then the no-cover condition. These results highlight the influence of plastic mulch under different water deficit periods.

In the dendrogram clustering of shoot fresh weight means, the smallest Euclidean distance occurred in the group with plastic mulch, while the group with no mulch and the longest water deficit period was the most distant (Figure 3A). The dendrogram for water productivity revealed two distinct groups: one exclusively composed of plastic mulch conditions and another including organic mulch and no-mulch conditions (Figure 3B). This indicates that plastic mulch produced a distinct response pattern for water productivity compared with organic mulch and no-mulch conditions.

Plastic mulch can create a favorable microclimate around the plants, protecting them from abrupt temperature variations and minimizing the impact of water stress. This additional protection can contribute to more stable soil moisture and temperature conditions, favoring crop development under water-limited conditions (Kader et al., 2017).

Figure 3 shows that the smallest Euclidean distance in the clustering of means occurred in the group with plastic mulch. This suggests that the plastic mulch treatments, across different water deficit periods, exhibited highly homogeneous results in terms of shoot fresh weight, indicating consistent lettuce shoot fresh weight.

Mulch decomposition and soil–water dynamics

The parameters of the equation and the half-life of rice straw are presented in Table 3. The straw decomposition equation enables the analysis of the interaction between the material and the environment, allowing for the development of soil cover management strategies.

Table 3
Parameters of dry matter decomposition equations of rice straw under different water deficit periods and half-life of the remaining matter

Water deficit period	Equation	R^2	Half-life (days)
0	y = -0.3538x + 97.336	0.87	133.79
7	y = -0.3619x + 97.911	0.92	132.39
14	y = -0.3572x + 98.659	0.96	136.22
21	Y= -0.2793x + 98.817	0.94	174.78

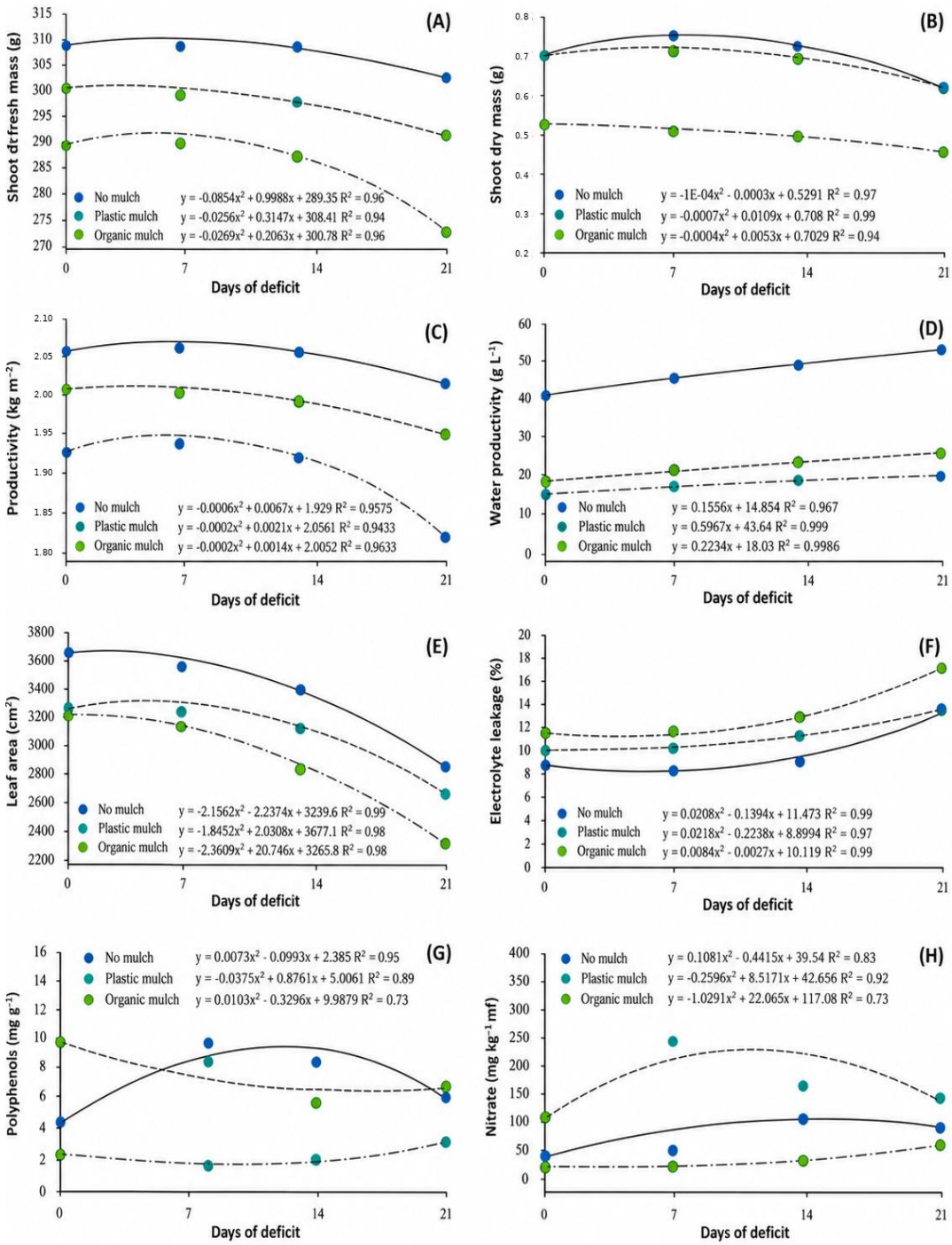

Figure 2. Characteristics of lettuce crops (shoot fresh weight (A), stem dry weight (B), yield (C), water productivity (D), leaf area (E), electrolyte leakage (F), polyphenols (G), and nitrate (H)) as a function of deficit days for the three types of soil cover.

Plants under mild water deficits associated with regulated deficit irrigation (RDI) often exhibit varying levels of response in photosynthesis and respiration because RDI is implemented with different levels of severity and at different growth stages (Chai et al., 2016).

In the present study, rice-straw decomposition was similar under 0, 7, and 14 days of deficit, with estimated half-lives ranging from 132.39 to 136.22 days. In contrast, the 21-day deficit increased the estimated half-life to 174.78 days (Table 3), indicating slower straw decomposition under the longest period of water restriction.

This hormonal regulation and water-use efficiency process is closely linked to soil cover management practices. The decomposition equation of the remaining straw (Table 3) allows for evaluating the material's interaction with the environment and defining soil cover management strategies (Figure 4). The slower decomposition observed under the 21-day deficit is consistent with reduced water availability limiting the biological processes involved in residue decomposition. Thus, although rice straw contributes to soil protection and water conservation, its persistence on the soil surface may also depend on irrigation management and the duration of water restriction.

The decomposition process showed significant differences ($p<0.05$) across sampling intervals. The amount of remaining biomass also influences soil cover conditions and, consequently, the decomposition process and nutrient release (Cavalli et al., 2018; Wenneck et al., 2021).

Figure 4 illustrates the differences in the amount of residual biomass on the soil surface throughout the lettuce growth cycle, with values estimated according to the equations presented in Table 3. It also shows that the half-life of the biomass is shorter when there is more water in the system, indicating faster decomposition under these conditions.

Reduced water availability in the soil is associated with a lower organic matter decomposition rate (Figure 4). The cultivation condition receiving 100% of ETc and the condition receiving 70% of ETc only during the last seven days of the crop cycle had a more adequate water supply, likely creating favorable conditions for microbial activity responsible for straw decomposition.

The half-life of the remaining dry matter is a measure that indicates the decomposition rate of organic residues in the soil. It represents the time required for half of the initial dry matter to decompose and be incorporated into the soil. This metric is essential in studies of nutrient cycling, agricultural residue management, and the evaluation of soil organic matter dynamics.

In tropical and subtropical regions, residual straw plays a crucial role in protecting the soil surface by moderating temperature fluctuations, reducing evapotranspiration, maintaining moisture in the upper soil layers, providing nutrients to crops through organic matter mineralization, and contributing to soil aggregate stabilization (Bueno & Rodrigues, 2019; Bonetti & Fink, 2020).

Wenneck et al. (2021) highlighted that the decomposition of residual biomass from agricultural species is influenced by environmental conditions, particularly water availability, which directly affects plant development, biomass accumulation, and yield.

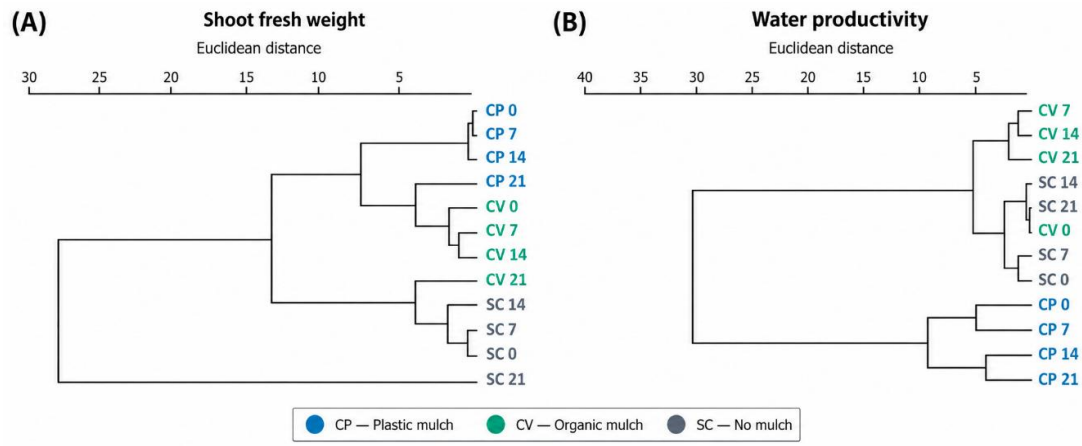

Figure 3. Dendrogram of lettuce shoot fresh weight (A) and water productivity (B). Legend: CP0 - Plastic mulch and 0 days of deficit; CP7 - Plastic mulch and 7 days of deficit; CP14 - Plastic mulch and 14 days of deficit; CP21 - Plastic mulch and 21 days of deficit; CV0 - Organic mulch and 0 days of deficit; CV7 - Organic mulch and 7 days of deficit; CV14 - Organic mulch and 14 days of deficit; CV21 - Organic mulch and 21 days of deficit; SC0 - No mulch and 0 days of deficit; SC7 - No mulch and 7 days of deficit; SC14 - No mulch and 14 days of deficit; SC21 - No mulch and 21 days of deficit.

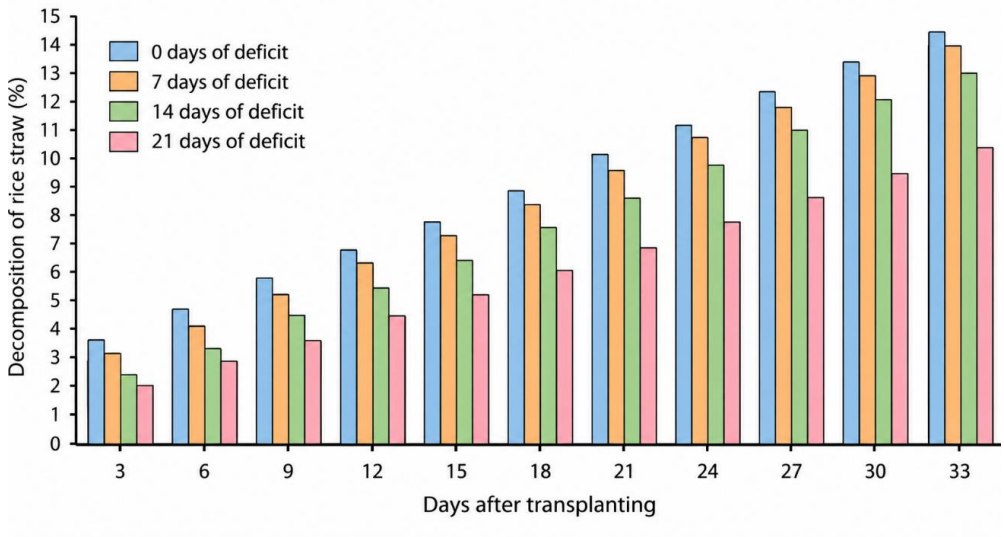

Figure 4. Decomposition of rice straw during the development of the lettuce crop.

In the decomposition process, the degradation rate of residues by soil microbiota depends on their chemical composition, especially the C/N ratio and lignin content, as well as environmental conditions such as temperature and moisture (Cunha et al., 2015). The persistence of straw on the soil surface is essential for maintaining and protecting the soil-plant system, promoting moisture retention, benefiting soil biota, and enhancing nutrient cycling. In no-tillage vegetable systems, understanding the decomposition of residual straw is crucial for implementing practices that enhance system efficiency. Organic residues are also effective in retaining water by reducing evaporation. Longhini et al. (2019) demonstrated this by cultivating lettuce with organic residues, particularly *Brachiaria brizantha* straw, which retained 87.1% soil moisture.

Hyperspectral response under water deficit and soil cover

As previously noted, the significant effects of soil cover and water deficit periods on morphological and yield parameters also influenced the hyperspectral behavior of lettuce plants. Figure 5 presents this hyperspectral behavior, highlighting differences in crop responses under various cultivation conditions.

In spectral datasets from plastic-covered treatments (Figure 5C), a subtle change in the mid-infrared pattern, associated with the vegetation's water condition, was observed (Zhang & Zhou, 2019). Wenneck et al. (2024) found greater spectral variation in tomato cultivation under water stress and without silicon application. Damm et al. (2018) highlighted that water-stressed plants exhibit higher leaf reflectance values than well-watered plants. Hyperspectral measurements have also been successfully used specifically in lettuce to distinguish plants subjected to water stress and to estimate physiological and quality-related attributes, supporting the sensitivity of spectral information to changes induced by plant water status (Yu et al., 2023).

Spectral data from plastic-covered deficit treatments (Figure 5C) showed reduced variation, suggesting that plastic mulch acts as a mitigating factor, which may have reduced differences in plant water status among deficit periods and, consequently, the magnitude of spectral variation.

Chen et al. (2019) and Michelon et al. (2020) observed improved water use efficiency in lettuce (*Lactuca sativa* L.) under RDI combined with plastic or rice straw mulch. Almeida et al. (2015) also found plastic mulch to be effective in retaining soil moisture and reducing irrigation needs by 50%. Similarly, Refai et al. (2019) reported the highest water use efficiency (16.8 kg of lettuce per m^3 of water) with 60% ETc irrigation and black polyethylene mulch in Assuit, Egypt.

Mulching reduced the blue water footprint by 3.6%, and combining mulching with drip irrigation achieved a 4.7% reduction (Nouri et al., 2019). Other studies have reported increased crop productivity and water use efficiency with the combination of mulching and drip irrigation compared to conventional methods (Refai et al., 2019; Devi et al., 2020). Understanding how crops handle moderate water deficits is key for successful RDI implementation. Crop water needs at each growth stage reflect their sensitivity to water, indicating critical and peak water demand periods (Wang et al., 2022; Terassi et al., 2021).

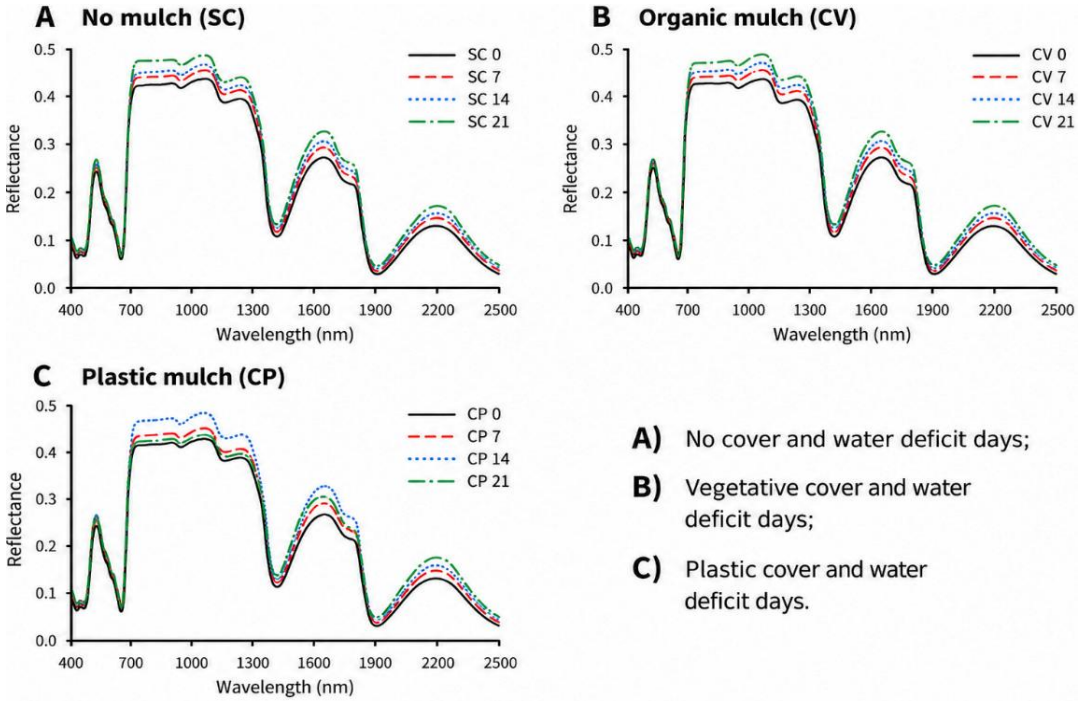

Figure 5. Hyperspectral behavior of lettuce under different cultivation conditions. Legend: CP0 - Plastic mulch and 0 days of deficit; CP7 - Plastic mulch and 7 days of deficit; CP14 - Plastic mulch and 14 days of deficit; CP21 - Plastic mulch and 21 days of deficit; CV0 - Organic mulch and 0 days of deficit; CV7 - Organic mulch and 7 days of deficit; CV14 - Organic mulch and 14 days of deficit; CV21 - Organic mulch and 21 days of deficit; SC0 - No mulch and 0 days of deficit; SC7 - No mulch and 7 days of deficit; SC14 - No mulch and 14 days of deficit; SC21 - No mulch and 21 days of deficit.

Moderate water deficits have shown positive effects on water productivity and crop resilience through physiological protective mechanisms (Yang et al., 2017). RDI enhances crop quality and water use efficiency by allowing crops to tolerate moderate water shortages during less water-sensitive growth stages with minimal yield loss (Ji et al., 2015; Chai et al., 2016). Lu et al. (2019) demonstrated improved water productivity with moderate RDI.

These findings reinforce that the effectiveness of RDI depends on deficit intensity, duration, and crop developmental stage. In the present study, combining a moderate pre-harvest deficit (70% ETc) with soil mulching reduced irrigation water requirements while limiting adverse effects on lettuce growth, with plastic mulch showing the most stable productive and spectral responses under moderate water restriction.

4. Conclusions

Applying a regulated deficit irrigation of 70% ETc during the last 14 days before harvest, the use of plastic mulch reduced the irrigation depth from 47.15 to 39.37 mm, corresponding to a 16.5% water saving, while maintaining lettuce fresh weight and yield stable compared to the treatment without water deficit, demonstrating efficiency in water management.

The imposed water deficit during three growth periods caused greater losses in lettuce production when no mulch was used. Extending the water deficit to 21 days intensified the negative effects on crop performance, indicating that the duration of pre-harvest water restriction is critical for maintaining lettuce production.

Under the conditions of this study, the combination of plastic mulch and 70% ETc during the final 14 days before harvest can be considered a practical water-saving strategy for lettuce production. Further studies should validate this irrigation strategy across different growing seasons, cultivars, and environmental conditions to determine its consistency and broader applicability.

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