

Article

From Farm to Fork: Irrigation Management and Cold Storage Strategies for the Shelf Life of Seedless Sugerthirtyfive Table Grape Variety

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Abstract: Background: Sustainable water management for table grape has the primary goal of optimizing irrigation through Smart Irrigation (SI) approaches, particularly in Mediterranean regions. In addition, extending the shelf life of table grapes through effective cold storage practices is crucial to meet consumer demands year-round. This research examined the journey “from farm to fork” of Sugerthirtyfive variety (Autumn Crisp[®] brand), exploring the combined effects of Irrigation Volumes (IV), SO₂-Generating Pads (SGPs) and Cold Storage Duration (CSD) on the quality of grapes. Methods: Normal Irrigation (NI—based on the farmer’s experience) and SI (100% vine evapotranspiration restored) were supplied in 2023 to Sugerthirtyfive variety white table grape, trained to an overhead tendone system. Yield and quality parameters, berry texture, CIELAB colour coordinates, phenolic content, flavonoids, antioxidant activity and sensory attributes were evaluated on grapes subjected to different times and methods of cold storage. Results: SI grapes showed higher Total Soluble Solids (TSSs) and nutraceutical content, as well as improved CIELAB coordinates with interesting improved berry texture parameters. No differences emerged between single- or dual-release SGPs after 15 days (T1) and 40 days (T2) of CSD. Conclusions: Under our cold storage conditions (3 °C, 85% U.R.), 40 days represent the maximum temporal limit for the cold storage of Sugerthirtyfive variety, regardless of IV, provided they are refrigerated with the aid of SGPs.

Keywords: sustainable water management; table grapes; cold storage; SO₂-Generating Pads; shelf life



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1. Introduction

Limited natural water resources are the primary constraint for table grape cultivation, particularly in the Mediterranean region, where the ambient evapotranspirative demand exceeds the modest precipitation levels, resulting in a water deficit extending from spring to early autumn [1,2]. In a Mediterranean climate with hot and dry summers, irrigation is absolutely necessary for grapevines to secure production [3], especially in Southern Italy. Precipitation often does not exceed the threshold of 500 mm/year [4]. Moreover, the rainfall is mostly concentrated in the autumn–winter period and is not usable during phenological phases with higher water requirements, such as the flowering–beginning of berry ripening period [5].

Sustainability in water use in agriculture thus becomes a priority, achievable through the optimization of the irrigation variables involved in the water balance. In addition, the scarcity of water resources in these environments must avoid using empirical irrigation scheduling. This methodology could overestimate irrigation volumes, resulting in unnecessary water losses due to runoff and drainage [2].

Adopting solutions capable of correctly determining the crop water requirement through the losses due to evapotranspiration is necessary. The use of soil water balance integrated with dedicated sensors (Smart Irrigation) is a sustainable solution. Theoretically, many Decision-Support Systems (DSSs) can be generated to satisfy the above exigencies, and these DSSs have become available in the scientific literature over the past 30 years [6]. The most widely used DSSs are based on evapotranspirative methods.

The literature reveals a growing interest in the impact of irrigation practices on grape quality attributes, underscoring the intricate relationship between irrigation levels and qualitative and quantitative traits of table grapes [7–11].

The production of table grapes in Puglia is increasingly diverse, covering the period from June to December, due to the cultivation of various early and late varieties and the adoption of plastic film covering and agronomic techniques to force early ripening or to delay harvest [12]. In addition to this, the table grape viticulture in Puglia is undergoing a phase of profound renewal in response to increased global competition from new competitors in both the northern hemisphere (Spain, Egypt, India) and the southern hemisphere (Chile, South Africa, Peru) [13], offering seedless varieties that cater to European consumer preferences. In particular, the varietal landscape of table grapes has undergone a significant evolution in recent years. In newly established vineyards, greater emphasis is placed on incorporating novel seedless grape varieties, reflecting a progressive shift towards aligning production with market demands. Among these new table grape varieties, Sugrathirtyfive is a patented (commercial name Autumn Crisp[®]—United States Plant Patent USOOPP20491 P2) late-season white seedless table grape variety, with extra-large, oval, milky-green berry with excellent flavor, firmness and berry attachment (Figure 1). As consumer demand for fresh products transcends seasonal boundaries, the need to extend the shelf life of table grapes through effective cold storage practices becomes paramount. Moreover, offering the consumer grapes with high nutraceutical properties even many days after harvesting is essential, considering that consuming fresh grapes significantly benefits human health [14–16]. The intricate balance between maintaining optimal conditions for grape preservation and the inherent perishability of this fruit poses a fascinating challenge [17].

To fulfil market demands and ensure a year-round supply of high-quality grapes to consumers, it is essential to employ techniques that enhance grape shelf life. Thanks to table grape's low sensitivity to chilling, minimal respiration rates and low ethylene production, cold storage is a widely employed post-harvest method, proven to be effective in extending fruit shelf life, significantly mitigating mass loss, and managing the occurrence of pathogens like grey mold induced by *Botrytis cinerea* [18,19]. Grapes exhibit diverse responses to cold storage, depending on the cultivar and storage duration, which is constrained by specific factors, necessitating effective methods for handling, packaging and specialized cooling to ensure the optimal condition of grapes upon delivery, ranging from a few days immediately after harvest up to even a month away [20]. Several papers report the impact of different storage times and conditions on table grape cultivars like Thompson Seedless [21], Italia and Red Globe [19,22], Kyoho [23], Regal Seedless [24] and Benitaka [18]. Cold storage combined with the utilization of sulfur dioxide (SO₂)-Generating Pads has exhibited promising outcomes in controlling post-harvest diseases, presenting a convenient and effective alternative. This combination facilitates gas circulation within the storage container, preventing mass loss while ensuring the desired preservation outcomes [25,26]. In this sense, the storage of table grapes represents a critical juncture in ensuring the provision of high-quality, flavorful grapes to consumers year-round. The delicate nature of table grapes demands a nuanced understanding of the interplay between storage duration, cold storage conditions and the resulting impact on grape quality.

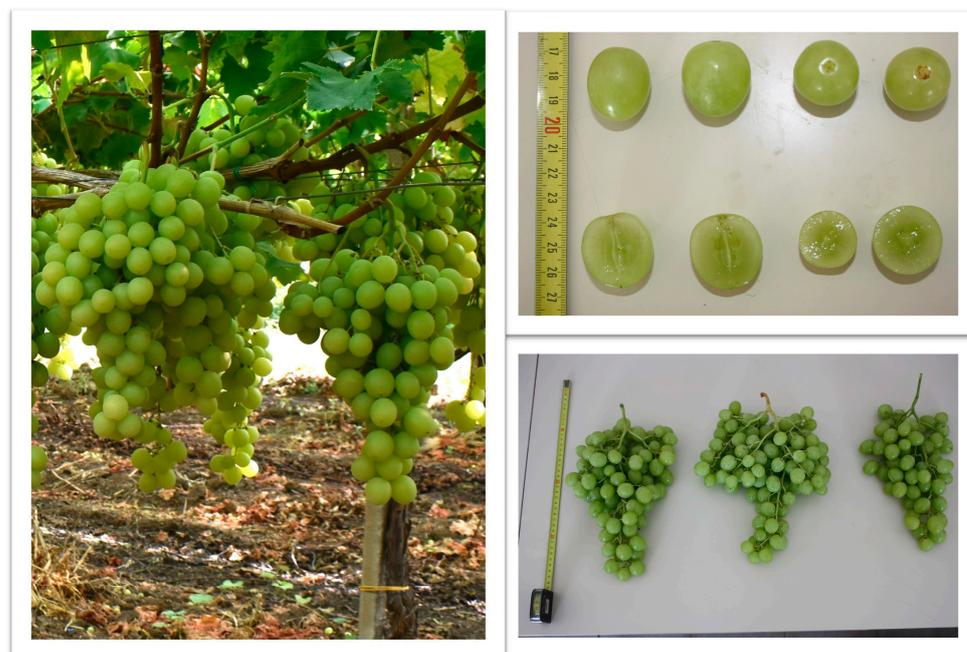


Figure 1. Sugerthirtyfive seedless table grape ready to harvest grown in a private commercial farm trained using an overhead covered tendone trellis system (left), clusters, berries and their section (right).

Until now, research on table grapes has considered irrigation factors, methods and storage duration individually, or, at most, by separating the phases related to vineyard irrigation management from the subsequent post-harvest phase. Therefore, integrating irrigation effects with post-harvest storage conditions, especially concerning a newly introduced seedless grape variety on the market, represents a research frontier that merits deeper investigation. This research focuses on an exploration of the interplay between two different Irrigation Volumes (IVs), different post-harvest types of SO_2 -Generating Pads (SGPs) and the Cold Storage Duration (CSD). In particular, their collective influence was investigated from field to table by evaluating grape quality and productive traits, texture, color and nutraceutical content (polyphenols, flavonoids and antioxidant activity) of berries over time, with a final sensory evaluation of the grapes—emerging high-quality seedless Sugerthirtyfive table grapes.

2. Material and Methods

2.1. Field Trial and Irrigation Volumes

The experimental trial was conducted in 2023 on a private commercial vineyard that was 9 years old, situated in Adelfia (BA), Southern Italy (latitude: $40^{\circ}59'14''$ N, longitude: $16^{\circ}51'34''$ E, elevation: 172). *Vitis vinifera* cv. Sugerthirtyfive (Autumn Crisp[®] brand), grafted onto *Vitis berlandieri* × *Vitis rupestris* 34 E.M. rootstock, was spaced at 2.50×2.50 m (1600 vines ha^{-1}). The vines were pruned to 30 buds per vine, trained using an overhead tendone system (Apulia type) and subjected to drip irrigation. Additionally, the vineyard was covered with netting and a polyethylene plastic film with a $200 \mu\text{m}$ sheet thickness from budbreak to harvest to protect the canopy and clusters from adverse effects of wind, rain, and hail.

According to the United States Department of Agriculture (USDA) classification, soil texture was clay. At 0.5 m of depth, there was a parent rock that reduced the capacity of the root systems to expand beyond this layer. Soil water content in volume at field capacity (f_c , -0.03 MPa) and wilting point (w_p , -1.5 MPa) were 0.34 and $0.26 \text{ m}^3 \text{ m}^{-3}$, respectively (measured in the Richards chambers).

Irrigation was supplied by a drip irrigation system having 3 drippers per vine and a flow rate of 16 L h^{-1} per dripper. Two Irrigation Volumes (IV) were considered:

- Normal Irrigation (NI): empirical irrigation management based on the knowledge and experience of the farmer, tendentially at fixed intervals approximately every 7 days, depending on the occurrence of rain, starting from 24 June (175th Julian day) until the last irrigation intervention on 10 October (283rd Julian day), for a total of 14 watering rounds;
- Smart Irrigation (SI), which restored 100% of crop evapotranspiration. Irrigation occurred when ready water availability was exhausted, according to the methodology of Allen et al. [27]. In particular, the tabulated crop coefficients ($K_{cinit} = 0.15$; $K_{cmed} = 0.80$; $K_{cend} = 0.40$) and depletion fraction value of 0.45 were adopted. Correction of K_{cini} (for precipitation events), K_{cmed} and K_{cend} (for climatic conditions and crop height) was performed according to the methodology of Allen et al. [27].

Soil water content in volume (SWC) was measured by capacitive probes 10HS (Meter Group Inc., Pullman, WA, USA). For each treatment, three vines were monitored. At each point, two capacitive probes were installed horizontally into the soil profile and transversely to the row, at -0.125 and -0.375 m from the soil surface, to intercept the dynamics of SWC below the dripping lines. All sensors were connected to data-loggers (TECNO.EL srl, Roma, Italy) and data were transferred to a web server via GPRS mode. Daily soil water content for the soil profile (0.5 m) was determined as an average of the values measured for each depth.

The farm did not have its own well, and water was supplied on a rotational basis from consortium irrigation systems. For this reason, the study focused on defining the irrigation volume rather than the irrigation timing.

2.2. Yield and Grapes Quality Parameters

Grapes were commercially harvested on 19 October 2023 when they reached $\sim 18^\circ$ Brix. Five clusters for each IV were considered and the following parameters were recorded: Cluster Weight, 20 Berry Weight, Equatorial Diameter, Total Soluble Solids (TSSs), pH, Titratable Acidity (TA).

A total of 100 berries per treatment were collected and pooled and a sample of 20 berries was employed to determine the color coordinates and texture attributes. Berry color was determined by a chromameter CM-5 (Konica Minolta, Chiyoda, Tokyo, Japan) using the CIELAB color system. The CIELAB, or CIE $L^* a^* b^*$, system is a three-dimensional color-space consisting of three axes: L^* axis (Lightness)—a grey scale with values from 0 (black) to 100 (white), a^* axis—a red/green axis with positive (red) and negative (green) values and b^* axis—a yellow/blue axis with positive (yellow) and negative (blue) values.

Compression and tensile tests were performed on the 20 berries/cluster/thesis using a Zwick Roell ver. Z 0.5 Materials Testing Machine (Woonsocket, RI, USA). A 2-cycle compression test was carried out on each whole berry in the equatorial position under a deformation of the berry of 20%, with waiting time between the two bites of 1 s, using a crosshead speed of 3.334 mms^{-1} , with a standard force of 0.1 N and a 0.02 m diameter cylindrical probe. Typical berry texture parameters scored were Hardness (N), Cohesiveness (adimensional), Gumminess ($\text{N} - \text{Hardness} \times \text{Cohesiveness}$), Springiness (mm) and Chewiness (mJ, $\text{Gumminess} \times \text{Springiness}$).

2.3. Preparation of Grape Skin Extracts (GSEs) and Total Phenolic Content (TPF), Total Flavonoids (FLV) and Antioxidant Activity (DPPH)

Skins from 10 frozen berries were manually separated from the pulp and extracted, according to Di Stefano and Cravero [28] with slight modifications. Briefly, skins were incubated overnight in the dark in 25 mL of 70% ethanol containing 1% chloridric acid. Then, the extracts were filtered through a $0.45 \mu\text{m}$ syringe cellulose filter and stored at -20°C until further analysis.

TPF in GSEs was determined by the Folin–Ciocalteu colorimetric method described by Waterhouse [29]. Briefly, 1 mL of water, 0.02 mL of extract sample, 0.2 mL of the Folin-Ciocalteu reagent and 0.8 mL of 10% sodium carbonate solution were mixed and brought to 4 mL. The mixture was stored for 90 min at room temperature in the dark, and the absorbance was measured at 760 nm with a spectrophotometer Agilent 8453 (Agilent Technologies, Santa Clara, CA, USA). Results were expressed as milligrams of gallic acid equivalent/kg (mg GAE/Kg fw) of fresh grape based on a gallic acid calibration curve (50 to 500 mg/L with $R_2 = 0.998$).

FLV was determined by the aluminum chloride method [30] with some modifications. First, 1 mL of the GSE (diluted 1:10 with ethanol) was mixed with 1 mL of 2% aluminum chloride and incubated at 25 °C for 30 min. Then, the absorbance of the mixture was measured at 402 nm. Results were expressed as μg of rutin equivalent per kg ($\mu\text{g RE/Kg fw}$) of fresh grape using the calibration curve of quercetin (0–150 mg/L).

The antioxidant activity was evaluated by DPPH (2,2 O-diphenyl-1-picrylhydrazyl) assays, a radical scavenging assay based on single-electron transfer. The DPPH assay was conducted according to the technique of Brand-Williams et al. [31] with some modifications. A free-radical working solution was prepared by dissolving 2.5 mg of DPPH stock solution in 100 mL ethanol. The solution absorbance was adjusted at 0.7 ± 0.02 in 515 nm using a UV–Vis spectrophotometer Agilent 8453 (Agilent Technologies, Santa Clara, CA, USA). An aliquot of 200 μL of the sample, appropriately diluted, was mixed with 2 mL of DPPH solution (A_{sample}). A solution without grape extract was used as a blank (A_{blank}). The decrease in absorbance at 515 nm was measured after 30 min of incubation at 37 °C. Calibration curves were prepared using Trolox (Sigma-Aldrich, St. Louis, MO, USA). DPPH values were expressed as μM Trolox equivalents/kg of fresh grape ($\mu\text{g TE/Kg fw}$).

2.4. Times and Methods of Cold Storage

In order to test the storage suitability of the Sugrathirtyfive variety subjected to two different IVs, at harvest, grapes were refrigerated in fruit crates at 3 °C and 85% U.R. Three treatments for each of the two IVs were defined. Specifically, a Control (C) thesis was refrigerated without SO₂-Generating Pads (SGPs), while the other two theses were treated with the following:

SmartPac[®] bags (SPB) (Sodium Metabisulphite 12.5% *w/w*) (Serroplast, Rutigliano, Italy) are patented single-release SO₂-Generating Pads composed of a single multilayer film that allows the fruit's natural moisture to circulate through the inner layers of the coating, enabling linear preservation of the product for extended periods;

DECCO Grapage[®] (DECCO), (DECCO ITALIA S.R.L., Belpasso, Italy) a dual release SO₂-Generating Pad (5 g Sodium Metabisulphite 50%, Inert Technical Coadjuvants 50%);

The grapes were evaluated for quality parameters at different values of Cold Storage Duration (CSD): harvest (T0), after 15 days (T1) and after 40 days (T2) of cold storage.

2.5. Sensory Evaluation

To evaluate the sensory attributes and resilience to CSD of Sugrathirtyfive grapes cultivated under different IVs and subjected to two distinct SGP treatments, they underwent sensory assessment at 15 days (T1) and 40 days (T2) post-harvest. The sensory evaluation was conducted on blind samples within specially equipped individual workstations with neutral-colored walls and odor-neutral surfaces. The environmental temperature was maintained at a comfortable 22 °C, ensuring optimal conditions for evaluation. Brightness within the room was adjusted to an appropriate level, and extraneous noise or distractions were minimized, adhering to the guidelines outlined by [32]. ISO 2007. The taster panel was composed of 20 trained judges from the Research Centre for Viticulture and Enology, Council for Agricultural Research and Economics. The judges were requested not to smoke or eat for 1 h prior to the sensory sessions. The grapes were evaluated based on 23 OIV descriptors for table grape sensory analysis [33] for visual, olfactive, taste and tactile traits on cluster, stem, berries, skin and pulp.

Judges scored each attribute on a preference scale structured from 1 (low perception of the descriptor) to 10 (maximum perception of the descriptor).

2.6. Statistical Analysis

A three-way ANOVA with interactions between factors was performed on a total of 14 theses derived by the combination of the three factors (IV, SGP and CSD) as follows: NI-C-T0, SI-C-T0, NI-C-T1, NI-SPB-T1, NI-DECCO-T1, SI-C-T1, SI-SPB-T1, SI-DECCO-T1, NI-C-T2, NI-SPB-T2, NI-DECCO-T2, SI-C-T2, SI-SPB-T2, SI-DECCO-T2. Means were firstly by Tukey test, while a subsequent Dunnett's test was employed to compare the values of each individual trait for each thesis against the control sample, which, in our case, was NI-C-T0. Furthermore, a multivariate approach by means of a biplot PCA was performed at T0, T1 and T2. In addition, the differences in the perception of each descriptor during sensory evaluation of grapes were statistically analyzed by Non-Parametric Kruskal–Wallis test, and a Box Plot for the descriptors that resulted in statistically significant differences is provided. All the statistical analyses were performed using R Statistical Software v4.3.2.

3. Results

3.1. Soil Water Content (SWC) and Irrigation Volumes (IVs)

In the Smart Irrigation (SI) treatment, the irrigation scheduling allowed the optimization of the SWC (from -0.10 m to -0.50 m soil depth) within the RAW threshold ($0.296 \text{ m}^3 \text{ m}^{-3}$), avoiding any water stress. In particular, the SWC reached the field capacity, after irrigation or consistent precipitations. In August, irrigation was carried out before the SWC reached the RAW threshold, as irrigation was provided rotationally. In the Normal Irrigation (NI), SWC exceeded the field capacity almost throughout the entire vine cycle (Figure 2). This resulted in only water losses due to drainage because the flat ground and drip irrigation system avoided runoff losses. In this case, NI was excessive. Seasonal IVs were 335 and 264 mm for NI and SI treatments, respectively, with the number of irrigations during the 2023 season being 14. Thus, with SI treatment, 21% of the irrigation water was spared.

3.2. Univariate Analysis

This manuscript presents a comprehensive investigation into the impact of two different Irrigation Volumes (IVs)—Normal Irrigation (NI) and Smart Irrigation (SI), distinct SO_2 -Generating Pads (SGPs)—Control (C), SmartPac[®] Bag (SPB), and DECCO Grapage[®] (DECCO) and three different Cold Storage Durations (CSDs)—harvest (T0), 15 days post-harvest (T1) and 40 days post-harvest (T2) on various parameters related to carpometry, must composition, berry skin colorimetric coordinates, berry texture, nutraceutical traits and cluster damages induced by cold storage on Sugrathirtyfive table grape. Table 1 presents the outcomes of a three-way ANOVA, illustrating interactions among the three factors and means separated by post hoc Tukey tests for each factor individually.

Regarding IVs, no differences in carpometric data were observed, indicating a substantial equality in the size and weight of berries between the two IV levels. Similar observations were noted for the other two factors, SGP and CSD. However, a statistically significant interaction was identified between SGP and CSD, specifically in relation to the 20 berries' weight. Additionally, a significant interaction was found regarding berry diameters, expressed as Equatorial Diameter, between IV and SGP. Cluster weight and its related weight loss over time (Figure 3) were analyzed independently of the other parameters. Clusters were weighed at harvest before packaging and cold storage. The direct monitoring of this parameter on the same clusters allowed for a paired sample *t*-test analysis, unlike other indices and parameters that, due to the destructive nature of the relief methods, did not permit time-dependent measurements on the same biological sample.

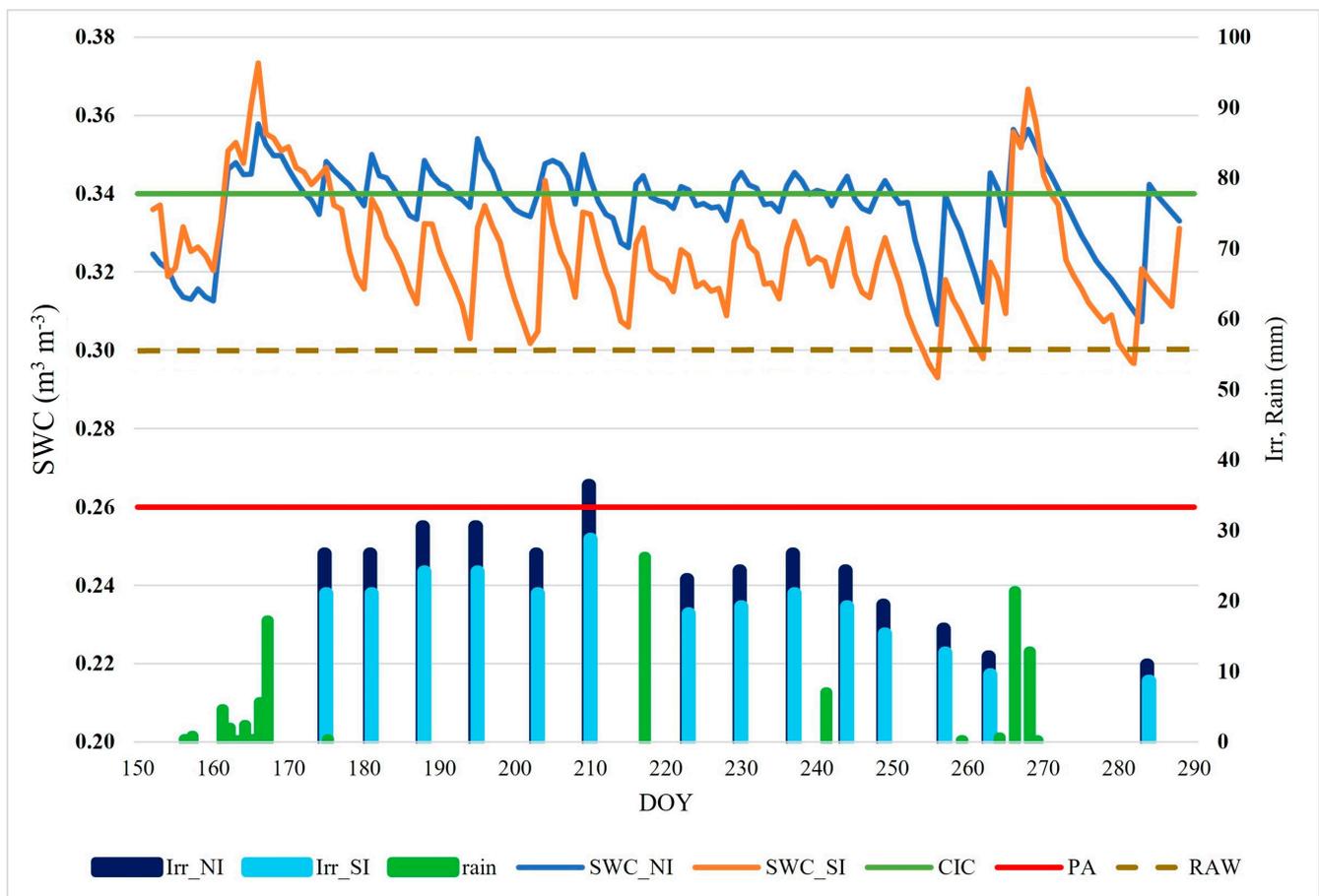


Figure 2. Soil water content (SWC) and Irrigation Volumes (IVs) of Normal Irrigation (NI) and Smart Irrigation (SI) provided to Sugrathirtyfive in 2023 on a private commercial farm trained using an overhead covered tendone trellis system.

By T2, grapes from the cold storage treatment without SGP were entirely covered in mold, rendering them unprocessable. Comparing cluster weight between T0 and T1, no statistical difference was found, except for the theses NI-C and SI-DECCO. At T2, cluster weight loss appeared generalized in all theses, except for those treated with SPB, regardless of IV. Concerning berry juice composition, Total Soluble Solids (TSSs) were significantly influenced by IV, with SI treatment showing higher values than NI and the employed SGP. Treatments with SPB or DECCO preserved sugar content integrity compared to the Control. CSD had no isolated effect on TSSs, except when combined with the other two factors. Juice pH behaved similarly, influenced by IV and SGP, with CSD also affecting it. Titratable Acidity (TA) remained relatively constant across all factor levels, with significant interactions.

IV statistically influenced the CIELAB coordinates, with an increase in Lightness (L^*) in SI, where grapes also exhibited lower greenness (a^*), indicating berries with a less intense green color compared to those under NI. Likewise, concerning SGP, SPB and DECCO demonstrated opposing effects. DECCO appeared to preserve L^* better but lost a^* compared to both SPB and the Control treatment. Additionally, it is noteworthy that L^* tended to decrease with increasing CSD, while a^* remained relatively unchanged over time. In contrast, yellowness (b^*) was unaffected by IV and SGP but increased from T0 to T1 and T2, suggesting a shift towards yellow coloration over time. Importantly, no significant interactions were found among the combination of the three factors for all CIELAB coordinate parameters.

Table 1. Means of carpometry, juice berry composition, colorimetric coordinates, texture, nutraceutical traits and cold storage damages of Sugrathirtyfive table grapes grown under two different Irrigation Volumes (IVs) (NI = Normal Irrigation; SI = Smart Irrigation), different SO₂-Generating Pads (SGP) (C = Control; SPB = SmartPac[®] bags; DECCO = DECCO Grapage[®]), three different Cold Storage Durations (CSDs) (T0 = harvest; T1 = after 15 days; T2 = after 40 days) and relative interactions.

	Factors								Interactions			
	IV		SGP			CSD			IV × SGP	IV × CSD	SGP × CSD	IV × SGP × CSD
	NI	SI	C [†]	SPB	DECCO	T0	T1	T2 [†]				
20 berries' weight (g)	244.4	241.5	246.8	239.2	243.0	250.9	238.3	246.1	ns	ns	*	ns
Equatorial diameter (mm)	24.9	25.1	24.7	24.9	25.3	25.2	24.7	25.3	**	ns	ns	ns
Total Soluble Solids (°Brix)	15.7 ^b	17.3 ^a	15.7 ^b	17.2 ^a	16.6 ^{ab}	16.0	16.7	16.5	***	***	*	***
pH	3.75 ^a	3.63 ^b	3.63 ^b	3.70 ^{ab}	3.75 ^a	3.57 ^b	3.70 ^b	3.74 ^a	*	ns	***	***
TA (g/L tartaric acid)	4.1	4.0	4.1	4.1	4.0	4.1	4.0	4.1	**	***	**	***
L*	39.90 ^b	40.91 ^a	40.26 ^{ab}	39.88 ^b	41.07 ^a	41.17 ^a	40.51 ^{ab}	39.86 ^b	ns	ns	ns	ns
a*	−3.48 ^b	−3.22 ^a	−3.35 ^{ab}	−3.24 ^a	−3.47 ^b	−3.36	−3.40	−3.27	**	ns	***	ns
b*	9.15	9.37	9.20	9.15	9.42	8.68 ^b	8.79 ^b	9.79 ^a	ns	ns	ns	***
Hardness (N)	14.38 ^b	16.25 ^a	15.74	14.81	15.40	17.61 ^a	15.13 ^b	14.44 ^b	ns	ns	ns	ns
Springiness (mm)	4.97	5.01	4.94	4.98	5.05	5.04	4.93	5.05	**	ns	ns	ns
Cohesiveness (adim)	0.65	0.65	0.62 ^b	0.67 ^a	0.66 ^a	0.63 ^b	0.65 ^b	0.68 ^a	ns	ns	ns	*
Chewiness (mj)	46.51 ^b	53.06 ^a	48.61	49.8	50.95	55.07	47.99	49.84	ns	**	ns	ns
Gumminess (N)	9.34 ^b	10.64 ^a	9.78	9.95	10.23	10.90	9.79	9.84	ns	*	ns	ns
TPF mg/kg fresh grape GAE	90.42 ^b	103.61 ^a	91.99 ^b	109.88 ^a	89.17 ^b	97.57	99.17	93.51	**	ns	ns	*
FLV g RE/kg	0.51 ^b	0.70 ^a	0.52 ^{ab}	0.78 ^a	0.50 ^b	0.44	0.73	0.49	ns	ns	**	ns
DPPH μmol TE /kg	452.86 ^b	502.40 ^a	437.20	502.29	463.41	468.13 ^{ab}	501.88 ^a	446.01 ^b	ns	ns	ns	ns
% berries damaged by SO ₂	0.5%	0.5%	0.0% ^b	0.9% ^a	0.9% ^a	0.0% ^b	0.0% ^b	1.2% ^a	ns	ns	*	ns
% berries with gray rot/mold	16.3%	15.0%	36.3 ^a	0.6% ^b	1.9% ^b	0.0% ^b	7.9% ^b	27.6% ^a	ns	ns	*	ns
% stem browning	6.2%	4.7%	3.8%	7.0%	6.2%	0.0% ^b	2.1% ^b	10.2% ^a	ns	ns	ns	ns

TPF = Total Phenolic Content, FLV = Total Flavonoids, DPPH = 2,2-diphenyl-1-picrylhydrazyl. Means were separated by post hoc Tukey test in each factor singularly. Different letters correspond to statistically significant differences at $p < 0.05$. ns = not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$, [†] Means calculated excluding NI-C-T2 and SI-C-T2, if excepted for cold storage damages traits, for the unprocessability and non-marketability of grapes without SO₂-Generating Pads in T2, due to extensive development of mold on the berries.

Compression and texture tests on the berries provided insights into firmness and crunchiness. Hardness, representing the force required to achieve a given deformation, was significantly higher in the SI group compared to NI. SGP showed no significant effect on Hardness. Conversely, a notable decline in Hardness was observed with increasing CSD, with no significant interactions among the three factors. Springiness, representing the rate of material returning to its original state after deformation, remained constant and unaffected by individual factors. However, a significant interaction was observed between IV and SGP. Cohesiveness, reflecting a product's tendency to cohere, was unaffected by IV but was higher in grapes refrigerated with SGPs than Control. Similarly, CSD exerted an effect, progressively resulting in higher cohesiveness values. Only the interaction among the three factors was statistically significant in this case. Chewiness and Gumminess were influenced by IV, being higher in SI grapes, while remaining unaffected by the other two factors. Only the interaction between IV and SGP was statistically significant in both cases. In the analysis of the nutraceutical aspects of grapes, both Total Polyphenol Content (TPF) and Flavonoid (FLV) concentrations were influenced by IV. Within the scope of SGP, only SPB significantly preserved the concentration of both PFT and FLV, with no discernible effect from CSD. Significant interactions were observed for the combinations IV \times SGP and IV \times SGP \times CSD for TPF, while FLV displayed a significant interaction for the combination SGP \times CSD. Additionally, the radical-scavenging activity, assessed as the antioxidant power of extracts from grape skins using DPPH, corroborated the aforementioned trend. Grapes from SI exhibited a higher DPPH concentration, unaffected by SGP. Conversely, concerning CSD, there was an increase in DPPH until T1, followed by a decline at T2, returning to values comparable to those at harvest. No significant interaction was observed in this case, indicating an independent behavior of the three factors.

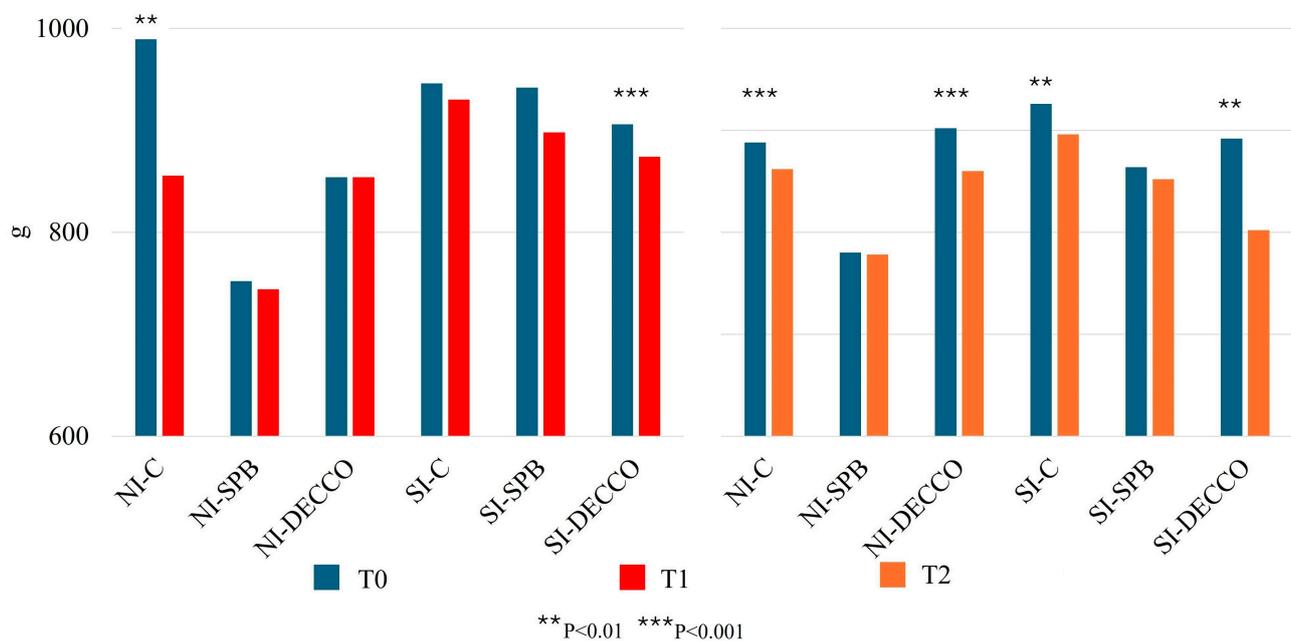


Figure 3. Comparison of cluster weight loss by means of paired sample t-test between clusters weighted at three different storage durations (T0 = at harvest; T1 = after 15 days; T2 = after 40 days) for each of the combined factors: Irrigation Volumes (IVs) (NI = Normal Irrigation; SI = Smart Irrigation) and SO₂-Generating Pads (C = Control; SPB = SmartPac® bags; DECCO = DECCO Grapage®).

Regarding parameters related to damages from storage, the percentage of berries damaged by SO₂ was minimal but present in modest quantities in the SGP treatments. Concerning CSD, damage from SO₂ onset was observed only at T2. Consequently, the only statistically significant interaction occurred in the combination of SGP \times CSD. The

percentage of berries with rot/mold exhibited a similar trend, with SGP use naturally reducing its incidence compared to the Control. As expected, a considerable increase was noted, particularly at T2, with values exceeding 27%. In this case, the combination of SGP \times RSD also showed a statistically significant interaction. Regarding the percentage of stem browning, no effect of IV and SGP was recorded, while, though CSD showed no difference between T0 and T1, its effects were visible at T2, with stem browning values exceeding 10%. The data suggested that this issue arose only when a substantial CSD was reached, regardless of the other two factors.

In pursuit of a comprehensive assessment and identification of the most effective combination among the factor levels, these factors were consolidated into 14 overall theses. This amalgamation aimed to facilitate a Dunnett test (Table 2) for comparing each thesis with combined factors against the Control thesis. In our study, the Control thesis is represented by NI without SGP during cold storage and at CSD T0 (NI-C-T0). While no discernible differences were noted between the theses for berry weight and equatorial diameter compared to the Control, significant variations were observed for Total Soluble Solids (TSSs). The only theses that did not exhibit significant differences in TSSs were NI-C-T1, SI-C-T1 and NI-SPB-T2. In contrast, all other theses displayed higher TSSs values, particularly those derived from SI, regardless of the SGP employed and the considered CSD (SI-SPB-T1, SI-SPB-T2, SI-DECCO-T1, SI-DECCO-T2), with values close to or exceeding 18°Brix, compared to the 15.6 °Brix of NI-C-T0. At harvest (T0), juice pH was confirmed to be higher in the NI thesis, and a general increase was observed for all theses at T2, with SGP DECCO also showing an increase at T1. Furthermore, variations in Total Acidity (TA) were exclusive to the SI-DECCO, theses, lower at T1 and higher at T2 compared to the Control, affirming the stability of parameters among theses as reported in Table 1.

Few differences were identified in CIELAB coordinates. Specifically, Lightness (L^*) was higher than the Control in the SI-C-T0 and SI-DECCO-T1 theses, and more stable in the other theses. Parameters a^* and b^* demonstrated relatively stable values, with SI-SPB-T1 exhibiting lower values of greenness, while, conversely, in the NI-DECCO-T1 theses, the berries displayed more pronounced green notes. Furthermore, higher yellowness (i.e., higher b^* values) compared to the Control was observed for the NI-C-T1, SI-SPB-T1, and NI-DECCO-T1 theses. In terms of texture analysis parameters, including Hardness, Chewiness and Gumminess, SI-C-T0 was the only thesis showing significantly higher values compared to the Control. Conversely, regardless of IV or SGP, all other theses displayed similar values to the Control, even with the progression of CSD. On the contrary, Springiness remained generally constant, with no significant differences observed between the theses. Regarding nutraceutical parameters, in the SI-SPB-T1 thesis, both Flavonoid content (FLV) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical-scavenging activity yielded significantly higher values compared to the reference thesis NI-C-T0. SI-C-T0 (at harvest), and SI-SPB at both T1 and T2 exhibited higher TPF contents, while all the theses from NI and those treated with SGP DECCO were identical to the Control thesis in all CSD. Finally, regarding cold storage damages, the percentage of berries damaged by SO_2 was negligible when no SGP was used. However, both SPB and DECCO systems showed mild signs of SO_2 scorching, never exceeding 1.8%. A distinct consideration must be made for the incidence of the percentage of berries with rot/mold, absent at harvest (T0) but progressively increasing from T0 to T1 and T2, exclusively in the theses without the SGP device, as expected. This phenomenon rendered the clusters at T2 entirely unusable for analysis, reaching stem browning percentages of 76.0% and 80.0%, respectively, in the NI-C and SI-C theses. Thus, it can be affirmed that both SPB and DECCO preserved the grapes from the onset of mold. The significant onset of percentage of stem browning occurred for all the theses at T2, irrespective of the IV. Additionally, the thesis treated with DECCO proved to be less effective than SPB in containing this phenomenon, already exhibiting issues of stem browning at T1.

Table 2. Means separation by Dunnet test of carpometry, berry juice composition, colorimetric coordinates, texture, nutraceutical traits and cold storage damages for merged factors on Sugrathirtyfive table grapes grown under two different Irrigation Volumes (IVs) (NI = Normal Irrigation; SI = Smart Irrigation), different SO₂-Generating Pads (SGPs) (C = Control; SPB = SmartPac[®] bags; DECCO = DECCO Grapage[®]), three different Cold Storage Durations (CSDs) (T0 = harvest; T1 = after 15 days; T2 = after 40 days).

	<i>NI-C T0</i>	<i>NI-C T1</i>	<i>NI-C T2</i>	<i>SI-C T0</i>	<i>SI-C T1</i>	<i>SI-C T2</i>	<i>NI-SPB T1</i>	<i>NI-SPB T2</i>	<i>SI-SPB T1</i>	<i>SI-SPB T2</i>	<i>NI- DECCO T1</i>	<i>NI- DECCO T2</i>	<i>SI- DECCO T1</i>	<i>SI- DECCO T2</i>
20 berry weight (g)	252.3	238.5	-	249.5	246.8	-	223.1	252.1	233.5	248.0	243.9	256.7	243.7	227.5
Equatorial diameter (mm)	25.4	24.2	-	25.1	24.3	-	24.1	24.6	25.1	25.9	25.6	25.5	24.8	25.3
TSSs (°Brix)	15.6	15.1	-	16.4 ***	15.9	-	16.2 ***	15.8	18.8 ***	18.0 ***	17.0 ***	14.4 ***	16.9 ***	17.9 ***
pH	3.61	3.77 ***	-	3.52 ***	3.62	-	3.64	3.84 ***	3.64	3.66 *	3.86 ***	3.78 ***	3.66 *	3.69 ***
TA (g/L tartaric acid)	4.1	4.2	-	4.2	4.0	-	4.2	4.2	4.0	3.9	4.1	3.7	3.5 **	4.7 ***
L*	39.94	38.73	-	42.40 *	39.98	-	39.79	39.57	40.64	39.51	41.68	39.66	42.24 *	40.69
a*	-3.33	-3.45	-	-3.40	-3.24	-	-3.52	-3.46	-2.93 *	-3.04	-3.78 **	-3.36	-3.51	-3.22
b*	8.20	10.12 **	-	9.16	9.34	-	8.82	9.23	10.25 **	8.31	10.29 **	8.24	9.80 *	9.37
Hardness (N)	13.67	13.54	-	21.55 ***	14.18	-	15.85	13.89	13.74	15.76	16.73	12.60	16.75	15.50
Springiness (mm)	5.08	4.83	-	5.01	4.85	-	4.81	4.90	5.02	5.17	5.12	5.08	4.96	5.05
Cohesiveness (adim)	0.63	0.62	-	0.62	0.62	-	0.66	0.67	0.65	0.70 ***	0.64	0.68	0.66	0.68
Chewiness (mI)	43.20	41.01	-	66.93 ***	43.30	-	50.96	45.42	45.34	57.48	55.29	43.20	52.07	53.25
Gumminess (N)	8.52	8.46	-	13.29 ***	8.87	-	10.53	9.26	8.92	11.10	10.77	8.52	11.17	10.49
DPPH umol TE /kg	451.23	436.58	-	485.03	495.98	-	513.43	444.31	538.90 **	472.50	473.12	398.49	513.26	468.74
FLV g RE/kg	0.55	0.62	-	0.34	0.58	-	0.77	0.40	0.88 ***	0.66	0.34	0.35	0.77	0.55
TPF mg/kg fresh grape GAE	82.10	96.47	-	113.03 ***	76.35	-	101.33	91.73	133.94 ***	112.53**	93.56	77.31	93.34	92.46
% berries damages SO ₂	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.8% *	0.0%	1.8% *	0.0%	1.8% *	0.0%	1.8% *	0.0%
% berries with rot/mold	0.0%	32.0% ***	76.0% ***	0.0%	15.0%**	80.0% ***	0.0%	0.8%	0.0%	1.6%	0.2%	1.8%	0.2%	5.4%
% stem browning	0.0%	0.0%	13.0%**	0.0%	0.4%	8.0% **	2.0%	12.0% **	2.0%	12.0% **	7.0% *	8.0% **	1.2%	8.4% **

TPF = Total Phenolic Content, FLV = Total Flavonoids, DPPH = 2,2-diphenyl-1-picrylhydrazyl. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. The reference control is NI-C-T0, reported in bold and italics.

3.3. Multivariate Analysis

A Principal Component Analysis (PCA) biplot analysis was conducted at T0, T1 and T2 to gain a comprehensive understanding of the data. In Figure 4, the PCA at T0 focused on freshly harvested grapes from two levels of the IV factor. PC1 explained 52.47% of the variance, PC2 described 24.92%, totaling 77.39%, rendering further analysis on the third axis PC3 unnecessary. Notably, the NI and SI treatments were distinct, as illustrated by 95% confidence ellipses. The SI treatment was characterized by texture parameters, berry juice composition, colorimetric aspects, and significant contents of TPF and DPPH. In contrast, the NI treatment was predominantly characterized by FLV and pH, followed by Cohesiveness and, marginally, by Equatorial Diameter. Other variables contributed mainly to PC2, which explained variances within groups rather than distinguishing between NI and SI treatments.

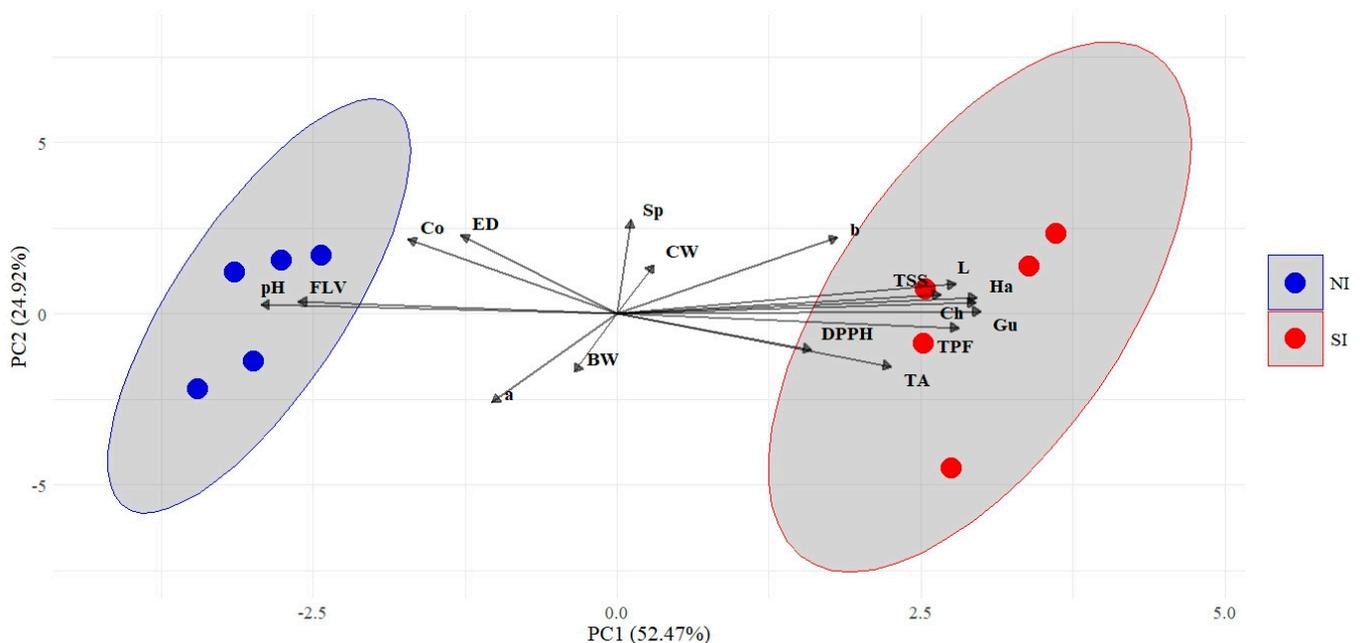


Figure 4. Biplot of Principal Component Analysis: eigenvalues, eigenvectors and percent of variation accounted for the first three principal components (PCs) of carpometric, must, colorimetric coordinates, texture and nutraceutical traits at harvest (T0) of Autumn Crisp table grapes grown with two different Irrigation Volumes (IVs) (Normal Irrigation = NI; Smart Irrigation = SI). Ellipse 95% is shown. CW = Cluster weight; BW = 20 berries' weight; ED = Equatorial Diameter; TSSs = Total Soluble Solids; TA = Titratable Acidity; Ha = Hardness; Sp = Springiness; Co = Cohesiveness; Ch = Chewiness; Gu = Gumminess; TPF = Total Polyphenolic Content; FLV = Flavonoids; DPPH = 2,2-diphenyl-1-picrylhydrazyl; DSO₂ = % berries damaged by SO₂; BRM = % berries with rot/mold; SB = % stem browning.

As expected, the PCA biplot at T1 significantly changed, necessitating consideration of IV levels, SGP and damages caused by CSD (Figure 5). PC1 explained 32.91% of the variance, PC2 contributed 20.32% and PC3 added 11.82%, totaling 76.32%. Variables contributing to PC1 included texturometric parameters, colorimetric aspects, berry dimensions and parameters derived from cold storage damages. Simultaneously, PC2 was strongly characterized positively by nutraceutical parameters, TSSs content and higher a* values, leading to a distinct separation of the SI-SPB treatment. Conversely, the NI-DECCO treatment exhibited opposite behavior, overlapping with treatments refrigerated without SGP, highlighting a significant incidence of the percentage of berries with post-harvest decay, as expected. Using PC3, correlated with carpometric variables, all treatments tended to overlap, except for NI-SPB.

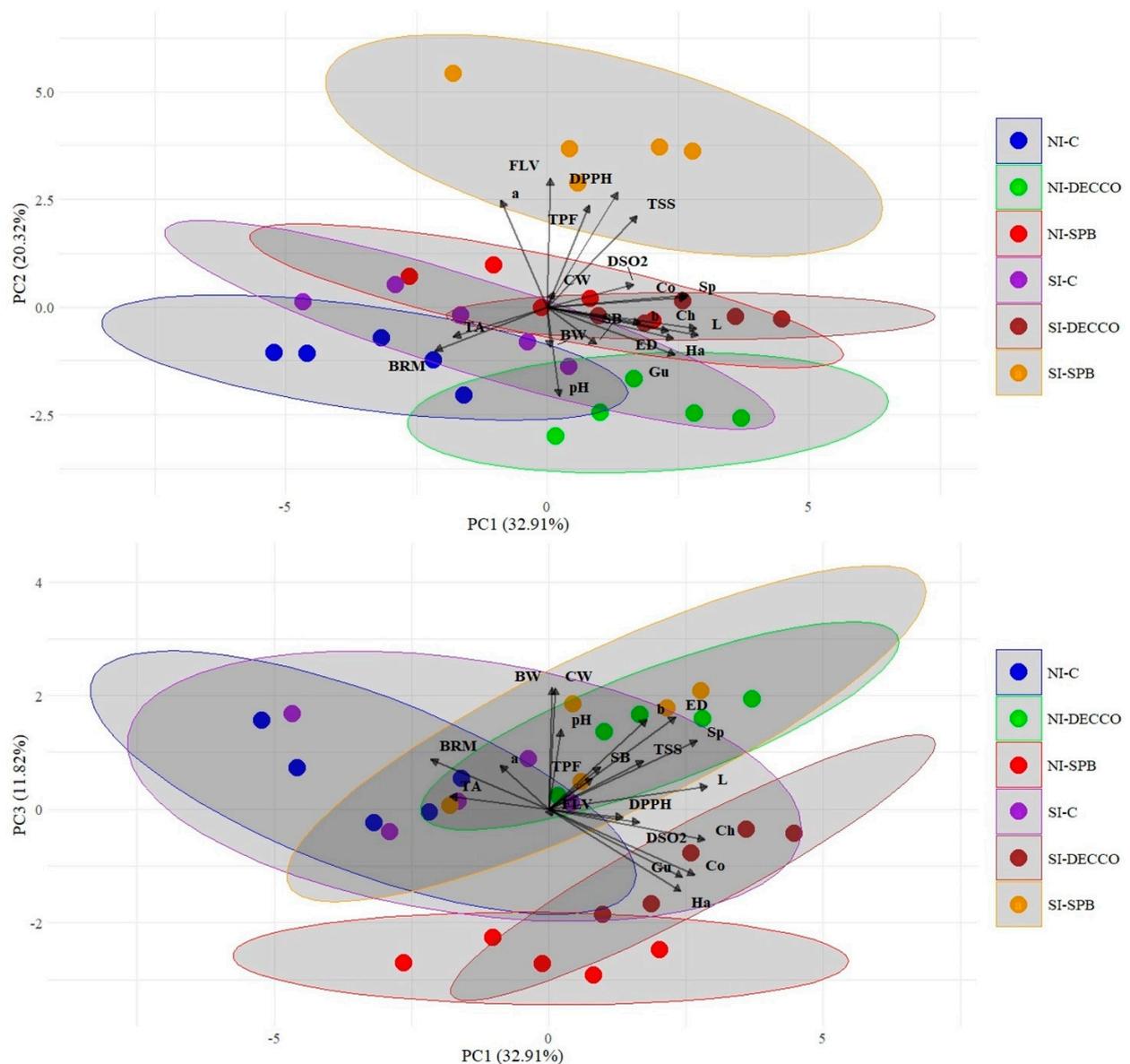


Figure 5. Biplot of Principal Component Analysis: eigenvalues, eigenvectors and percent of variation accounted for the first three principal components (PCs) of carpometric, must, colorimetric coordinates, texture and nutraceutical traits after 15 days' Cold Storage Duration (CSD) (T1) of Autumn Crisp table grapes grown with two different Irrigation Volumes (IVs) (Normal Irrigation = NI; Smart Irrigation = SI) and different SO₂-Generating Pads (SGPs) (C = Control; SPB = SmartPac® bags; DECCO = DECCO Grapage®). Ellipse 95% is shown. CW = Cluster weight; BW = 20 berries' weight; ED = Equatorial Diameter; TSSs = Total Soluble Solids; TA = Titratable Acidity; Ha = Hardness; Sp = Springiness; Co = Cohesiveness; Ch = Chewiness; Gu = Gumminess; TPF = Total Polyphenolic Content; FLV = Flavonoids; DPPH = 2,2-diphenyl-1-picrylhydrazyl; DSO₂ = % berries damaged by SO₂; BRM = % berries with rot/mold; SB = % stem browning.

The latest PCA biplot at T2 (Figure 6) excluded the NI-C and SI-C treatments due to their deterioration. Similar to T1, PC1 (46.24%) and PC2 (16.00%) explained the most variance, and PC3 (14.08%) was necessary, totaling 76.32%. As in T1, berry texture, colorimetric and nutraceutical variables contributed positively to PC1, while parameters related to cold storage damages correlated with PC2. SI treatments, whether SPB or DECCO, substantially overlapped, while NI-DECCO showed reduced cold storage damages, lower nutraceutical content, but good values of 20 berries' weight, while NI-SPB was positioned intermediately.

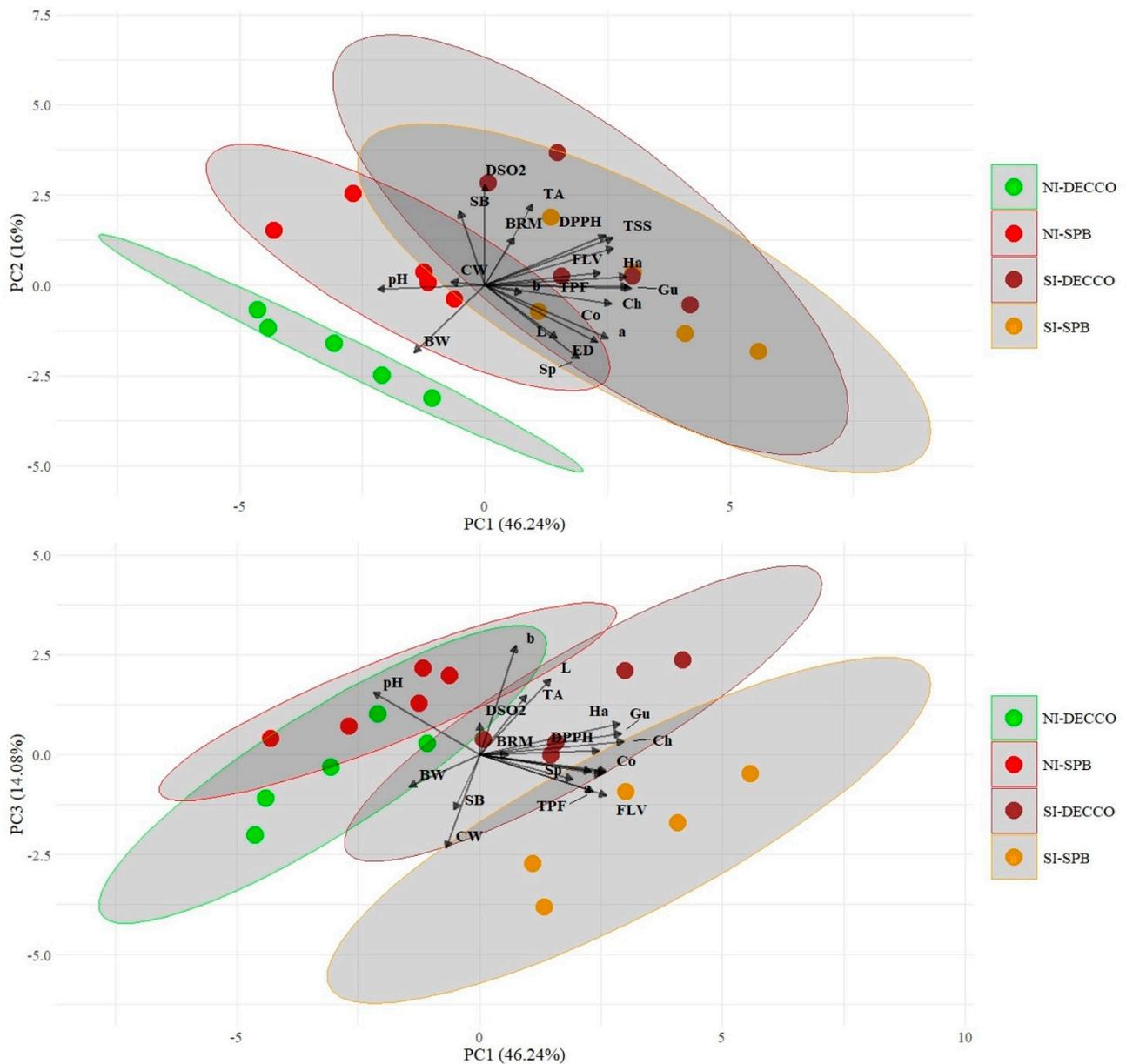


Figure 6. Biplot of Principal Component Analysis: eigenvalues, eigenvectors and percent of variation accounted for the first three principal components (PCs) of carpometric, must, colorimetric coordinates, texture and nutraceutical traits after 40 days' Cold Storage Duration (CSD) (T2) of Sugratable grapes grown with two different Irrigation Volumes (IVs) (Normal Irrigation = NI; Smart Irrigation = SI) and different SO₂-Generating Pads (SGPs) ((C = Control; SPB = SmartPac[®] bags; DECCO = DECCO Grapage[®]). Control (i.e., grapes with no SGP) was excluded in T2, due to extensive development of mold on the berries. Ellipse 95% is shown. CW = Cluster weight; BW = 20 berries' weight; ED = Equatorial Diameter; TSSs = Total Soluble Solids; TA = Titratable Acidity; Ha = Hardness; Sp = Springiness; Co = Cohesiveness; Ch = Chewiness; Gu = Gumminess; TPF = Total Polyphenolic Content; FLV = Flavonoids; DPPH = 2,2-diphenyl-1-picrylhydrazyl; DSO₂ = % berries damaged by SO₂; BRM = % berries with rot/mold; SB = % stem browning.

Analyzing PC1 and PC3, NI-SPB and NI-DECCO practically overlapped, characterized by higher pH values and greater yellowness (b^*), positively correlated with PC3. SI-SPB and SI-DECCO stood out distinctly, showing higher nutraceutical contents, texture parameters and reduced effects of variables related to cold storage damages. This suggests good storage resilience for SI treatments, with better outcomes for SPB refrigerated treatments.

3.4. Sensory Analysis of Grapes

During the initial tasting session at T1 (Figure 7), all experimental treatments were included, encompassing grapes refrigerated without any SGP devices, which, as previously noted, remained in satisfactory condition both in terms of edibility and marketability at 15 days post-harvest. Beyond the inherent variations in descriptors due to the subjective nature of evaluation, the Kruskal–Wallis test unveiled statistically significant differences among treatments for the attributes “Berry crunchiness” ($p < 0.01$) and “Pulp consistency” ($p < 0.001$). Specifically, “Berry crunchiness” was notably higher in the NI-SPB and SI-SPB treatments compared to NI-C and SI-C, with NI-DECCO and SI-DECCO exhibiting intermediate values. Moreover, NI-C and SI-C displayed statistically lower values for “Pulp consistency”, while all other treatments exhibited statistically similar results.

The sensory analysis was reiterated 40 days post-harvest (T2) (Figure 8). As previously mentioned, in this session, grapes from refrigerated treatments without SGP (NI-C and SI-C) were excluded due to their inedibility resulting from a high incidence of percentage of berries with rot/mold (Table 2). In this subsequent evaluation, descriptors that exhibited statistically significant differences among treatments were Stem coloration ($p < 0.05$); Stem turgidity ($p < 0.05$); Peduncle browning ($p < 0.01$); Berry color uniformity ($p < 0.05$) and Overall appearance ($p < 0.05$).

“Stem coloration” was notably lower in the NI-DECCO treatment compared to the NI-SPB and SI-DECCO treatments, with SI-SPB positioned in an intermediate position. Regarding “Stem turgidity,” contradictory results were observed, with NI-SPB and SI-DECCO showing statistically higher values than NI-DECCO and SI-SPB, as rated identically by the panel. Concerning “Peduncle browning,” the SI-SPB treatment notably better preserved the grapes for this descriptor, while the others were evaluated similarly. Additionally, “Berry colour uniformity” received positive evaluations for all treatments except SI-DECCO, which was statistically less favored. Moreover, “Overall Appearance” exhibited statistical differences among treatments, with the SI-DECCO treatment being judged to have the overall best appearance, followed by the NI-SPB and NI-DECCO treatments in an intermediate position and the SI-SPB treatment being the least appreciated.

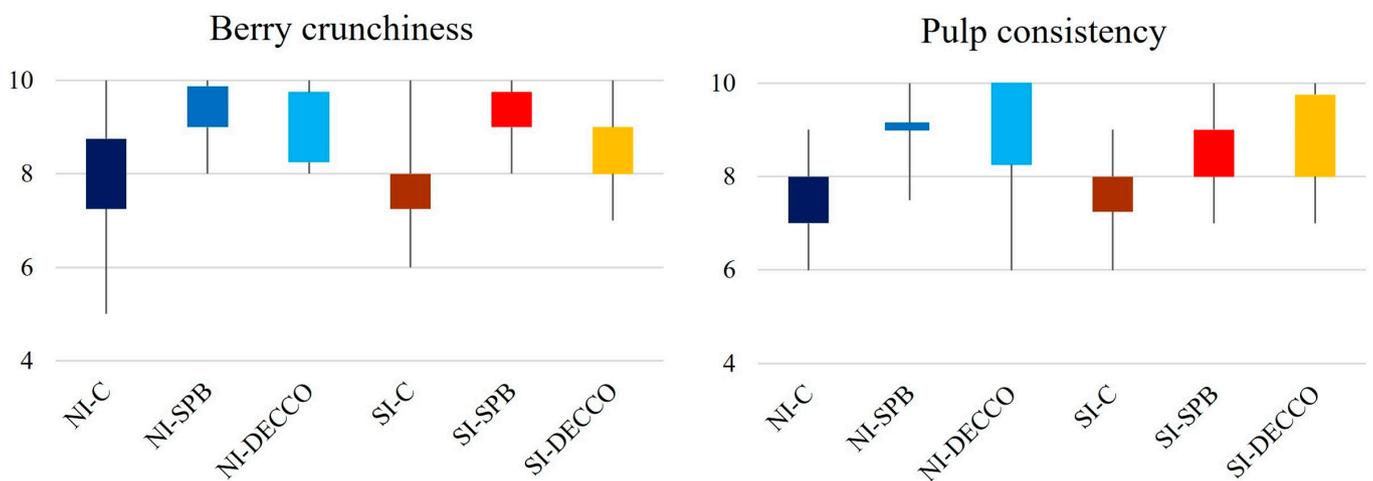
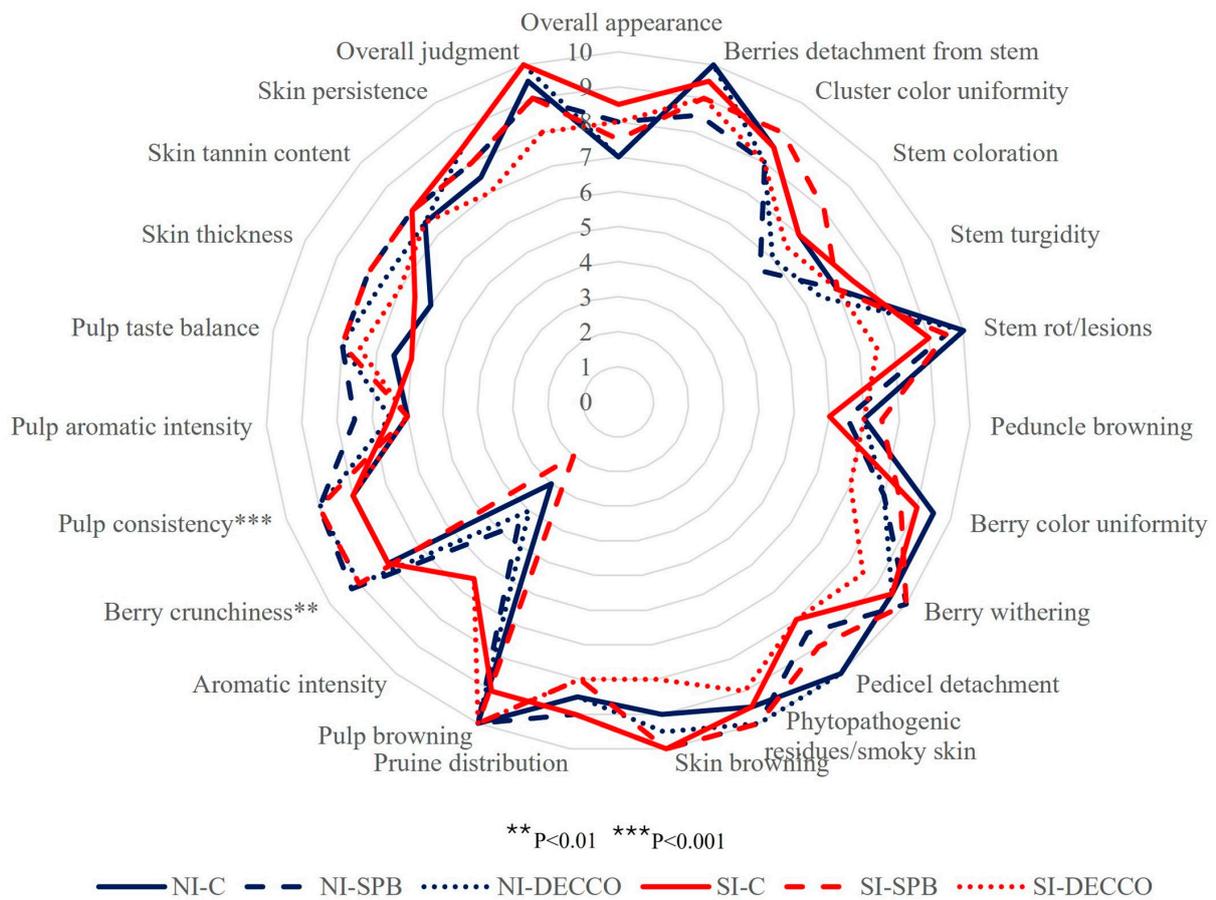


Figure 7. Spider chart of medians of sensory descriptors on Autumn Crisp table grapes grown with two different Irrigation Volumes (IVs) (Normal Irrigation = NI; Smart Irrigation = SI) and different SO₂-Generating Pads (SGPs) (C = Control; SPB = SmartPac® bags; DECCO = DECCO Grapage®) after 15 days' Cold Storage Duration (CSD) (T1). Box and Whisker plot of descriptors, showing statistically significant differences for the Kruskal–Wallis test, are reported on the right.

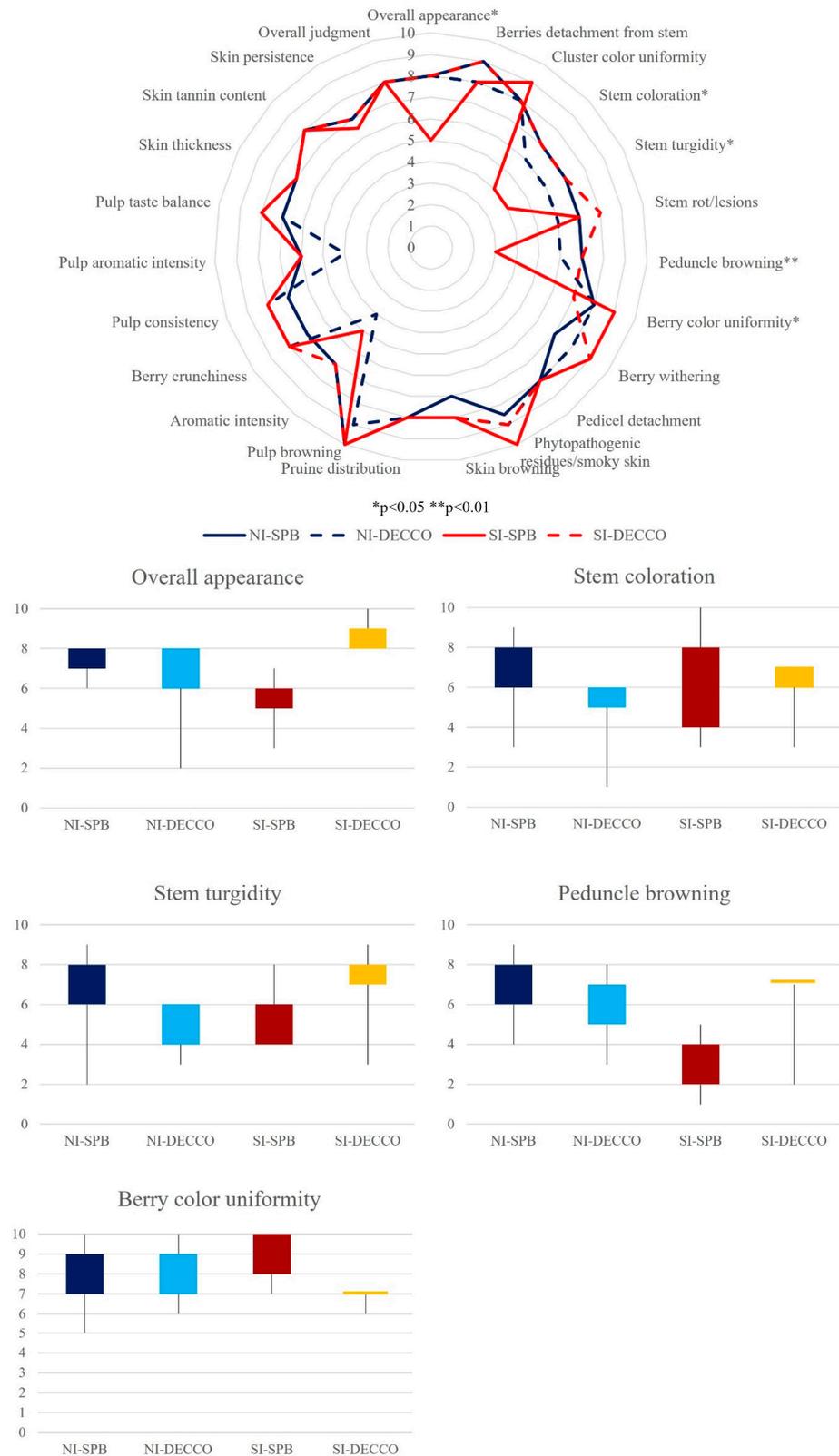


Figure 8. Spider chart of medians of sensory descriptors on table grapes grown with two different Irrigation Volumes (IVs) (Normal Irrigation = NI; Smart Irrigation = SI) and different SO₂-Generating Pads (SGPs) (SPB = SmartPac[®] bags; DECCO = DECCO Grapage[®]) after 40 days' Cold Storage Duration (CSD) (T2). Box and Whisker plot of descriptors, showing statistically significant differences for the Kruskal–Wallis test, are reported below the chart.

4. Discussion

This research aimed to monitor and evaluate a recently introduced seedless table grape cultivar, SUGRATHIRTYFIVE, throughout its journey from the field to cold storage and, ultimately, to the final consumer. The study investigated the potential for reducing irrigation water inputs to enhance agronomic and production sustainability, the ability to maintain premium quality characteristics of grapes through cold storage aided by SO₂-releasing devices and the sensory appreciation of the grape.

Reducing water inputs in table grape cultivation is a pressing objective, as evidenced by the publication of guidelines on the sustainable use of water in winegrape vineyards by the International Organization of Vine and Wine [34]. Among various strategies, Smart Irrigation (SI) in table grape cultivation represents a technological opportunity for growers, offering a simple and intuitive approach as part of Decision Support Systems (DSSs). SI is a well-established practice in both wine grapes [35–37] and table grapes [11,38], particularly in environments like Southern Italy, where growing without irrigation is impractical [3]. In a previous study conducted by Campi et al. [39] in the same area, IV calculated for Normal Irrigation (NI) by an empirical program was lower (296 mm) with respect to the value of 335 mm calculated in this trial. Meanwhile, Irrigation Volumes (IV) provided by SI were lower when compared to those provided by the deficit irrigation regime (300 mm) by Colak and Yazar [40] in Turkey. The IV saved with SI was about 80 mm higher than the water savings found by Vox et al. [41] for the cv. 'Crimson Seedless' that imposed a mild Deficit Irrigation (at 80% ETC).

Moderate water stress generally leads to improvements in grape quality, including increased Total Soluble Solids (TSSs), anthocyanins and phenolic concentrations, although berry weight and Titratable Acidity (TA) may decrease [42]. Instead, Conesa et al. [43] observed no significant differences in berry size and weight for another seedless variety, Crimson Seedless, under a 35% reduction in irrigation, indicating that production components were not compromised. These findings are in line with our data on grapes at harvest, for which TSSs and nutraceutical components were higher in SI, while berry weight and TA remained almost unchanged between NI and SI. In addition, Temnani et al. [44] reported that reducing irrigation by up to 40%, particularly post-veraison, enhanced water use efficiency and increased berry color and firmness. SI grapes exhibited higher berry firmness at harvest than NI grapes, particularly for parameters such as Hardness, Chewiness and glyming. SUGRATHIRTYFIVE generally revealed quite interesting firmness values when compared to other white berry varieties. As an example, SUGRATHIRTYFIVE showed similar values for Hardness and Gumminess compared to Regal seedless or Italia [45], while Springiness, Cohesiveness and Chewiness were even higher. Even the 10 white berry varieties analysed by Rolle et al. [46] provided results related to berry firmness that were absolutely in line with our values, except for Chewiness, which was significantly higher in SUGRATHIRTYFIVE. Chewiness is intended as the ability to measure the resistance to penetration of a given berry skin, and the very high values scored by SUGRATHIRTYFIVE suggest a skin thickness that makes it interesting for long refrigerated storage. In this sense, further investigation into the skin thickness of this variety should be undertaken.

At harvest, SI grapes showed significantly higher values of lightness (L*) and a greater tendency for berries to develop intense color (b*) compared to the greenness observed in NI grapes. In this sense, Pisciotta et al. [45] recorded slightly higher L* values around 40 in clusters of cv Regal seedless and around 37 for cv Italia, consistent with our values. The same authors also reported lower a* values for the same white berry varieties compared to SUGRATHIRTYFIVE, with a greater component of greenness and consistently higher b* (redness) values. These differences can be attributed to the training system (covered plastic film tendone or not), variety, vineyard management and environmental conditions. It is known that, in white grape varieties, color intensity and yellowness are primarily influenced by kaempferol, with minor contributions from quercetin and isorhamnetin [47,48]. These flavonols are part of the flavonoid group, and their biosynthesis is regulated by flavonol synthase (FLS), which studies have shown can be upregulated in response to water stress.

This upregulation is often a plant's defense mechanism to cope with stress by producing secondary metabolites that help mitigate its effects [49,50]. In our study, the higher flavonoid content in the SI treatment may be due to the upregulation of genes involved in their biosynthesis. Similarly, the total polyphenol content (TPF) was also stimulated to a greater extent in the SI treatment with reduced irrigation, which was expected, as polyphenol synthesis is generally triggered by plant defense mechanisms in response to abiotic stress [42]. Moreover, SI grapes showed significantly higher DPPH values than NI grapes. The antioxidant activity of grapes greatly depends on the quantitative and qualitative differences in phenolic compounds [51] and several classes of compounds (anthocyanins, phenolic acids and stilbenes) could contribute to the grape antioxidant activity, suggesting a synergic effect of these compounds. As well known, phenols are good antioxidants due to their susceptibility to oxidation resulting from the hydroxyl groups and unsaturated double bonds in their chemical structure [52].

Regarding the effects of SO₂-Generating Pads (SGPs) aimed at prolonged Cold Storage Duration (CSD), both SmartPac[®] bags (SPB) and DECCO Grapage[®] (DECCO) offered satisfactory results in preserving TSSs compared to the Control, and the berry characteristics of the grapes such as Berry weight and Equatorial Diameter. For its part, the average cluster weight (Figure 3) mainly remained constant in the T0-T1 comparison, except for NI-C and SI-DECCO. At T2, SPB proved to be more effective than DECCO on both NI and SI grapes, contrasting with what was reported by Fernández-Trujillo et al. [53], who stated that the dual-phase SGP showed better performance for the long-term storage of grapes than the single-phase one. As for CIELAB coordinates, the dual release SO₂ system (DECCO) generally proved to be more effective in maintaining brightness (L*), which, however, decreased over the cold storage period. On the contrary, DECCO showed a decline in the a* index, which led the grapes to have more pronounced shades of green. However, L* significantly decreased over time, while the b* yellowness index increased. Ahmed et al. [25], in a study conducted on cv Italia, a white berry table grape variety that, although seed-containing, can serve as a benchmark with Sugrathirtyfive, reported average L* values around 30 at both 7 and 50 days of refrigerated storage. In our case, under all conditions and for all factors, L recorded values close to 40, indicating that grapes were still in commercially acceptable conditions even at 40 days post-harvest. Regarding the firmness of the berries, no significant difference was observed in the use of the different SGPs in all cold storage periods evaluated, in line with Roberto et al. [18], except for Cohesiveness, which increased over time, probably due to dehydration phenomena of the berry that, however, did not reflect, as mentioned, their variation in weight and size.

Regarding the nutraceutical aspect, the sensitivity to SO₂ generally differs among the various table grape varieties. Previous studies reported that phenolic compounds presented a different behavior post-harvest. After 54 days, phenolic content decreased for the Crimson Seedless or increased for new seedless table grape cultivars Timco[™] and Krissy[™] stored in perforated polyethylene bags with an SO₂-generating mat [54]. In our study, the nutraceutical molecules TPF and FLV also did not suffer from the CSD effect, but rather from the SGP system considered, for which SPB proved to be more effective than the dual release SO₂ DECCO. However, the phytosanitary aspect of grapes is of fundamental importance for defining the commercial qualities of grapes over time after harvest. As known, SGPs have the function of preventing the incidence of grey mold, mainly caused by *Botrytis cinerea* [25]. This was also observed in our research, where both SGPs were effective in containing the percentage of berries with rot/mold compared to the Control, for which, as mentioned earlier, grapes at T2 were covered with mold to a rate exceeding 70% (Table 2) and thus deemed inedible. Moreover, the SGP, combined with cold storage, yielded appreciable results in terms of containing the phenomenon of stem browning, as reported in other studies [55]. It is also worth noting that the incidence of SO₂-induced damage caused by SGPs, while statistically significant compared to the Control, was marginal in terms of magnitude, with values averaging below 2%.

5. Conclusions

By examining the data in absolute terms through the combination of the levels of the three factors IV, SGP and CSD, the shelf life of Sugrathirtyfive grapes for periods exceeding 15 days (T1) requires the use of SGPs, under penalty of product loss. The use of SGPs allows grapes to still maintain commercially appreciable quality, with greater efficiency already at T1 in preserving the characteristics of firmness perceived by the panel in terms of Pulp Consistency and Berry Crunchiness with respect to Control. Subsequently, after 40 days of CSD (T2), regarding firmness aspects, no differences were observed among the treatments, describing a similar behavior despite the SGPs or IVs. On the contrary, some differences regarding stem and pedicel integrity began to emerge, with loss of berry color uniformity and the onset of phenomena such as peduncle browning and loss of stem turgidity. Some authors [54] reported that dual-phase release extends the shelf life of grapes by around 1 month. Under the storage conditions used in the study, the 40-day period may represent an appropriate time limit for the cold storage and consumption of Autumn Crisp grapes, even if grown more sustainably under SI, provided that they are refrigerated with the aid of SGPs.

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