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Timing Matters, Not Just the Treatment: Phenological-Stage-Specific Effects of Seaweed and Ethanol Applications on Postharvest Quality of 'Tarsus Beyazı' Grapes

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Abstract: In the context of increasing consumer demand for high-quality, residue-free fruits and the growing emphasis on sustainable postharvest technologies, identifying effective, eco-friendly treatments to maintain grape quality during storage has become a critical focus in modern viticulture. Over the course of this study, we examined the influence of seaweed extract (derived from *Ascophyllum nodosum*) and ethanol-based postharvest treatments on the postharvest quality of the 'Tarsus Beyazı' grape. The seaweed extract was applied at six specific phenological stages according to the BBCH scale: BBCH 13 (3rd–4th leaf stage, 0.40%), BBCH 60 (first flower sheath opening, 0.50%), BBCH 71 (fruit set, 0.50%), BBCH 75 (chickpea-sized berries, 0.50%), BBCH 81 (start of ripening, 0.60%), and BBCH 89 (harvest maturity, 0.60%). After harvest, grape clusters were subjected to four different postharvest treatments: untreated control, control + ethanol (20% ethanol immersion for 10 s), seaweed extract alone (preharvest applications only), and seaweed extract + ethanol (combining both preharvest and postharvest treatments). Grapes were stored at 0–1 °C and 90–95% RH for three weeks, followed by a shelf-life evaluation period of three days at 20 °C and 60–65% RH. The findings revealed that seaweed treatments, especially when applied during cluster formation and berry development, effectively mitigated physiological deterioration, preserving stem turgidity and enhancing berry firmness. In contrast, ethanol showed variable responses, occasionally exerting negative effects, with only marginal benefits observed when applied at optimal developmental stages. Both the type and timing of application emerged as critical determinants of key quality attributes such as weight loss, decay incidence, and must properties (TSS, pH, TA). Correlation and heat map analyses indicated the interrelationships among these parameters and the differential impacts of treatments. These results suggest that phenological-stage-specific seaweed applications hold significant potential as a sustainable strategy to extend the storage life and maintain the market quality of 'Tarsus Beyazı' grapes.

Keywords: biostimulant; grape storage; postharvest; seaweed extract; *Vitis vinifera* L.

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1. Introduction

The viticulture sector has been facing significant changes in recent years due to extreme climatic events, agricultural sustainability concerns, and increasing environmental pressures [1]. Grapevines are highly sensitive to abiotic stress factors, such as salinity, drought, temperature changes, and light deficiency, and biotic stress factors, such as pests, wound formation, and pathogen attacks, and these stress conditions lead to direct negative effects on yield and quality [2]. Chemical fertilizers and synthetic pesticides, which are used intensively to combat these stress factors, damage ecosystem health and threaten sustainable agricultural practices [3]. In addition, the fact that the viticulture sector is largely based on low-skilled labor further deepens the socioeconomic impacts of climate change [4]. Sustainable production techniques such as integrated pest management (IPM) and organic and biodynamic agriculture have been increasingly adopted in recent years [5]. Recently, bio stimulants, especially natural-source plant regulators such as seaweed extracts, have become an attractive alternative to increase yield and reduce environmental impact. Bio stimulants offer an environmentally friendly alternative to fertilizers and growth regulators with their versatile functions such as increasing plant performance, improving quality, supporting adaptation to stress conditions, and protecting soil health [6,7]. Seaweed extracts stimulate plant growth and increase stress tolerance thanks to the amino acids, carbohydrates, phytohormones, and osmo protectants they contain [8]. As an alternative to growth regulators commonly used in table grape production, the application of seaweed extracts is promising in sustainable viticulture with its natural structure and low environmental impact [9].

In the postharvest period, various antimicrobial applications are applied to maintain product quality and extend shelf life. Ethanol, one of these applications, is widely used as a food additive and stands out with its strong antifungal properties [10]. Ethanol vapor or immersion applications have been found effective in controlling postharvest diseases in products such as peach, citrus, and table grapes [11–14]. The applicability of high concentrations is limited by reasons such as cost, flammable properties, and occupational safety [15]. Therefore, low-concentration ethanol applications are being re-evaluated to create synergistic effects with other natural compounds, and efforts are being made to increase their application potential [16].

One of Turkey's native table grape varieties, 'Tarsus Beyazı', is a valuable grape variety that stands out with its large clusters and berries, regional adaptation ability, and high marketability. This variety, which is widely grown in Mersin and its surrounding production areas, is preferred by producers and consumers due to its high yield potential and physical properties suitable for table consumption [17]. However, there are limited studies on the physiological and technological responses of 'Tarsus Beyazı' grapes to bio stimulant applications. In particular, the effects of seaweed extracts on this variety have not yet been sufficiently investigated, and more scientific data are needed in this area. This study was conducted to investigate the effects of seaweed extract applied at different phenological periods and ethanol applied after harvest on the quality parameters of the 'Tarsus Beyazı' grape variety.

2. Materials and Methods

2.1. Trial Setup and Applications

The grapes used in this study belong to *Vitis vinifera* L. cv. 'Tarsus Beyazı', one of the important table grape varieties of Turkey, and were grown on their roots in a vineyard located within the borders of Mersin Province. The vines were shaped with the goblet training system to have a trunk height of 40–50 cm, and pruning was carried out by leaving seven to ten two-three-bud shoots on each. In the spring period at the vineyard, during

the phenological development phase E-L 3 stage, 12-12-17 + 2 MgO (commercial fertilizer containing nitrogen, phosphorus, potassium, and magnesium) was applied to the soil. Foliar fertilization was applied at a rate of 50 kg N per 0.1 hectare, corresponding to approximately 110 g per vine. The experimental vineyard was maintained under rainfed conditions throughout the study period.

Preharvest Applications

In the experiment, a commercial bio stimulant containing a seaweed extract from the species *Ascophyllum nodosum* (Crop Plus, Adama, Izmir, Turkey) was applied at three different doses (0.40%, 0.50%, and 0.60%; *v*/*v*). In the preparation of spray solutions, Tween 20 (Sigma-Aldrich, Izmir, Turkey) was used as a surfactant and was added to all solutions at a rate of 1 mL/L. The control group was treated with only pure water containing Tween 20. Bio stimulant applications were carried out at six different phenological stages of grape development according to the BBCH scale:

BBCH 13 (3rd–4th leaf stage): 0.40%;
BBCH 60 (first flower sheath opening): 0.50%;
BBCH 71 (fruit set): 0.50%;
BBCH 75 (chickpea-sized berries): 0.50%;
BBCH 81 (start of ripening): 0.60%;
BBCH 89 (harvest maturity): 0.60%.

After harvesting, grapes were brought to the laboratory and divided into four different treatment groups:

Control (no treatment);
Ethanol (only postharvest ethanol treatment);
Seaweed extract (only preharvest treatment);
Seaweed extract + ethanol (both preharvest and postharvest treatment).

For postharvest ethanol treatment, a 20% ethanol solution was prepared with distilled water, and grape clusters were immersed in this solution for 10 s, then allowed to dry, and placed in plastic crates. The study was planned with three replications, with two bunches used in each replication. The grapes were stored at 0–1 °C and 90–95% relative humidity for three weeks. Analyses were made each week, and the bunches were kept at 20 °C and 60–65% relative humidity for three days, after which the shelf life was evaluated [17].

2.2. Cluster Weight Measurements and Weight Loss Calculations

To determine the weight loss of grape bunches, the initial and final weights were measured separately at the end of each application and each period using a digital scale (±0.01 g precision). The initial weight was recorded by weighing the bunches before storage and at the end of each cold storage and shelf-life period. The weight loss percentage for each bunch was calculated according to the following formula:

$$\text{Weight Loss (\%)} = ((\text{Starting Weight} - \text{Final Weight})/\text{Starting Weight}) \times 100$$

2.3. Detachment Force Measurement

To determine the resistance of grape berries to detachment from the cluster, measurements of detachment force were conducted. This analysis was performed using 10 randomly selected, healthy, and mature berries from each treatment group. The berries were carefully excised with their pedicles intact to preserve their natural attachment to the rachis. The detachment force was measured using a digital texture analyzer. During the measurement, the pedicle of each berry was fixed to the device, and the berry was pulled downward at

a constant speed. The maximum force required to completely separate the berry from its pedicle was recorded in Newtons (N) [18].

2.4. Pedicel Dehydration Measurement

To determine the pedicle drying rate, the pedicles of 10 healthy and mature berries randomly selected from clusters belonging to each treatment group were evaluated. Each pedicle was carefully cut in connection with the berry and weighed before analysis, and the initial weights were recorded. The pedicles were kept at room temperature under constant-humidity conditions (approximately 20 ± 2 °C, 60–65% relative humidity) for 24 h and then weighed again, and their final weights were determined. Pedicle dehydration was calculated as a percentage (%), taking the difference between the initial and final weights to the initial weight [19]. The pedicle drying rate was expressed with the following formula:

$$\text{Pedicel Dehydration (\%)} = ((\text{Initial Weight} - \text{Final Weight})/\text{Initial Weight}) \times 100$$

2.5. Rotten Berry Ratio Determination

In order to determine the rotten berry ratio, randomly selected bunches from each treatment group were evaluated. In each bunch, berries showing signs of deterioration, color change, mold growth, or softening that could be seen with the naked eye were considered "rotten". During the evaluation, the total number of berries in each bunch and the number of berries classified as rotten were counted. Based on the obtained data, the rotten berry ratio (%) was calculated with the following formula [20]:

$$\text{Rotten Berry (\%)} = (\text{Number of Rotten Berries}/\text{Total Number of Berries}) \times 100$$

2.6. Determination of Total Soluble Solids (TSS, °Brix)

The total soluble solids (TSSs) were determined in °Brix. For this purpose, analyses were performed using healthy and ripe berries randomly selected from each treatment group. Approximately 10 berries were selected for each repetition and then crushed with their skins under sterile conditions to obtain a homogeneous juice. The juice was filtered with a strainer and measured without sediment. TSS values were read directly in °Brix using a calibrated digital hand refractometer (Greinorm Refraktometre 0–80 Brix, Lemgo, Germany). Measurements were performed at 20 ± 1 °C, and one value was recorded for each repetition [21].

2.7. Determination of pH

The pH was determined from healthy and ripe berries randomly selected from each treatment group. Approximately 10 berries were selected for each replication and crushed under sterile conditions to prepare a homogeneous juice. After filtration, clear samples were used for analysis. pH measurements were performed with a previously calibrated digital pH meter (Milwaukee Instruments MW151, Milwaukee, WI, USA). Measurements were made at room temperature (20 ± 1 °C), and the device was calibrated with pH 4.01, 7.00, and 10.01 buffer solutions before each measurement. A pH value was recorded for each replication [21].

2.8. Determination of Titratable Acidity (TA)

Total titratable acidity (TA) determined by titration was measured by analyzing the juice obtained from 10 healthy and ripe berries randomly selected from each treatment group. The berries were crushed in a sterile mortar and then filtered to obtain clear juice samples. In each analysis, 10 mL of juice was diluted with 50 mL of distilled water, and a few drops of phenolphthalein indicator were added. The solution was titrated with 0.1 N sodium hydroxide (NaOH) solution until a weak and permanent pink color was formed.

The amount of NaOH consumed as a result of the titration was recorded, and the total acidity value was calculated as tartaric acid in g/L. Each measurement was made with three replicates [22].

2.9. Statistical Analysis

All experiments were conducted using a randomized design, and data were collected in triplicate during the cold storage periods. Statistical analyses were performed using IBM SPSS Statistics version 22.0. A one-way analysis of variance (ANOVA) was employed to assess the effects of carboxymethyl cellulose (CMC) and beeswax (KB) edible coatings, as well as seaweed extract, on the measured parameters during storage. Mean separation was carried out using Tukey's HSD test at the 5% significance level ($p < 0.05$). Results are expressed as mean values ± standard deviations (SDs). To further elucidate the relationships between treatments and storage periods, Principal Component Analysis (PCA) was performed by using GraphPad Prism version 9.3.1 (GraphPad Software, LLC, San Diego, CA, USA), and the output was visualized as a biplot. Additionally, a hierarchical clustering heatmap was constructed using the SRPLOT online platform (https://www.bioinformatics.com.cn/en, accessed 30 March 2024) to depict the association patterns and variation intensities among treatments and evaluated traits throughout the storage duration.

3. Results

At harvest time, seaweed application produced the highest average cluster weight (232.97 ± 25.23 g), followed by control + ethanol (204.23 ± 3.30 g), seaweed + ethanol (200.37 ± 16.32 g), and control (188.43 ± 15.44 g). Weight loss occurred in all treatments during storage; however, seaweed application minimized this loss most effectively. After three weeks of cold storage, clusters in the seaweed treatment maintained the highest weight (263.83 ± 116.78 g), followed by seaweed + ethanol (243.33 ± 82.13 g), control + ethanol (202.33 ± 65.54 g), and control (201.33 ± 70.111 g). This pattern continued throughout shelf life, with seaweed application maintaining the highest values. Across all periods, the highest average cluster weights were observed during three-week cold storage (227.71 ± 78.54 g), the first week of shelf life (210.04 ± 26.70 g), and the first week of storage (208.88 ± 53.36 g). The lowest average was recorded in the third week of shelf life (192.42 ± 50.55 g). Examining treatment averages, seaweed application showed the highest value (223.00 ± 54.60 g), while control + ethanol (192.65 ± 34.58 g), seaweed + ethanol (190.79 ± 42.93 g), and control (177.99 ± 41.03 g) exhibited lower values. Statistical analysis confirmed that seaweed application was significantly more effective in preventing weight loss ($p < 0.05$). The lowest weight loss percentage was observed in seaweed application (5.07%), statistically lower than the control and ethanol + control groups. The highest weight loss occurred in the control + ethanol group (6.66%), suggesting ethanol application alone may negatively impact weight maintenance. The seaweed + ethanol combination showed an intermediate value (5.76%), indicating ethanol partially reduces seaweed's protective effect. Among storage periods, the lowest average weight loss was observed in the second week (4.40%), while the highest occurred during the first week of shelf life (8.18%). The detachment force between cluster stem and berry averaged 166.82 ± 12.26 N at harvest, with similarly high values during the second (168.47 ± 31.52 N) and third weeks (166.40 ± 21.98 N) of shelf life. The lowest average detachment force was observed at the end of the second week of cold storage (101.23 ± 14.18 N). Variance analysis showed that storage period significantly affected detachment force ($p < 0.05$). No statistically significant differences were found between treatments regarding detachment force ($p = 0.288$), nor was there a significant interaction between storage period and treatments ($F = 0.946$, $p = 0.531$) (Table 1).

Table 1. Effects of seaweed and ethanol applications on some quality parameters of 'Tarsus Beyazı' grape variety during cold storage and shelf life (means ± standard deviation).

Period	Treatment	Initial Weight (g)	Cluster Weight (g)	Weight Loss (%)	Detachment Force (N)	Pedicel Dehydration (%)	Rotten Berry (%)	TSS (°Brix)	pH	Titratable Acidity (g/L)
Harvest	Control	–	188.43 ± 15.44	–	172.83 ± 6.38	0.10 ± 0.00 h	–	21.00 ± 1.11	3.79 ± 0.08	0.52 ± 0.03
	Control + Ethanol	–	204.23 ± 3.30	–	172.83 ± 12.35	0.10 ± 0.00 h	–	21.70 ± 0.78	3.80 ± 0.08	0.52 ± 0.03
	Seaweed	–	232.97 ± 25.23	–	158.93 ± 6.27	0.10 ± 0.00 h	–	20.07 ± 0.38	3.54 ± 0.07	0.63 ± 0.03
	Seaweed + Ethanol	–	200.37 ± 16.32	–	162.67 ± 19.14	0.10 ± 0.00 h	–	20.07 ± 0.38	3.50 ± 0.07	0.63 ± 0.03
One Weeks After Storage	Control	224.00 ± 75.44	213.50 ± 70.26	4.53 ± 1.61 c–g	132.37 ± 34.24	0.70 ± 0.00 f	26.78 ± 4.34 e–h	20.86 ± 0.14	3.74 ± 0.04	0.56 ± 0.02
	Control + Ethanol	210.00 ± 35.27	196.50 ± 29.33	6.17 ± 3.76 b–g	135.57 ± 4.24	0.60 ± 0.10 g	22.23 ± 7.52 f–h	21.73 ± 1.33	3.71 ± 0.08	0.58 ± 0.03
	Seaweed	220.33 ± 66.54	218.17 ± 66.46	1.07 ± 0.47 h	163.20 ± 34.24	0.57 ± 0.06 g	24.58 ± 9.23 f–h	20.23 ± 0.51	3.53 ± 0.08	0.62 ± 0.02
	Seaweed + Ethanol	181.17 ± 51.03	170.17 ± 52.78	6.63 ± 3.13 b–g	139.17 ± 31.39	0.70 ± 0.00 f	20.86 ± 4.50 gh	19.86 ± 0.75	3.52 ± 0.03	0.62 ± 0.02
Two Weeks After Storage	Control	155.00 ± 19.58	148.67 ± 18.71	4.07 ± 0.35 e–h	86.27 ± 6.99	0.93 ± 0.12 a–c	37.17 ± 8.25 c–g	20.83 ± 0.42	3.67 ± 0.06	0.60 ± 0.05
	Control + Ethanol	200.50 ± 29.40	193.67 ± 28.07	3.37 ± 0.72 gh	112.10 ± 7.53	0.83 ± 0.06 de	23.28 ± 11.05 f–h	20.41 ± 0.92	3.60 ± 0.03	0.58 ± 0.04
	Seaweed	229.50 ± 45.71	214.67 ± 47.29	6.73 ± 3.50 b–g	101.67 ± 16.25	0.77 ± 0.06 ef	18.52 ± 5.07 h	19.39 ± 0.74	3.48 ± 0.03	0.63 ± 0.04
	Seaweed + Ethanol	206.67 ± 20.10	199.50 ± 18.38	3.43 ± 0.51 f–h	104.87 ± 14.26	0.83 ± 0.06 de	32.00 ± 6.52 d–h	20.31 ± 0.64	3.47 ± 0.12	0.62 ± 0.07
Three Weeks After Storage	Control	201.33 ± 70.11	188.83 ± 66.62	6.23 ± 1.23 b–g	129.60 ± 7.77	1.00 ± 0.00 a	65.81 ± 5.76 a	19.81 ± 0.87	3.61 ± 0.02	0.62 ± 0.06
	Control + Ethanol	202.33 ± 65.54	192.17 ± 62.01	4.97 ± 0.38 b–g	116.27 ± 15.21	1.00 ± 0.00 a	49.22 ± 6.92 bc	19.83 ± 0.76	3.65 ± 0.08	0.51 ± 0.08
	Seaweed	263.83 ± 116.78	254.83 ± 13.79	3.50 ± 0.40 f–h	126.00 ± 21.31	0.93 ± 0.06 a–c	61.63 ± 12.61 ab	20.99 ± 0.29	3.50 ± 0.10	0.63 ± 0.08
	Seaweed + Ethanol	243.33 ± 82.13	232.67 ± 78.94	4.37 ± 0.67 d–g	107.80 ± 38.85	1.00 ± 0.00 a	39.01 ± 4.53 c–f	19.55 ± 0.44	3.51 ± 0.08	0.64 ± 0.02
Shelf Life—Week One	Control	206.83 ± 23.38	190.83 ± 21.33	7.73 ± 1.08 a–d	127.37 ± 20.85	0.97 ± 0.06 ab	32.36 ± 3.89 d–h	20.80 ± 0.21	3.64 ± 0.05	0.68 ± 0.02
	Control + Ethanol	211.17 ± 34.54	189.33 ± 39.93	10.77 ± 4.30 a	125.70 ± 35.64	0.97 ± 0.06 ab	29.07 ± 6.74 d–h	22.47 ± 1.18	3.68 ± 0.09	0.64 ± 0.02
	Seaweed	229.83 ± 10.21	214.00 ± 10.50	6.90 ± 0.44 b–f	137.93 ± 32.45	0.90 ± 0.00 b–d	31.56 ± 0.96 d–h	20.94 ± 1.02	3.60 ± 0.02	0.63 ± 0.05
	Seaweed + Ethanol	192.33 ± 31.66	178.33 ± 29.78	7.30 ± 0.66 b–e	104.07 ± 37.83	1.00 ± 0.00 a	28.56 ± 11.60 d–h	20.47 ± 0.58	3.47 ± 0.05	0.68 ± 0.05
Shelf Life—Week Two	Control	170.00 ± 26.92	156.67 ± 25.59	7.87 ± 0.95 a–c	199.30 ± 21.24	0.90 ± 0.00 b–d	34.85 ± 7.23 c–h	21.46 ± 0.97	3.74 ± 0.10	0.62 ± 0.02
	Control + Ethanol	234.83 ± 31.19	219.33 ± 30.67	6.67 ± 2.06 b–g	173.33 ± 21.70	0.87 ± 0.06 cd	42.60 ± 12.77 c–e	21.63 ± 1.16	3.80 ± 0.17	0.57 ± 0.05
	Seaweed	195.67 ± 60.12	184.83 ± 57.71	5.67 ± 0.96 b–g	156.10 ± 15.69	1.00 ± 0.00 a	18.88 ± 6.32 h	20.43 ± 0.25	3.58 ± 0.09	0.64 ± 0.05
	Seaweed + Ethanol	207.67 ± 29.88	195.17 ± 27.11	5.97 ± 0.55 b–g	145.13 ± 42.30	0.90 ± 0.10 b–d	35.01 ± 9.33 c–h	20.83 ± 1.00	3.53 ± 0.08	0.69 ± 0.05
Shelf Life—Week Three	Control	173.33 ± 30.66	159.00 ± 27.78	8.27 ± 0.85 ab	171.67 ± 22.91	1.00 ± 0.00 a	45.46 ± 2.61 cd	21.20 ± 0.09	3.59 ± 0.22	0.60 ± 0.03
	Control + Ethanol	166.67 ± 17.01	153.33 ± 17.08	8.03 ± 1.72 ab	176.67 ± 16.26	1.00 ± 0.00 a	30.69 ± 4.10 d–h	21.77 ± 1.16	3.65 ± 0.10	0.65 ± 0.09
	Seaweed	258.67 ± 42.59	241.50 ± 38.80	6.57 ± 0.81 b–g	152.37 ± 13.96	1.00 ± 0.00 a	24.17 ± 5.71 f–h	20.24 ± 1.14	3.55 ± 0.11	0.62 ± 0.10
	Seaweed + Ethanol	171.00 ± 46.89	159.33 ± 43.82	6.83 ± 0.81 b–g	164.90 ± 34.26	1.00 ± 0.00 a	30.53 ± 23.47 d–h	20.11 ± 0.79	3.43 ± 0.08	0.65 ± 0.04
Average of Periods	Harvest	–	206.50 ± 22.39	–	166.82 ± 12.26 A	0.10 ± 0.00	–	20.71 ± 0.95 A–C	3.67 ± 0.15 A	0.58 ± 0.07 C
	One Weeks After Storage	208.88 ± 53.36	199.58 ± 52.43	4.60 ± 3.17	142.58 ± 27.74 B	0.64 ± 0.08	23.61 ± 6.20	20.67 ± 1.01 A–C	3.63 ± 0.11 AB	0.59 ± 0.03 BC
	Two Weeks After Storage	197.92 ± 38.44	189.13 ± 36.53	4.40 ± 2.11	101.23 ± 14.18 D	0.84 ± 0.09	27.74 ± 10.24	20.24 ± 0.81 BC	3.56 ± 0.11 B	0.61 ± 0.05 BC
	Three Weeks After Storage	227.71 ± 78.54	217.13 ± 76.39	4.77 ± 1.22	119.92 ± 22.12 CD	0.98 ± 0.04	53.92 ± 12.99	20.05 ± 0.79 C	3.57 ± 0.09 B	0.60 ± 0.08 BC
	Shelf Life—Week One	210.04 ± 26.70	193.13 ± 27.16	8.18 ± 2.50	123.77 ± 30.44 BC	0.96 ± 0.05	30.39 ± 6.20	21.17 ± 1.07 A	3.60 ± 0.10 AB	0.66 ± 0.04 A
	Shelf Life—Week Two	202.04 ± 41.49	189.00 ± 39.75	6.54 ± 1.39	168.47 ± 31.52 A	0.92 ± 0.07	32.83 ± 11.99	21.09 ± 0.93 A	3.66 ± 0.15 A	0.63 ± 0.06 AB
	Shelf Life—Week Three	192.42 ± 50.55	178.29 ± 47.70	7.43 ± 1.23	166.40 ± 21.98 A	1.00 ± 0.00	32.71 ± 13.30	20.83 ± 1.05 AB	3.56 ± 0.14 B	0.63 ± 0.07 AB
Average of Treatments	Control	188.42 ± 46.51 B	177.99 ± 41.03 B	6.45 ± 1.93	145.63 ± 39.52	0.80 ± 0.31	40.40 ± 13.89	20.85 ± 0.75 B	3.68 ± 0.11 A	0.60 ± 0.06 BC
	Control + Ethanol	204.25 ± 38.39 AB	192.65 ± 34.58 B	6.66 ± 3.25	144.64 ± 31.44	0.77 ± 0.31	32.85 ± 12.52	21.36 ± 1.24 A	3.70 ± 0.11 A	0.58 ± 0.07 C
	Seaweed	232.97 ± 59.87 A	223.00 ± 54.60 A	5.07 ± 2.55	142.31 ± 27.99	0.75 ± 0.31	29.89 ± 16.54	20.33 ± 0.78 C	3.54 ± 0.08 B	0.63 ± 0.05 AB
	Seaweed + Ethanol	200.36 ± 46.90 AB	190.79 ± 42.93 B	5.76 ± 1.86	132.66 ± 37.39	0.79 ± 0.31	30.99 ± 11.59	20.17 ± 0.69 C	3.50 ± 0.07 B	0.65 ± 0.05 A
Period	*p*-value	0.618	0.471	0.000	0.000	0.000	0.000	0.008	0.004	0.004
Treatments	*p*-value	0.070	0.018	0.038	0.288	0.006	0.003	0.000	0.000	0.000
Period × Treatments	*p*-value	0.749	0.826	0.014	0.531	0.001	0.023	0.176	0.793	0.209

Different lowercase letters indicate significant differences ($p < 0.05$). Different uppercase letters within the same column denote statistically significant differences according to Tukey's HSD test ($p < 0.05$).

The average detachment force values among treatments were as follows: control (145.63 ± 39.52 N), control + ethanol (144.64 ± 31.44 N), seaweed (142.31 ± 27.99 N), and seaweed + ethanol (132.66 ± 37.39 N). The overall average detachment force was 141.31 ± 34.16 N. Pedicel dehydration was minimal (0.10%) at harvest across all treatments, increasing significantly as storage progressed. The highest levels were observed during the third week of cold storage (0.98 ± 0.04%) and throughout all shelf-life periods (0.96–1.00%). By the third week of shelf life, all treatments recorded 1.00% pedicel dehydration. Statistical analysis confirmed that storage period significantly affected pedicel dehydration ($p < 0.05$), as did treatments ($p = 0.006$). A significant interaction between storage period and treatments was observed ($F = 2.877$, $p = 0.05$). Among treatments, seaweed application exhibited the lowest pedicel dehydration (0.75 ± 0.31%), followed by control + ethanol (0.77 ± 0.31%), seaweed + ethanol (0.79 ± 0.31%), and control (0.80 ± 0.31%). The overall average pedicel dehydration rate was 0.78 ± 0.31%. No rotten berries were observed at harvest. Rottenness rates increased with storage duration, with the highest rates observed during the third week of cold storage. During this period, the control group showed the highest rottenness (65.81 ± 5.76%), followed by seaweed application (61.63 ± 12.61%). The lowest rottenness rate was observed in the seaweed group during the second week storage period (18.52 ± 5.07%). Variance analysis showed that storage period significantly affected rottenness rate ($p < 0.05$), as did treatments ($p = 0.003$). The interaction between storage period and treatments was also significant ($F = 2.151$, $p = 0.023$). According to period averages, the lowest decay rate was observed in the first week of cold storage (23.61 ± 6.20%), while the highest was recorded in the third week of storage (53.92 ± 12.99%). During shelf life, decay rates ranged between 30% and 33%. When evaluated by treatment, the control group showed the highest average decay rate (40.40 ± 13.89%), while seaweed application had the lowest (29.89 ± 16.54%). Control + ethanol and seaweed + ethanol groups showed intermediate performance (32.85 ± 12.52% and 30.99 ± 11.59%, respectively). The overall average rot rate was 33.53 ± 14.09%. TSS content varied according to both storage periods and treatments. Variance analysis showed that storage period significantly affected TSS values ($p = 0.008$), while treatments had an even stronger effect ($p < 0.05$). The period × treatment interaction was not significant ($p = 0.176$). TSS values at harvest ranged between 20.07 and 21.70 °Brix, with the highest value in the control + ethanol group (21.70 ± 0.78). Partial decreases were observed during storage, particularly in the three-week cold storage period, where values of 19.81 ± 0.87 and 19.83 ± 0.76 were recorded in control and control + ethanol groups, respectively. According to the storage period, the highest TSS values were obtained in the first (21.17 ± 1.07) and second weeks of shelf life (21.09 ± 0.93). The lowest average was recorded in the third-week cold storage period (20.05 ± 0.79). Among treatments, the control + ethanol group showed the highest average TSS (21.36 ± 1.24), followed by the control group (20.85 ± 0.75), while seaweed (20.33 ± 0.78) and seaweed + ethanol (20.17 ± 0.69) applications had statistically lower values ($p < 0.05$). The overall average TSS was 20.68 ± 0.99 (Table 1).

In our results, pH values at harvest ranged between 3.54 and 3.80, with the highest values in the control and control + ethanol groups (both 3.80 ± 0.08). Lower pH values (3.54 ± 0.07) were recorded in the seaweed and seaweed + ethanol treatments. A general decreasing trend was observed during storage, with lower averages in the second and third week of cold storage. Variance analysis showed that the storage period significantly affected pH ($p = 0.004$), as did treatments ($p < 0.05$). The period × treatment interaction was not significant ($p = 0.793$). According to the storage period, the highest pH values were observed at harvest (3.67 ± 0.15) and during the second week of shelf life (3.66 ± 0.15). Lower values were detected during the second week of cold storage (3.56 ± 0.11), third week of cold storage (3.57 ± 0.09), and third week of shelf life (3.56 ± 0.14). Among treatments, the

highest average pH values were observed in the control (3.68 ± 0.11) and control + ethanol (3.70 ± 0.11) groups, with no significant difference between them. Significantly lower pH values were observed in seaweed (3.54 ± 0.08) and seaweed + ethanol (3.50 ± 0.07) applications ($p < 0.05$). The overall average pH was 3.60 ± 0.13. The lowest TA values at harvest were observed in the control and control + ethanol groups (0.52 ± 0.03), while significantly higher values were found in seaweed and seaweed + ethanol applications (0.63 ± 0.03). Variance analysis showed that both the storage period (F = 3.658, $p = 0.004$) and treatments ($p < 0.05$) significantly affected TA. The period × treatment interaction was not significant ($p = 0.209$). According to period averages, the highest TA was observed in the first week of shelf life (0.66 ± 0.04), which was significantly different from other periods ($p < 0.05$). The harvest period showed the lowest average TA (0.58 ± 0.07). A slight increase in TA values was generally observed with extended storage. Among treatments, the highest average TA was observed in the seaweed + ethanol group (0.65 ± 0.05), followed by seaweed (0.63 ± 0.05), while control + ethanol had the lowest (0.58 ± 0.07). These differences were statistically significant ($p < 0.05$). The overall average TA was 0.61 ± 0.06 (Table 1).

Heat map analysis showed significant clusters among sample groups and quality parameters. Seaweed (SW) and seaweed + ethanol (SW-ETH) treatments generally demonstrated lower weight loss, pedicel dehydration, and rot rate compared to control groups (CNT and CNT-ETH). Control groups showed weaker stem–fruit connections, indicating decreased postharvest durability. Chemical parameters like TA and TSS maintained relatively balanced values in samples with seaweed application (Figure 1). Correlation analysis revealed strong positive relationships between pedicel dehydration and initial weight (r = 0.84), pedicel dehydration and weight loss (r = 0.80), and pedicel dehydration and rot rate (r = 0.79). Significant correlations were also found between initial weight and rot rate (r = 0.71) and weight loss (r = 0.64).

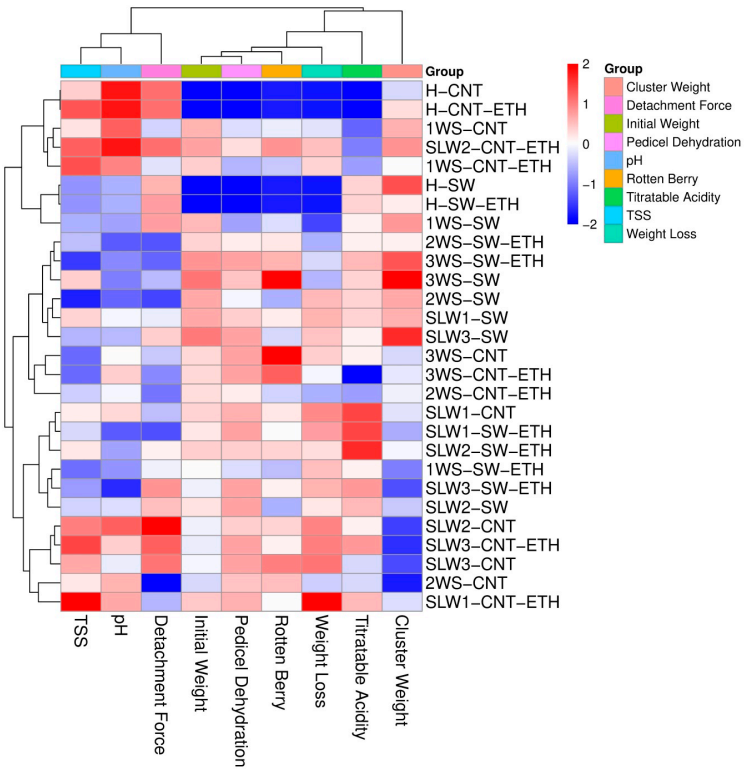

Figure 1. Evaluation of the effects of seaweed extract and ethanol treatments applied in different phenological periods on quality parameters of 'Tarsus Beyazı' table grape variety during cold storage using heat map.

Detachment force showed generally low and negative correlations with other variables. TA demonstrated a significant negative correlation with pH (r = −0.65) and positive correlations with weight loss (r = 0.42) and pedicel dehydration (r = 0.41) (Figure 2). Principal Component Analysis (PCA) showed that the first principal component (PC1) accounted for 40.60% of variance, while the second (PC2) accounted for 23.53%, collectively representing 64.13% of total variance. Cluster weight showed the highest positive loading on PC1, while quality loss parameters (weight loss, rotten berries, and pedicel dehydration) grouped positively on the same axis but at different angles. Parameters like pH, detachment force, and TSS showed negative loading on PC1 and significant separation on PC2. The seaweed + ethanol combination clustered with parameters positively affecting quality, while control groups were positioned near negatively charged quality parameters (Figure 3).

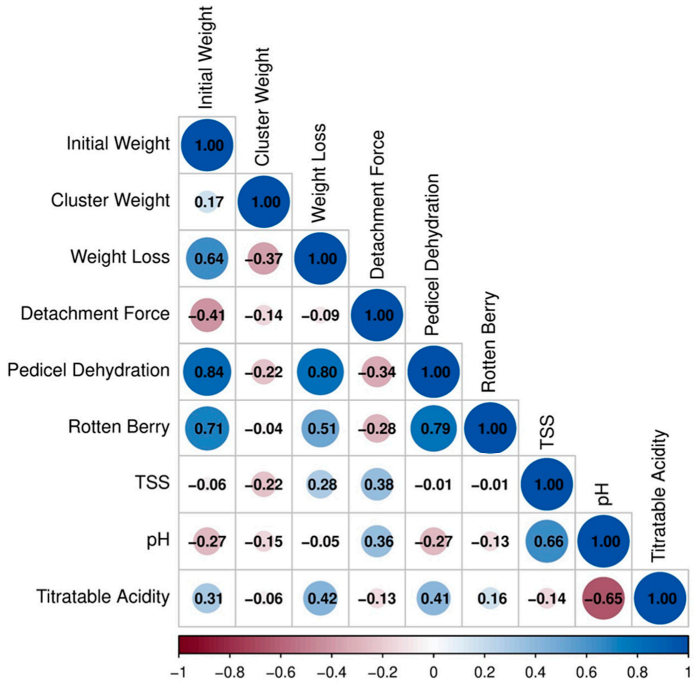

Figure 2. Investigation of relationships between quality parameters of "Tarsus Beyazı" grape variety with correlation matrix.

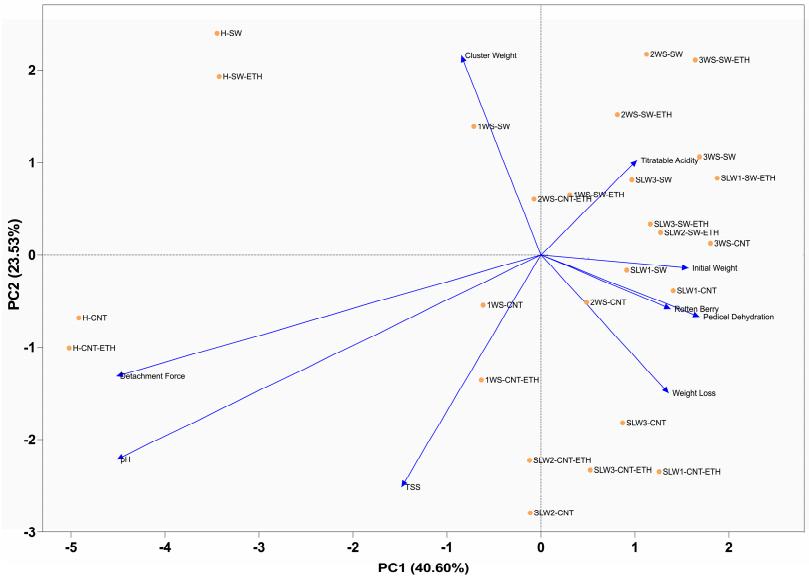

Figure 3. Evaluation of quality parameters in "Tarsus Beyazı" grape variety by Principal Component Analysis (PCA).

4. Discussion

Our investigation into the physiological and metabolic responses of *Vitis vinifera* L. cv. 'Tarsus Beyazı' to various pre- and postharvest treatments has yielded several compelling findings that merit careful consideration within the broader context of viticultural research. As experimental applications, we employed control, control + ethanol, seaweed extract, and seaweed + ethanol treatments, with each demonstrating distinctive effects on critical quality parameters during cold storage and subsequent shelf-life periods and offering valuable insights into potential approaches for extending postharvest durability while maintaining fruit quality. However, it should be noted that these findings are specific to the 'Tarsus Beyazı' cultivar, and extrapolation to other grape varieties may be limited without further cultivar-specific research. Weight loss in grape clusters represents a paramount quality concern, directly influencing both commercial value and consumer acceptance [23]. Our observations revealed a consistent increase in weight loss across all treatments over time, attributed primarily to water loss through fruit respiration and transpiration processes. This finding aligns with established principles of postharvest physiology, whereby evaporation and gas exchange persist even under optimal cold chain conditions [24–26]. Notably, seaweed extract application emerged as particularly efficacious in preserving cluster weight throughout both cold storage and shelf-life periods. After three weeks of cold storage, clusters treated with seaweed extract maintained the highest weight (263.83 g), indicating this application's significant role in decelerating moisture loss. The protective mechanism likely involves the formation of a semi-permeable film on the fruit surface that reduces water vapor diffusion, a principle similar to that observed with other naturally derived substances that preserve cell membrane integrity [27–29]. The efficacy of seaweed application in minimizing weight loss (average 5.07% compared to 6.66% in ethanol-treated samples) appears to stem from its capacity to establish a hydrophobic barrier that limits transpiration. Conversely, ethanol application when administered alone increased weight loss, presumably due to its respiration-promoting effects accelerating water loss. The combined seaweed + ethanol treatment (5.76% weight loss) demonstrated a slightly diminished preservation effect, suggesting a potential antagonistic interaction between these treatments. While seaweed-based coatings show promise, potential disadvantages such as high application costs and possible interference with natural ripening processes at elevated concentrations require consideration in commercial applications.

The detachment force parameter, representing the mechanical strength of the connection between cluster stem and berry, constitutes a critical quality factor influencing marketability and postharvest longevity. Our measurements revealed notable variations in detachment force values contingent upon both storage duration and applied treatments. The high initial detachment force at harvest (166.82 N) signals physiologically sound bond structures within the fruit. Similarly elevated values observed during the second and third weeks of shelf life (168.47 and 166.40 N, respectively) suggest preservation of the fruit–stalk bond during these periods. However, the marked decline to 101.23 N at the conclusion of the second week of cold storage indicates a temporal weakening in bond strength. Statistical analysis revealed no significant differences among treatments regarding detachment force values, suggesting limited influence of our experimental applications on this particular parameter. These findings partially align with results reported by previous authors [30–41], who observed that certain preharvest applications could enhance detachment force values and reduce fruit shedding rates. Pedicel dehydration serves as both a visual indicator of moisture loss and a structural quality parameter with direct implications for consumer perception and product marketability [42,43]. Our findings demonstrated significant variations in pedicel dehydration rates contingent upon both storage duration and applied treatments. Dehydration reached peak levels during the third week of cold storage and

throughout all shelf-life periods, reflecting accelerated moisture loss at elevated ambient temperatures resulting in pronounced drying of the cluster stem. Among the treatments evaluated, seaweed extract application yielded the lowest average pedicel dehydration value (0.75%), suggesting its capacity to partially restrict moisture loss from the cluster stem, potentially through the moisture-retaining properties of its constituent polysaccharides. Nevertheless, this protective effect appeared to diminish under shelf-life conditions, with even seaweed-treated samples reaching 1.00% dehydration by the conclusion of the third week. This temporal limitation of protective effects highlights a significant constraint of seaweed treatments that may limit their commercial viability in extended storage scenarios. Berry rot incidence exhibited significant responsiveness to both storage duration and applied treatments. While no rot was detected at harvest, substantial increases occurred during the third week of cold storage, with the control group exhibiting the highest rate (65.81%), followed by seaweed application (61.63%). Conversely, the lowest rot incidence (18.52%) was recorded at the end of the second week in seaweed-treated samples. These findings suggest seaweed application may possess potential for mitigating rot development during specific periods. Across average values, the control group exhibited the highest rot rate (40.40%), while the seaweed group maintained the lowest (29.89%), indicating that certain coating applications may exert partial effects in delaying rot development, though with temporal variability. These findings align with previous studies suggesting that certain natural coatings containing active ingredients can inhibit mold development on grape surfaces [44,45].

TSS content represents a crucial indicator of grape maturity and quality, with significant implications for consumer acceptance [46,47]. Our analysis revealed variations in TSS values dependent upon both storage duration and applied treatments. The elevated TSS average observed in control + ethanol-treated samples (21.36) may relate to ethanol's ripening-promoting effects, potentially through enhanced activity of enzymes involved in sucrose synthesis [48,49]. The relatively lower TSS means recorded in the seaweed and seaweed + ethanol groups (20.33 and 20.17, respectively) were statistically significant ($p < 0.05$) and may indicate the efficacy of natural coating materials in decelerating ripening processes. However, this ripening deceleration effect could potentially be viewed as disadvantageous in scenarios where rapid ripening completion is desired, particularly in commercial operations targeting specific harvest windows. The pH values of grape berries demonstrated variability contingent upon both coating materials and storage duration. A general declining trend in pH occurred over the storage period, becoming particularly pronounced during the second and third weeks. Significant pH reductions were observed specifically in seaweed and seaweed + ethanol applications, potentially attributable to the semi-permeable film structure of seaweed-based coatings limiting gas exchange and altering fruit internal atmosphere [50–57]. Such pH reduction may confer enhanced microbial stability, as lower pH environments restrict the proliferation of numerous microorganisms [58]. Titratable acidity (TA) values in 'Tarsus Beyazı' grapes exhibited changes dependent upon both storage period and applied treatments. Seaweed and seaweed + ethanol applications were notable for maintaining higher TA values compared to control groups. The lowest TA values were recorded in the control and control + ethanol groups during harvest (0.52), while significantly higher values characterized seaweed-containing applications (0.63). This suggests that seaweed-based coatings may decelerate respiration through their surface barrier properties, thereby contributing to organic acid preservation. The preservation of higher TA levels, in conjunction with lower pH, may enhance microbial resistance, though potentially affecting sensory perception and consumer acceptance due to increased acidity. On the other hand, heat map analysis revealed superior quality profiles in seaweed (SW) and seaweed + ethanol (SW-ETH) treatments compared to control groups. The reduced

weight loss, pedicel drying, and decay rates suggest that seaweed extract forms a protective barrier, limiting transpiration and microbial infection. SW-ETH applications indicated potential synergistic effects, where seaweed provides physiological resistance while ethanol reduces microbial load [59–61]. Correlation analyses revealed strong positive correlations between pedicel drying and quality loss indicators (r = 0.80–0.84), demonstrating that moisture loss contributes to deterioration. Principal Component Analysis (PC1: 40.60%, PC2: 23.53%) explained 64.13% of variance. Seaweed + ethanol samples clustered with high-quality parameters, confirming integrated applications' efficacy in mitigating quality loss [62,63].

5. Conclusions

Seaweed and ethanol treatments affected the postharvest quality of 'Tarsus Beyazı' grapes in notably different ways. Seaweed applications, particularly when applied during the flowering period, were effective in reducing physiological losses such as weight loss and pedicel dehydration, while also minimizing rot development. These treatments helped maintain both physical and chemical quality attributes, thereby extending cold storage and shelf life. In contrast, ethanol applied pre harvest accelerated the ripening process and showed limited impact, primarily affecting physical parameters such as bunch and berry weight. Overall, seaweed-based bio stimulants provided more consistent and comprehensive benefits, highlighting their potential as sustainable tools in postharvest grape management. While our findings demonstrate promising results for seaweed-based treatments in 'Tarsus Beyazı' grapes, several limitations must be acknowledged. The study's focus on a single cultivar limits the generalizability of results to other grape varieties, each of which may respond differently to seaweed applications due to varying skin thickness, metabolic rates, and inherent storage characteristics. Additionally, potential economic constraints associated with seaweed extract application costs and the temporal limitations of protective effects under extended storage conditions represent practical considerations for commercial implementation. Future research should encompass multiple cultivars and economic feasibility assessments to provide a more comprehensive understanding of seaweed-based postharvest treatments in viticulture.

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