

Article

Production System Influences Postharvest Physiology and Phytonutritional Quality of Cauliflower Cultivars During Refrigerated Storage

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Highlights

- Soil-grown cauliflower maintained lower respiration rates, better colour retention, reduced browning, and higher sensory quality than Gravel Film GFT-grown curds during refrigerated storage. Soil cultivation also enhanced the retention of phenolics, glucosinolates, pigments, and antioxidant activity, resulting in superior postharvest quality and nutraceutical value.
- ‘Sicilian Violet’ exhibited the highest phenolic, glucosinolate, anthocyanin, and antioxidant levels throughout storage, demonstrating the greatest nutraceutical potential, where-as ‘Macerata’ showed superior chlorophyll and β -carotene retention and ‘Snowball’ exhibited the greatest weight loss and respiratory activity. Production system $\times$ cultivar in-teractions strongly determined cauliflower shelf life, quality retention, antioxidant capacity, and nutritional value during refrigerated storage.

Abstract

Despite the increasing adoption of soilless cultivation systems, little is known about how the gravel flow technique (GFT) influences postharvest quality, phytonutritional composition, and shelf life of cauliflower compared with conventional soil cultivation, and how these effects interact with cultivar genotype. Therefore, this study evaluated the influence of production system (soil cultivation vs. GFT), cultivar, and storage duration on the postharvest physiology, quality, and phytonutritional attributes of three cauliflower cultivars (‘Macerata’, ‘Sicilian Violet’, and ‘Snowball’) stored at 4 °C for 8 days. Significant production system $\times$ cultivar $\times$ storage interactions affected physiological, biochemical, and sensory characteristics. Soil-grown curds maintained higher O₂ and lower CO₂ concentrations, indicating lower respiration rates and slower deterioration than GFT-grown curds. ‘Snowball’ exhibited the highest weight loss and respiratory activity, whereas ‘Sicilian Violet’ showed the lowest weight loss. Soil cultivation enhanced the retention of phenolics, glucosinolates, pigments, and antioxidant activity. After 8 days, soil-grown ‘Sicilian Violet’ exhibited the highest total phenolic content (55.25 mg GAE g⁻¹ DW) and antioxidant capacity, while the highest glucosinolate concentration was recorded in soil-grown ‘Macerata’ (48.23 μ mol g⁻¹ DW on day 6). ‘Macerata’ maintained the highest chlorophyll and β -carotene contents throughout storage, whereas ‘Sicilian Violet’ showed superior anthocyanin retention and antioxidant capacity. Although sensory quality declined during



Academic Editors: Xiaonan Li, Mingliang Jiang and Yuting Zhang

Received: 10 August 2026

Revised: 27 August 2026

Accepted: 4 September 2026

Published: 7 September 2026

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storage, soil-grown curds retained better quality and lower browning than GFT-grown curds. Overall, soil cultivation improved postharvest quality and nutraceutical value, highlighting the importance of integrating cultivar selection with production practices to optimise shelf life and nutritional quality.

Keywords: cauliflower varieties; hydroponics; postharvest quality; phytonutrients; antioxidant activity; glucosinolates

1. Introduction

Cauliflower (*Brassica oleracea* var. *botrytis* L.) is an important horticultural crop valued for glucosinolates, phenolic compounds, vitamins, and antioxidant constituents [1]. While white cauliflower remains the most widely cultivated type, breeding programmes have led to the development of coloured varieties, including purple and green types, which are associated with enhanced accumulation of bioactive compounds and improved antioxidant capacity [2,3]. However, like many fresh horticultural commodities, cauliflower is highly perishable, and its postharvest quality is strongly influenced by physiological and metabolic changes during storage [4,5].

Postharvest behaviour of cauliflower is governed by physiological processes such as respiration, transpiration, and senescence, which directly regulate biochemical composition and sensory quality. These processes control moisture loss, gas exchange, pigment degradation, and secondary metabolite dynamics, ultimately determining shelf life and marketability [6,7]. Increased respiration and transpiration accelerate tissue deterioration, leading to weight loss, discolouration, textural degradation, and the development of undesirable flavour compounds, thereby reducing consumer acceptance [4,8]. As a highly perishable commodity, cauliflower is particularly susceptible to postharvest quality losses, including enzymatic browning, off-odour development due to anaerobic respiration, and loss of firmness associated with tissue breakdown [5]. Effective postharvest handling, including appropriate storage conditions and packaging strategies, is therefore essential to minimise deterioration and maintain product quality.

Previous studies have reported inconsistent effects of soil-based and soilless production systems on phytochemical composition and antioxidant activity. While some studies have shown greater accumulation of bioactive compounds in soil-grown crops [9–11], others have reported comparable or enhanced nutritional quality under hydroponic cultivation [12]. Conventional soil cultivation remains the dominant production system worldwide and provides a natural rooting environment with substantial buffering capacity for water and nutrient supply. Soil also supports complex physical, chemical, and biological interactions that can enhance mineral uptake, plant resilience, and crop quality [13]. However, soil cultivation is often associated with inefficient water and fertilizer use, variability in nutrient availability, soil-borne diseases, and increasing pressure on arable land resources [14–16]. In contrast, soilless cultivation systems such as the Gravel Flow Technique (GFT) enable precise control of water and nutrient delivery, improve resource-use efficiency, reduce dependence on arable land, and minimize the occurrence of soil-borne pathogens [16]. The GFT system operates similarly to the nutrient film technique, where nutrient solution continuously flows through a gravel medium surrounding the root zone. Such systems are increasingly adopted because of their potential to improve productivity while reducing environmental impacts. Nevertheless, plants grown under soilless conditions may experience different root-zone environments, nutrient dynamics, and physiological responses compared with soil-grown plants, which can influence phytochemical accumulation, tissue

composition, and subsequent postharvest performance [17,18]. Increasing interest in soil-less cultivation systems has promoted the adoption of hydroponic technologies that allow precise management of water and nutrients [15,16,19].

In addition, genotype plays a key role in determining phytochemical accumulation and postharvest performance [16]. As preharvest growing conditions influence plant metabolism, cultivation practices can subsequently affect postharvest physiology, shelf life, and phytonutritional composition, particularly in highly perishable crops such as cauliflower [15,18]. Despite increasing interest in soilless cultivation systems, very limited information is available regarding the influence of GFT on the postharvest physiology, quality retention, and phytonutritional composition of cauliflower. While previous studies have compared soil-based and hydroponic production systems with respect to crop yield and nutritional quality, little is known about how these preharvest cultivation practices affect postharvest respiratory behaviour, sensory quality, pigment stability, antioxidant activity, and glucosinolate retention during storage. Furthermore, the extent to which production system $\times$ cultivar interactions affect postharvest responses during storage remains poorly understood. Therefore, the objective of this study was to determine how soil cultivation and GFT production affect postharvest physiological responses, sensory attributes, pigment stability, antioxidant activity, and bioactive compounds in three contrasting cauliflower cultivars during refrigerated storage.

2. Materials and Methods

2.1. Study Site and Plant Material

The experiment was conducted in a shade-net facility at the Agricultural Research Council–Vegetable Industrial and Medicinal Plants (ARC-VIMP), Roodeplaat, South Africa (25.56° S, 28.35° E). The study was conducted in two independent experimental runs during the same growing season. In both runs, seeds were sown in May, and seedlings were transplanted in June under identical environmental and management conditions."

Seeds (Livingseeds Heirloom Seeds, Pretoria, South Africa) were sown in 200-cell polystyrene trays filled with commercial growth medium (Hygromix[®], Hygrotech Pty. Ltd., Pretoria, South Africa) and covered with vermiculite. Trays were maintained in a nursery under controlled conditions for four weeks before transplanting. Fertigation was initiated at the two-leaf stage using Multifeed[®] (AECI Ltd., Petoria South Africa) at 1 g L⁻¹ and continued until transplanting.

The mean day/night temperatures during the growing period ranged from 7.9 to 23 °C, with an average RH of 62.4% and a mean photosynthetically active radiation (PAR) of 764.9 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Three cauliflower cultivars, 'Macerata', 'Snowball', and 'Sicilian Violet', were grown under two production systems: GFT and soil cultivation. Treatments were arranged in a randomized complete block design with four replicates. Each replicate comprised a 2 m $\times$ 1 m plot containing 16 plants spaced at 30 cm $\times$ 40 cm (8.3 plants m⁻²). Each treatment, therefore, comprised four independent field plots.

2.1.1. GFT System

Seedlings were transplanted into GFT gullies measuring 1 m wide and 17 m long, constructed with a 2.8–3.0% slope to facilitate continuous gravitational flow of the nutrient solution. Experimental plots measured 2 m $\times$ 1 m and contained 16 plants spaced at 30 cm $\times$ 40 cm, equivalent to a planting density of 8.3 plants m⁻². A 6-cm-deep layer of gravel served as the growing medium (Figure 1). The GFT system operates similarly to the nutrient film technique, in which a shallow layer of nutrient solution continuously flows through the gravel medium by gravity. Nutrient solution was pumped from a reservoir to the upper end of each gully and distributed through four inlet tubes, each

delivering approximately 700 mL min^{-1} . The solution flowed along the gully as a thin film surrounding the gravel and root zone before draining back to the reservoir for recirculation.

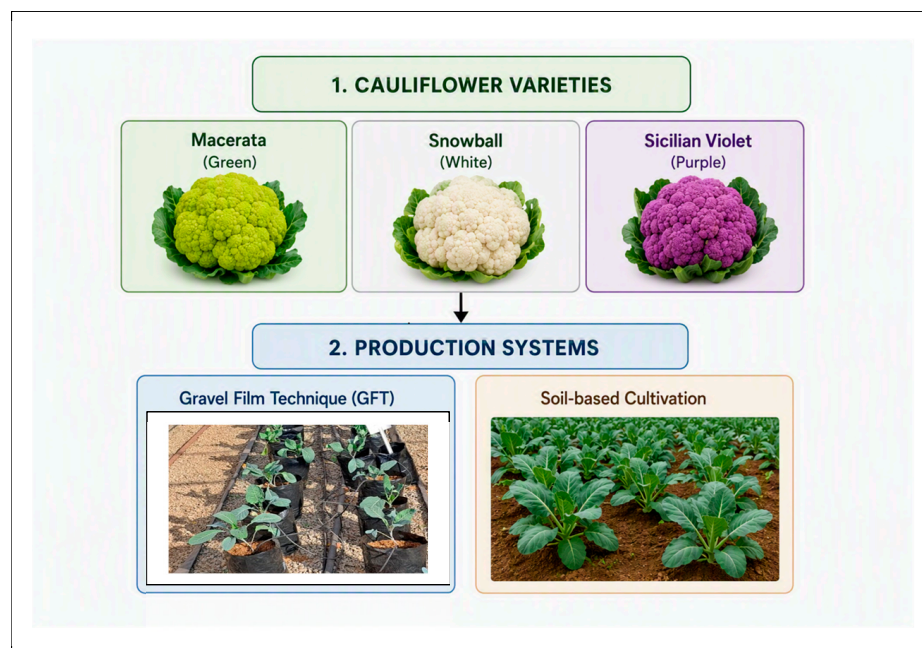


Figure 1. Experimental workflow illustrating the effects of production system (GFT and soil cultivation) and cultivar ('Macerata', 'Snowball', and 'Sicilian violet') on postharvest physiology, colour quality, phytonutritional composition, antioxidant activity, sensory quality, and storage performance of cauliflower during refrigerated storage at 4°C .

The hydroponic nutrient solution was prepared using a water-soluble commercial fertiliser (Hygroponic[®], Hygrotech, Pretoria, South Africa) supplemented with calcium nitrate [$\text{Ca}(\text{NO}_3)_2$] and potassium nitrate (KNO_3). The final nutrient solution contained $198.8 \text{ mg L}^{-1} \text{ N}$, $42.0 \text{ mg L}^{-1} \text{ P}$, $246.6 \text{ mg L}^{-1} \text{ K}$, $166.0 \text{ mg L}^{-1} \text{ Ca}$, $30.0 \text{ mg L}^{-1} \text{ Mg}$, and $64.0 \text{ mg L}^{-1} \text{ S}$. Micronutrient concentrations were maintained at $1.25 \text{ mg L}^{-1} \text{ Fe}$, $0.37 \text{ mg L}^{-1} \text{ B}$, $0.30 \text{ mg L}^{-1} \text{ Mn}$, $0.15 \text{ mg L}^{-1} \text{ Zn}$, $0.04 \text{ mg L}^{-1} \text{ Mo}$, and $0.02 \text{ mg L}^{-1} \text{ Cu}$. The electrical conductivity (EC) and pH of the nutrient solution were monitored daily and adjusted as required to maintain target levels. The nutrient solution was adjusted according to crop developmental stage, with nutrient replenishment based on routine monitoring of solution EC and pH. Electrical conductivity was maintained between 2.0 and 2.4 dS m^{-1} and pH between 5.8 and 6.2 throughout the production cycle. Fresh nutrient stock solutions were added as required to maintain target nutrient concentrations and ensure uniform nutrient availability throughout crop growth.

2.1.2. Soil-System

Seedlings were transplanted into sandy clay loam soil comprising 68.0% sand, 8.0% silt, and 24.0% clay within the top 30 cm soil profile. Soil micro-plots ($2 \text{ m} \times 1 \text{ m}$) were established under a shade-net structure (Figure 1) with intra-row and inter-row spacings of 30 cm and 40 cm , respectively. Each plot consisted of two planting rows. Fertigation was supplied through a drip irrigation system, with one dripper per plant delivering $140\text{--}210 \text{ mL}$ per irrigation event at two-day intervals. Plants were established in sandy clay loam soil comprising 68.0% sand, 8.0% silt, and 24.0% clay. Irrigation was supplied through a drip irrigation system, with one emitter per plant delivering $140\text{--}210 \text{ mL}$ per irrigation event at two-day intervals. To ensure comparable nutrient supply between production systems, soil-grown plants received the same nutrient formulation used in the GFT system.

through fertigation. Nutrient applications were adjusted according to crop developmental stage, while irrigation volumes were modified according to crop water requirements.

2.2. Leaf Stomatal Conductance

Leaf stomatal conductance (gs) was measured on the abaxial surface of the youngest fully expanded leaf using a steady-state porometer (SC-1, Decagon Devices Inc., Pullman, WA, USA). Measurements were taken between 09:00 and 11:00 h under clear-sky conditions to minimize diurnal variation. Stomatal conductance was expressed as $\text{mol H}_2\text{O m}^{-2} \text{ s}^{-1}$.

2.3. Packaging and Storage

Curds were harvested at commercial maturity (123 days after transplanting), immediately placed in cooler boxes, and transported within 3 h to the laboratory. Cauliflower curds were packaged in expanded polystyrene (EPS) trays and wrapped with commercial food-grade polyethylene cling film (10–15 μm thickness; density 0.915–0.930 g cm^{-3} ; water vapour transmission rate, 15–30 $\text{g m}^{-2} \text{ d}^{-1}$; oxygen transmission rate, 9000–11,000 $\text{cm}^3 \text{ m}^{-2} \text{ d}^{-1} \text{ atm}^{-1}$; and carbon dioxide transmission rate, 45,000–55,000 $\text{cm}^3 \text{ m}^{-2} \text{ d}^{-1} \text{ atm}^{-1}$ at 23 °C), which allows gas and moisture exchange and facilitates the development of a passive modified atmosphere during storage [14]. Packaged samples were stored at 4 °C and 95% relative humidity in a completely randomised design for 8 days [20]. At each sampling date (0, 2, 4, 6, and 8 d), curds were randomly selected from each biological replicate for physiological, biochemical, and sensory analyses.

Postharvest physiological parameters, including weight loss, package headspace gas composition, and colour attributes, were evaluated at each sampling point. Samples were then frozen at −80 °C in an ultra-low temperature freezer (Blizzard NU-99828J, NuAire, Plymouth, MN, USA) prior to freeze-drying. Frozen samples were freeze-dried (VirTis BenchTop Pro with Omnitronics, SP Scientific, NY, USA) for 7 d, reweighed, and ground into a fine powder. The resulting powder was used for the analysis of phytonutritional and biochemical attributes, including total glucosinolates, total phenolic content, antioxidant activity (FRAP, DPPH, and ABTS assays), β -carotene, total anthocyanins, total chlorophyll, and ascorbic acid. Figure 1 summarizes the experimental workflow used to evaluate the effects of production system, cultivar, and storage duration on physiological characteristics, colour, sensory quality, phytochemical composition, and antioxidant activity.

2.4. Weight Loss

Initial weight of each cauliflower curd (without leaves) was recorded immediately after harvest and subsequently at two-day intervals during storage. Weight loss was calculated as the percentage reduction in weight relative to the initial weight [21,22] using the following equation:

$$\% \text{ Weight Loss} = [\text{Initial Weight} - \text{Final Weight}] / \text{Initial Weight} \times 100$$

2.5. Gas Composition

The headspace concentrations of ethylene (C_2H_4), oxygen (O_2), and carbon dioxide (CO_2) within sealed packages were measured using a portable gas analyser (F-950 The Gas Analyzer, Felix Instruments, Washington, DC, USA), according to the method described by Kinhal [23]. Package integrity was maintained throughout storage to preserve the modified atmosphere. At each sampling interval, gas samples were withdrawn using a gas-tight syringe inserted through a septum and analysed immediately. The instrument was calibrated prior to each sampling according to the manufacturer's instructions to ensure accuracy of measurements. Changes in gas composition were used to evaluate respiration-driven gas exchange within the packaging system.

2.6. Colour Measurement

Colour parameters (L^* , a^* , b^*) of cauliflower curds were measured using a chromameter (CR-400, Konica Minolta Sensing Inc., Osaka, Japan), following the method described by Tshilongo et al. [24]. Prior to measurements, the instrument was calibrated using a standard white calibration tile supplied by the manufacturer to ensure accuracy and repeatability.

In the CIE colour system, L^* represents lightness (0 = black, 100 = white), a^* represents the red–green axis (positive values indicate redness and negative values indicate greenness), and b^* represents the yellow–blue axis (positive values indicate yellowness and negative values indicate blueness) [23]. Total colour difference (ΔE), representing overall colour change during storage, was calculated using the following equation (Nzimande et al., 2024) [25]:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2}$$

2.7. Extraction of Phenolic Compounds

Phenolic compounds were extracted following the method described by Bhengu et al. [26]. Freeze-dried samples (100 mg) were mixed with 2 mL of methanol/water (80:20, v/v) and vortexed thoroughly. The mixture was subjected to sonication in an ultrasonic bath (42 kHz, 135 W; Branson Ultrasonic Corporation, Buffalo, NY, USA) at 23 °C for 30 min. Subsequently, samples were centrifuged (HermLe Z326K, HermLe Labortechnik GmbH, Wehingen, Germany) at 3000 rpm for 10 min at 4 °C. The supernatant was collected and used for the determination of total phenolic content and antioxidant activities (FRAP, DPPH, and ABTS).

2.8. Total Phenolic Content

Total phenolic content (TPC) was determined using the Folin–Ciocalteu method as described by Singleton et al. [27]. For the analysis, 100 μL of extract was mixed with 200 μL of Folin–Ciocalteu reagent (diluted 1:10 with distilled water) and 800 μL of 7.5% (w/v) sodium carbonate (Na_2CO_3) solution. The reaction mixture was incubated at room temperature for 2 h. Absorbance was then measured at 765 nm using a spectrophotometer (SPECTROstar® Nano, BMG Labtech, Ortenberg, Germany). TPC was quantified using a standard calibration curve prepared with gallic acid at concentrations of 0–500 $\mu\text{g mL}^{-1}$. Results were expressed as milligrams of gallic acid equivalents per gram of dry weight ($\text{mg GAE g}^{-1} \text{ DW}$).

2.9. Ferric Reducing Antioxidant Power (FRAP)

Ferric reducing antioxidant power (FRAP) was determined according to the method described by Bhengu et al. [25]. The FRAP working solution was freshly prepared by mixing 10 mmol L^{-1} 2,4,6-tri(2-pyridyl)-1,3,5-triazine (TPTZ), acetate buffer (pH 3.6), and 20 mmol L^{-1} ferric chloride (FeCl_3) in a ratio of 1:10:1 ($v/v/v$) and used within 2 h. For the assay, 180 μL of the FRAP working solution was mixed with 10 μL of sample extract in a 96-well microplate and incubated at 37 °C in the dark for 15 min. Absorbance was measured at 593 nm using a microplate reader. Antioxidant power was quantified using a Trolox (TE) standard curve (0–2.5 mg mL^{-1}) and expressed as $\text{mg TE g}^{-1} \text{ DW}$.

2.10. 2,2-Diphenyl-1-picrylhydrazyl (DPPH) Radical Scavenging Activity

The 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity was determined according to the method described by Phahlane et al. [28]. Briefly, DPPH solution was prepared by dissolving 1.03 mg of DPPH in 31.25 mL of absolute methanol and incubated in the dark for 2 h prior to use. Different volumes (20–100 μL) of sample extracts were transferred into a 96-well microplate and adjusted to 100 μL with 80% methanol. Subse-

quently, 200 μL of DPPH solution was added to each well, and the mixture was incubated in the dark at room temperature for 30 min. Absorbance was measured at 515 nm using a microplate reader. Radical scavenging activity was expressed as percentage inhibition and calculated using the following equation:

$$\text{DPPH inhibition (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100$$

where A_{control} is the absorbance of the control and A_{sample} is the absorbance of the sample extract.

Trolox was used as the reference antioxidant standard, and a calibration curve was established under identical assay conditions. Sample inhibition values were interpolated from the Trolox calibration curve to obtain the corresponding Trolox-equivalent concentration (CCC). Antioxidant activity was expressed as milligrams of Trolox equivalents per gram dry weight ($\text{mg TE g}^{-1} \text{DW}$) according to:

$$\text{DPPH}(\text{mgTEg}^{-1}\text{DW}) = \frac{\text{mC} \times \text{V} \times \text{DF}}{\text{m}}$$

where C is the Trolox-equivalent concentration (mg mL^{-1}), V is the extraction volume (mL), DF is the dilution factor, and m is the sample dry weight (g).

2.11. ABTS 2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) Radical Scavenging Activity

ABTS radical scavenging activity was determined according to the method of Re et al. [29]. The ABTS radical cation ($\text{ABTS}^{\bullet+}$) was generated by reacting 109.74 mg ABTS dissolved in 25 mL deionised water with potassium persulfate solution and allowing the mixture to stand in the dark at room temperature for 12 h. The $\text{ABTS}^{\bullet+}$ stock solution was diluted with phosphate buffer (pH 7.4) prepared from sodium chloride, disodium hydrogen phosphate (Na_2HPO_4), and sodium dihydrogen phosphate (NaH_2PO_4) to obtain an absorbance of 0.70 ± 0.02 at 734 nm.

Various concentrations of sample extracts (20–100 μL) were transferred into a 96-well microplate and adjusted to a final volume of 100 μL with 80% methanol. Thereafter, 200 μL of the diluted $\text{ABTS}^{\bullet+}$ working solution was added to each well and mixed thoroughly. The reaction mixtures were incubated in the dark at room temperature for 30 min. Absorbance was measured at 734 nm using a microplate reader. Methanol served as the blank, while the $\text{ABTS}^{\bullet+}$ working solution without extract was used as the control.

ABTS radical scavenging activity was calculated as follows:

$$\text{ABTS scavenging activity (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100$$

where A_{control} is the absorbance of the control reaction, and A_{sample} is the absorbance of the extract-containing reaction mixture.

A Trolox calibration curve was generated using standard Trolox solutions analyzed under identical conditions. The antioxidant activity of each sample was quantified as Trolox equivalent antioxidant capacity (TEAC), and the results were expressed as milligrams of Trolox equivalents per gram dry weight ($\text{mg TE g}^{-1} \text{DW}$) according to:

$$\text{ABTS}(\text{mgTEg}^{-1}\text{DW}) = \frac{\text{mC} \times \text{V} \times \text{DF}}{\text{m}}$$

where CCC is the Trolox equivalent concentration determined from the calibration curve (mg mL^{-1}), V is the extraction volume (mL), DF is the dilution factor, and m is the dry weight of the sample (g).

2.12. Total Glucosinolates

Total glucosinolate content was determined according to the spectrophotometric method described by Mawlong et al. [30]. Freeze-dried samples (0.1 g) were homogenised in 80% methanol (*v/v*) and extracted overnight at room temperature. The extracts were centrifuged at 3000 rpm for 10 min, and 1 mL of the supernatant was collected and diluted to 2 mL with 80% methanol. The sodium tetrachloropalladate reagent was prepared by dissolving 58.8 mg sodium tetrachloropalladate in 170 μ L concentrated hydrochloric acid (HCl) and making up the volume to 100 mL with double-distilled water. For glucosinolate determination, 100 μ L of the diluted extract was mixed with 300 μ L double-distilled water and 3 mL of 2 mM sodium tetrachloropalladate solution. The reaction mixture was incubated at room temperature for 1 h, after which absorbance was measured at 425 nm using a spectrophotometer (SPECTROstar® Nano, BMG Labtech, Ortenberg, Germany). A reagent blank was prepared using the same procedure without sample extract.

Total glucosinolate content was calculated according to the equation proposed by Mawlong et al. [30].

$$\text{Total glucosinolates } (\mu\text{mol g}^{-1} \text{ DW}) = (A_{425} \times 1.40) - 0.13$$

where A_{425} is the absorbance measured at 425 nm.

For expression in $\mu\text{g g}^{-1}$ DW, the glucosinolate concentration was converted using the molecular weight of sinigrin equivalent ($\text{MW} = 397.5 \text{ g mol}^{-1}$).

2.13. β -Carotene Content

β -Carotene extraction and quantification were performed according to the method described by Bhengu et al. [26] without modifications. Freeze-dried samples (0.1 g) were homogenised with 5 mL of cold acetone containing 0.1% (*w/v*) butylated hydroxytoluene (BHT) to prevent oxidation during extraction. The homogenate was vortexed thoroughly and sonicated for 15 min in an ice-cold ultrasonic bath. Samples were subsequently centrifuged at $10,000 \times g$ for 10 min at 4 $^{\circ}\text{C}$, and the supernatant was collected. The extraction procedure was repeated until the residue became colourless, and the supernatants were pooled. The combined extracts were filtered through a 0.22 μm PTFE syringe filter and transferred into amber HPLC vials for analysis. β -carotene separation was carried out using high-performance liquid chromatography (HPLC) equipped with a photodiode array detector (PDA). Separation was achieved on a C18 reverse-phase column maintained at 25 $^{\circ}\text{C}$. The mobile phase consisted of solvent A (methanol: water, 95:5, *v/v*) and solvent B (methyl tert-butyl ether), delivered under gradient elution at a flow rate of 1.0 mL min $^{-1}$. β -carotene was monitored at 450 nm and identified by comparing its retention time and UV-visible spectrum with those of authentic standard β -carotene; results were expressed as mg 100 g $^{-1}$ DW.

2.14. Chlorophyll Content

Chlorophyll pigments were extracted and quantified according to the method described by Mampholo et al. [31], with slight modifications. Freeze-dried samples (100 mg) were homogenised in 4 mL of 80% (*v/v*) acetone, and the volume was adjusted to 10 mL with the same solvent. The extraction was performed under dim light and ice-cold conditions to minimise pigment degradation. Samples were centrifuged at 3000 rpm for 10 min at 4 $^{\circ}\text{C}$ using a refrigerated centrifuge (HermLe Z326K, HermLe Labortechnik GmbH, Wehingen, Germany).

The supernatant was collected, and absorbance was measured at 663.2, 646.8 and 470 nm using a UV-Vis spectrophotometer (SPECTROstar® Nano, BMG Labtech, Orten-

berg, Germany). Chlorophyll a (C_a) and chlorophyll b (C_b), and total chlorophyll contents were calculated according to Mampholo et al. [31] (using the following equations):

$$C_a = 12.25A_{663.2} - 2.79A_{646.8}$$

$$C_b = 21.50A_{646.8} - 5.10A_{663.2}$$

$$\text{Total chlorophyll} = C_a + C_b$$

where $A_{663.2}$ and $A_{646.8}$ are the absorbance values measured at 663.2 and 646.8, respectively.

C_a = chlorophyll a concentration, C_b = chlorophyll b concentration.

Pigment concentrations were calculated from the extract volume and sample weight and expressed as mg g^{-1} DW.

2.15. Total Anthocyanin Content

Total anthocyanin content was determined using the pH differential method described by Hosseinian and Beta [32], with slight modifications. Freeze-dried samples (0.1 g) were extracted with 1 mL of acidified methanol (methanol: HCl, 85:15, v/v) and sonicated for 30 min at room temperature. The extracts were centrifuged at 10,000 rpm for 30 min at 15 °C, and the supernatants were collected for analysis. For anthocyanin determination, aliquots of the extracts were diluted separately with 0.025 M potassium chloride buffer (pH 1.0) and 0.4 M sodium acetate buffer (pH 4.5) according to Le et al. [33]. Subsequently, 200 μL of each diluted extract was transferred into a 96-well microplate, and absorbance was measured at 520 and 700 nm using a microplate spectrophotometer (SPECTROstar® Nano, BMG Labtech, Ortenberg, Germany).

The absorbance difference (A) was calculated as:

$$A = (A_{520}A_{700})_{\text{pH } 1.0} - (A_{520}A_{700})_{\text{pH } 4.5}$$

Total anthocyanin content, expressed as cyanidin-3-glucoside equivalents (C3GE), was calculated using the following equation:

$$\text{Anthocyanin content} = \frac{A \times \text{MW} \times \text{DF} \times V \times 1000}{\epsilon \times l \times m}$$

where A = absorbance difference determined by the pH differential method.

- MW = molecular weight of cyanidin-3-glucoside (449.2 g mol^{-1})
- DF = dilution factor
- V = final extract volume (mL)
- ϵ = molar extinction coefficient of cyanidin-3-glucoside (26,900 $\text{L mol}^{-1} \text{ cm}^{-1}$)
- l = path length (1 cm)
- m = sample dry weight (g)

Results were expressed as mg cyanidin-3-glucoside (C3GE) equivalents per g DW.

2.16. Sensory Evaluation

Sensory evaluation involving human participants was conducted in accordance with the approval granted by the Human Research Ethics Committee (HREC Approval No. HRE2024-10-012; Reference No. 219997205). Written informed consent was obtained from all participants prior to the sensory assessment. Participant anonymity and confidentiality were strictly maintained, and no personally identifiable information, including names, gender, or other personal details, was collected or disclosed in this study. Twenty panellists participated in three training sessions prior to data collection. During these sessions, they were familiarized with the evaluation criteria, rating scales, sensory quality attributes

(odour, texture, colour, browning, taste, and overall quality), and reference samples representing different levels of quality deterioration. Each training session lasted [2 h].

Sensory quality of cauliflower curds was evaluated on days 2, 4, 6, and 8 of storage. Prior to evaluation, samples were equilibrated at ambient temperature for 15 min. A trained panel of 20 members (10 males and 10 females) assessed sensory attributes, including odour, texture, colour, browning, taste, and overall quality. Overall quality was rated using a 9-point hedonic scale, where 9 = excellent, 7 = slightly off, 5 = moderate, 3 = strongly off, and 1 = intolerable [34]. Taste was evaluated on a similar scale, ranging from 9 = sweet to 1 = bitter. Texture was assessed based on compactness and degree of riciness, with higher scores indicating firmer and more compact curds. A mean score of 4.5 was considered the threshold of acceptability for each attribute. Between evaluations, panellists rinsed their mouths with water and consumed unsalted crackers to minimise carry-over effects. Samples were presented anonymously to avoid bias.

2.17. Statistical Analysis

Four field replicate plots per treatment served as biological replicates ($n = 4$). At commercial maturity, marketable curds were harvested from each plot and transported to the laboratory for postharvest evaluation. Four field plots were established for each production system $\times$ cultivar treatment combination and served as the biological replicates ($n = 4$). At each storage interval (0, 2, 4, 6, and 8 d), six marketable curds were randomly collected from each plot and used as subsamples for physiological, biochemical, and sensory analyses. Measurements obtained from individual curds within a plot were composited or averaged to generate a single value for each plot at each sampling interval. Consequently, the field plot, rather than the individual curd, was considered the experimental unit for statistical analysis. Analysis of variance (ANOVA) was conducted using plot means ($n = 4$) as the biological replicates. Values presented in the tables are expressed as mean $\pm$ standard deviation (SD) of analytical measurements obtained from the composite samples. Subsamples were used solely to estimate within-plot variation and were not treated as independent biological replicates in the statistical analyses.

During postharvest storage, samples were maintained at 4 °C and 95% relative humidity in a completely randomized design. Data were analysed using STATISTICA version 13.5 (TIBCO Software Inc., Palo Alto, CA, USA). Production system (P), cultivar (C), storage duration (D), and their interactions ($P \times C$, $P \times D$, $C \times D$, and $P \times C \times D$) were evaluated using three-way factorial analysis of variance (ANOVA), with all factors considered fixed effects. Different curds were assessed at each storage interval; therefore, observations collected at successive storage durations were independent, and storage duration (D) was included as a fixed factor rather than a repeated-measures factor. Prior to analysis, residuals were tested for normality and homogeneity of variance using the Shapiro–Wilk and Levene tests, respectively.

The experiment was conducted in two independent runs during the same growing season under identical environmental and management conditions. Preliminary ANOVA indicated that neither the effect of experimental run nor the run $\times$ treatment interaction was significant ($p > 0.05$). Therefore, data from both runs were pooled prior to subsequent statistical analyses. When significant treatment effects were detected, means were separated using Tukey's honestly significant difference (HSD) test at $p < 0.05$. Results are presented as mean $\pm$ standard deviation (SD). Pearson's correlation analysis was performed to determine relationships among physiological parameters, colour attributes, sensory quality, phytochemical content, and antioxidant activity. Heat maps were generated using R version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria) with the heatmap package to visualise associations among the measured variables.

3. Results

3.1. Stomatal Regulation and Gas Exchange Responses of Cauliflower Varieties Under GFT and Soil Systems

Leaf stomatal conductance was not significantly affected by production system, cultivar, or their interaction ($p > 0.05$). However, numerical differences were observed among treatments. Cauliflower grown under the GFT system generally exhibited higher stomatal conductance than soil-grown plants. ‘Macerata’ recorded the highest stomatal conductance values ($0.33\text{--}0.35 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ under GFT and $0.22\text{--}0.25 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$ under soil), followed by ‘Snowball’ and ‘Sicilian Violet’ (Table S1).

3.2. Influence of Production System, Cultivar, and Storage Duration on Postharvest Weight Loss

Weight loss increased significantly during storage in all treatments ($p < 0.05$; Figure 2). After 8 d of storage, weight loss ranged from 2.30 to 3.11% in soil-grown curds and from 2.41 to 2.78% in GFT-grown curds. Among the cultivars, ‘Snowball’ exhibited the greatest weight loss, reaching 3.11% under soil cultivation, whereas ‘Sicilian Violet’ showed the lowest weight loss (2.41%), particularly under GFT production. Significant cultivar $\times$ production system $\times$ storage duration interactions were observed for weight loss ($p < 0.05$), indicating that the response to storage varied according to both cultivar and production system. Weight loss responses varied among cultivars and production systems. The lowest weight loss after 8 d of storage was recorded in soil-grown ‘Sicilian Violet’ (2.30%) and GFT-grown ‘Sicilian Violet’ (2.41%), whereas ‘Snowball’ exhibited the greatest weight loss under both production systems. These results indicate that cultivar differences exerted a stronger influence on weight loss than production system alone.

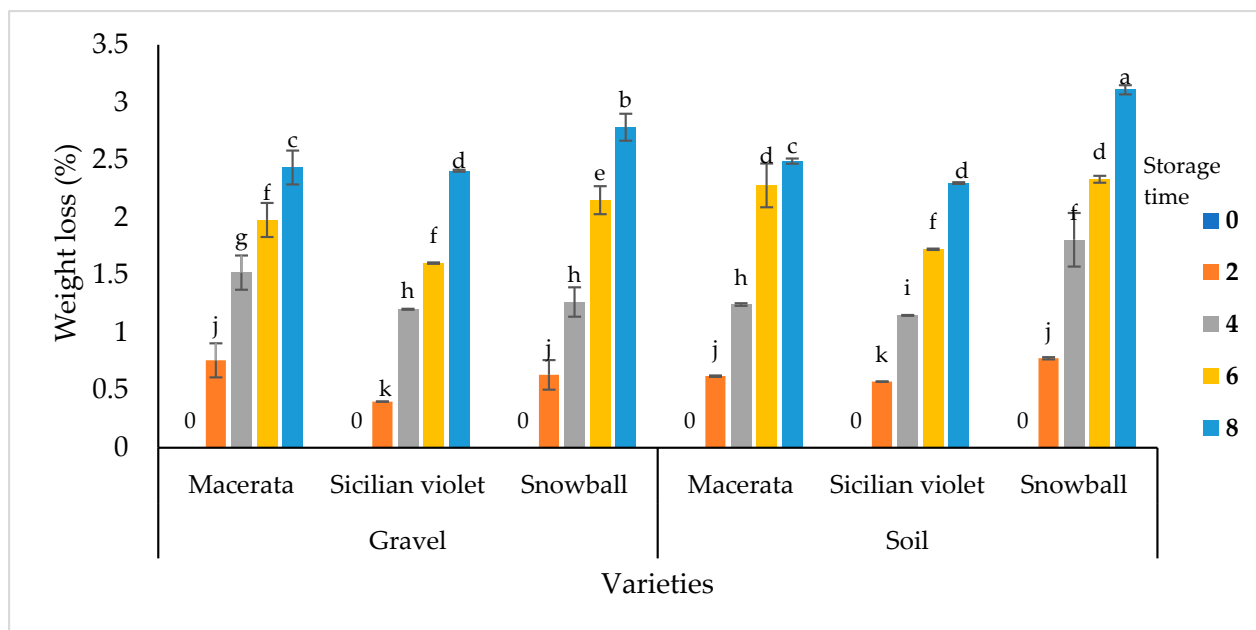


Figure 2. Changes in weight loss of cauliflower cultivars grown under GFT and soil cultivation during refrigerated storage at 4 °C. Bars with different letters indicate significant differences among means according to Tukey’s honestly significant difference (HSD) test at $p < 0.05$. Bars sharing at least one letter are not significantly different.

3.3. Interactive Effects of Growing System, Cultivar, and Storage Period on Headspace Gas Composition

Headspace gas composition was significantly affected by cultivar, production system, storage duration, and their interactions ($p < 0.05$; Figure 3 (Top, Bottom)). Initial package headspace gas composition was similar across all treatments, with O_2 concentrations

ranging from 18 to 19% and negligible CO₂ concentrations at the onset of storage. O₂ concentrations decreased, whereas CO₂ concentrations increased, during storage in all cultivar × production system combinations ($p < 0.05$). Under GFT cultivation, package headspace O₂ concentrations declined to 14.1%, 11.9%, and 10.2% in ‘Macerata’, ‘Sicilian Violet’, and ‘Snowball’, respectively, after 8 d of storage. Correspondingly, CO₂ concentrations increased to 4.19%, 4.75%, and 5.34%, respectively. In contrast, under soil cultivation, O₂ concentrations after 8 d of storage were 15.25%, 13.00%, and 12.65% in ‘Macerata’, ‘Sicilian Violet’, and ‘Snowball’, respectively, while the corresponding CO₂ concentrations reached 3.76%, 4.19%, and 4.98%. Among the cultivars, ‘Macerata’ maintained the highest O₂ concentrations and lowest CO₂ accumulation throughout storage, whereas ‘Snowball’ exhibited the lowest O₂ concentrations and greatest CO₂ accumulation. ‘Sicilian Violet’ showed intermediate responses. Across all cultivars, GFT-grown curds consistently exhibited greater O₂ depletion and CO₂ accumulation than soil-grown curds during storage.

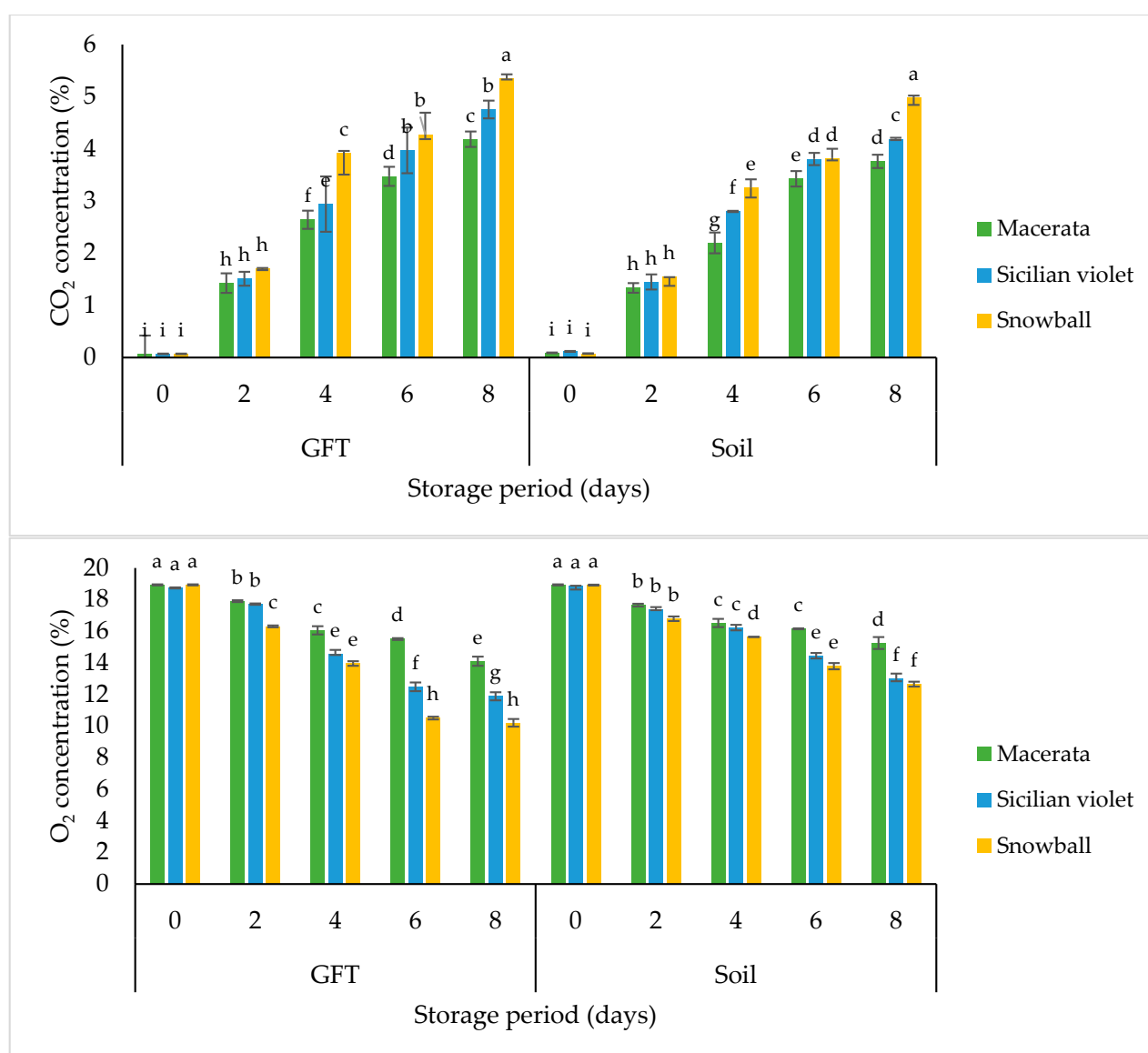


Figure 3. Effects of the interaction between production system and cultivar on cauliflower weight loss during postharvest storage and on headspace gas composition, including (Top) CO₂ and (Bottom) O₂ (dynamics during storage). Bars with different letters indicate significant differences among means according to Tukey’s honestly significant difference (HSD) test at $p \leq 0.05$. Bars sharing at least one letter are not significantly different.

3.4. Interactive Influence of Growing System, Cultivar, and Storage Period on Colour Quality of Cauliflower

Colour attributes were significantly affected by cultivar, production system, storage duration, and their interactions (Table 1). The interaction between production system, cultivar, and storage duration significantly influenced the b^* (yellowness) values of cauliflower curds ($F = 3.40$, $p < 0.01$), whereas no significant three-way interaction was observed for L^* ($F = 1.45$, $p > 0.05$), a^* ($F = 1.92$, $p > 0.05$), or total colour difference (ΔE ; $F = 0.98$, $p > 0.05$). Regardless of production system, storage duration resulted in a progressive decline in L^* values, indicating a gradual loss of brightness during refrigerated storage. Among the cultivars, ‘Snowball’ exhibited the highest lightness throughout storage, with initial L^* values of 84.30 and 80.88 under soil and gravel systems, respectively, whereas ‘Sicilian Violet’ maintained significantly lower L^* values due to its inherent pigmentation.

Table 1. Effects of production system, cultivar, and postharvest storage duration on colour attributes and total colour difference (ΔE) of cauliflower.

Growth System	Variety	Days	Colour			
			L*	a*	b*	ΔE
Gravel	‘Macerata’	0	56.82 ± 3.02 ij	−5.22 ± 1.05 g	42.64 ± 0.90 g	0
		2	48.52 ± 3.04 kl	−5.46 ± 1.20 g	45.18 ± 1.38 fg	8.94 ± 0.50 ijklm
		4	48.10 ± 2.21 kl	−5.66 ± 1.18 g	48.20 ± 3.25 def	10.71 ± 1.41 fghijk
		6	47.89 ± 1.60 kl	−7.20 ± 0.72 gh	54.17 ± 0.82 abc	14.94 ± 3.10 cdefg
		8	44.23 ± 0.62 l	−9.76 ± 0.73 hi	57.86 ± 0.98 a	20.53 ± 1.40 ab
	‘Snowball’	0	80.88 ± 1.75 ab	−1.09 ± 0.35 f	22.57 ± 1.04 j	0
		2	74.72 ± 2.78 cde	−0.44 ± 0.48 f	23.14 ± 0.89 ij	6.33 ± 2.43 ijklm
		4	70.30 ± 1.85 efg	0.72 ± 0.11 f	26.99 ± 0.39 hi	11.82 ± 2.10 fghij
		6	67.81 ± 3.39 fgh	0.89 ± 1.14 f	28.46 ± 2.00 h	14.71 ± 3.82 defgh
		8	65.67 ± 2.29 h	1.35 ± 0.08 f	30.38 ± 1.47 h	17.55 ± 2.06 abcde
	‘Sicilian violet’	0	13.28 ± 0.83 opq	29.32 ± 0.08 bc	−4.80 ± 0.06 m	0
		2	15.98 ± 1.68 op	26.08 ± 2.68 c	−2.94 ± 0.32 lm	5.05 ± 1.10 lmn
		4	21.86 ± 0.39 mn	19.69 ± 0.60 d	−1.52 ± 0.51 lm	13.36 ± 0.41 defghi
		6	22.85 ± 0.24 mn	14.45 ± 2.47 e	−1.07 ± 0.02 lm	18.16 ± 1.68 abcd
		8	24.96 ± 0.38 m	13.03 ± 0.15 e	−0.99 ± 0.84 lm	20.42 ± 0.46 abc
Soil	‘Macerata’	0	65.90 ± 2.81 gh	−8.08 ± 0.87 hi	46.82 ± 0.69 efg	0
		2	61.40 ± 0.43 hi	−9.45 ± 0.53 hi	50.89 ± 1.89 cde	6.51 ± 2.10 ijklm
		4	57.30 ± 1.93 ij	−10.22 ± 1.19 hi	51.55 ± 2.5 bcd	9.82 ± 3.66 hijklm
		6	55.08 ± 2.39 j	−10.95 ± 2.66 i	52.20 ± 2.34 bc	12.36 ± 3.00 efghi
		8	51.81 ± 1.12 jk	−11.53 ± 0.48 i	55.32 ± 1.08 ab	16.89 ± 2.37 abcdef
	‘Snowball’	0	84.30 ± 1.75 a	−0.40 ± 0.19 f	15.54 ± 1.86 k	0
		2	80.30 ± 0.87 abc	0.36 ± 0.10 f	20.17 ± 0.02 j	6.10 ± 2.33 klm
		4	76.15 ± 1.45 bcd	0.52 ± 0.27 f	20.90 ± 1.09 j	10.03 ± 2.13 ghijkl
		6	75 ± 1.84 bcde	0.61 ± 0.33 f	22.44 ± 1.28 j	11.17 ± 0.46 fghij
		8	72.87 ± 2.05 def	0.70 ± 0.65 f	22.90 ± 1.14 ij	14.96 ± 1.68 bcdefg
	‘Sicilian violet’	0	8.47 ± 0.77 q	35.11 ± 0.77 a	−1.87 ± 0.76 lm	0
		2	10.46 ± 1.98 pq	32.55 ± 0.96 ab	−1.38 ± 1.05 lm	3.84 ± 2.21 mn
		4	17.78 ± 0.85 no	28.88 ± 3.04 c	−1.01 ± 0.67 lm	12.67 ± 0.25 defghi
		6	18.44 ± 0.95 no	20.20 ± 1.10 d	−0.65 ± 0.40 lm	18.00 ± 0.86 abcd
		8	22.53 ± 0.65 mn	19.19 ± 1.83 d	1.06 ± 1.60 l	21.49 ± 1.48 a
F-statistics						
Growth system × variety × Days			1.45 ns	1.92 ns	3.40 **	0.98 ns

Values are presented as mean $\pm$ SD ($n = 4$). Means within a column followed by different lowercase letters differ significantly according to Tukey’s HSD test ($p < 0.05$). ns = not significant; ** $p < 0.01$. L^* = lightness; a^* = green (−) to red (+); b^* = blue (−) to yellow (+); ΔE = total colour difference relative to Day 0. The Production system $\times$ Cultivar $\times$ Storage duration interaction was significant only for b^* values ($F = 3.40$, $p < 0.01$), while interactions for L^* , a^* , and ΔE were not significant.

The a^* values remained negative for ‘Macerata’, indicating the persistence of green colouration, while positive a^* values recorded for ‘Snowball’ and especially ‘Sicilian Violet’ reflected red–purple pigmentation characteristics. Storage significantly altered colour coordinates across cultivars, with ‘Sicilian Violet’ showing a marked reduction in positive a^* values over time, suggesting degradation of purple pigments during storage. Significant changes in b^* values were observed throughout storage, particularly in ‘Macerata’, where yellowness increased from 42.64 to 57.86 under gravel cultivation and from 46.82 to 55.32 under soil cultivation after 8 d of storage. The significant three-way interaction for b^* indicates that the effect of storage duration on yellowness was dependent on both cultivar and production system. Total colour difference (ΔE) increased progressively during storage in all cultivars, demonstrating cumulative colour changes relative to harvest. The greatest ΔE values were observed in ‘Sicilian Violet’ grown in soil (21.49) and gravel (20.42) after 8 d of storage, indicating more pronounced visual colour alterations. Although ΔE increased with storage duration, the production system $\times$ cultivar $\times$ storage duration interaction was not significant ($p > 0.05$), suggesting a similar trend of colour change across treatments. Overall, soil-grown curds generally maintained higher lightness and more stable colour attributes than gravel-grown curds during storage, while cultivar-specific differences exerted a stronger influence on colour retention than the production system itself.

3.5. Interactive Influence of Production System, Cultivar, and Storage Duration on Bioactive Compounds and Antioxidant Activity

The three-way interaction among production system, cultivar, and storage duration significantly affected all measured bioactive compounds and antioxidant parameters, including TPC, FRAP, DPPH, ABTS, and glucosinolate concentrations ($p < 0.001$; $F = 22.30, 4.35, 206.30, 18.70$, and 7.40 , respectively), indicating that the effects of storage on cauliflower quality depended on both cultivar and cultivation system (Table 2).

TPC was significant ($p < 0.05$). influenced by cultivar, production system, storage duration, and their interactions. Overall, TPC increased during storage across all cultivars $\times$ production system combinations. The highest TPC values were observed in ‘Sicilian Violet’, particularly under soil cultivation, where TPC increased significantly from $48.72 \text{ mg GAE g}^{-1}$ at harvest to $53.82, 55.12$, and $55.25 \text{ mg GAE g}^{-1}$ on days 4, 6, and 8, respectively. Under GFT cultivation, TPC similarly increased from $40.61 \text{ mg GAE g}^{-1}$ at harvest to $51.46, 52.25$, and $53.56 \text{ mg GAE g}^{-1}$ on days 4, 6, and 8, respectively. According to Tukey’s HSD test, no significant differences were detected among the values recorded from days 2 to 8 under GFT or among days 4, 6, and 8 under soil cultivation, indicating that phenolic accumulation reached a plateau during the later stages of storage. Maximum TPC values were recorded on day 8 in ‘Macerata’, reaching 46.50 and $46.63 \text{ mg GAE g}^{-1}$ under GFT and soil cultivation, respectively, and in ‘Snowball’, reaching 43.75 and $41.53 \text{ mg GAE g}^{-1}$, respectively. These values were significantly higher than those at harvest, confirming the positive effect of storage duration on phenolic accumulation.

In GFT-grown ‘Macerata’, glucosinolate concentration increased from $35.51 \text{ } \mu\text{g g}^{-1}$ at harvest to $41.77 \text{ } \mu\text{g g}^{-1}$ on day 2 and thereafter remained relatively stable, with no significant differences among days 2, 4, 6, and 8 ($41.77\text{--}42.64 \text{ } \mu\text{g g}^{-1}$), indicating that glucosinolate accumulation reached a plateau early during storage. In GFT -‘Snowball’, glucosinolate concentration increased from $33.85 \text{ } \mu\text{g g}^{-1}$ at harvest to $38.45 \text{ } \mu\text{g g}^{-1}$ on day 4 and $39.44 \text{ } \mu\text{g g}^{-1}$ on day 6. However, no significant differences were observed among the concentrations recorded on days 4 and 6, indicating a relatively stable glucosinolate content during the mid-storage periods. Subsequently, glucosinolate concentration declined significantly to $31.31 \text{ } \mu\text{g g}^{-1}$ on day 8. In contrast, GFT-grown ‘Sicilian Violet’ exhibited a continuous and significant increase in glucosinolate content during storage, reaching 45.10 and $48.31 \text{ } \mu\text{g g}^{-1}$ on days 4 and 6, respectively. The concentrations recorded on days 6 and

8 did not differ significantly, indicating maintenance of high glucosinolate levels during the later stages of storage.

Table 2. Interactive effects of production system, cultivar, and storage duration on bioactive compounds and antioxidant capacity of cauliflower during refrigerated storage.

Growth System	Cultivar × Days	Total Phenolic Content mg GAE g ⁻¹ DW	Ferric Reducing Antioxidant Power mg TE g ⁻¹ DW	DPPH Scavenging Activity mg TE g ⁻¹ DW	ABTS Scavenging Activity mg TE g ⁻¹ DW	Total Glucosinolate Content μmol g ⁻¹ DW
Gravel	‘Macerata’ × 0	29.37 ± 0.39 kl	5.61 ± 0.23 k	0.08 ± 0.01 ij	0.43 ± 0.03 no	35.51 ± 1.07 kl
	‘Macerata’ × 2	30.55 ± 0.78 jkl	5.71 ± 0.24 ijk	0.11 ± 0.01 hi	0.52 ± 0.03 mn	41.77 ± 0.30 fghij
	‘Macerata’ × 4	33.95 ± 1.38 j	5.82 ± 0.05 ijk	0.13 ± 0.01 fg	0.79 ± 0.05 hi	42.01 ± 0.42 efghi
	‘Macerata’ × 6	40.22 ± 0.99 hi	6.72 ± 0.07 defghijk	0.16 ± 0.01 fg	1.04 ± 0.06 de	42.64 ± 0.12 efgh
	‘Macerata’ × 8	46.50 ± 0.99 def	6.61 ± 0.15 defghijk	0.17 ± 0.01 ef	1.24 ± 0.07 cd	40.98 ± 1.96 ghij
	‘Snowball’ × 0	27.80 ± 1.57 l	7.25 ± 0.27 defgh	0.06 ± 0.01 k	0.11 ± 0.01 p	33.85 ± 2.97 lm
	‘Snowball’ × 2	28.46 ± 0.23 l	7.54 ± 0.28 bcdefg	0.07 ± 0.01 jk	0.26 ± 0.02 op	34.52 ± 0.77 lm
	‘Snowball’ × 4	30.81 ± 0.99 jkl	7.72 ± 0.54 bcdef	0.11 ± 0.01 hi	0.60 ± 0.04 lm	38.45 ± 1.60 jk
	‘Snowball’ × 6	32.51 ± 0.78 jk	9.26 ± 1.08 a	0.13 ± 0.01 fg	0.88 ± 0.05 gh	39.44 ± 2.26 hijk
	‘Snowball’ × 8	43.75 ± 0.23 efg	8.75 ± 0.33 ab	0.14 ± 0.01 fg	1.21 ± 0.07 cd	31.31 ± 0.65 m
	‘Sicilian violet’ × 0	40.61 ± 0.60 ghi	7.07 ± 0.30 efghijk	0.15 ± 0.01 fg	0.60 ± 0.04 lm	39.03 ± 0.95 ij
	‘Sicilian violet’ × 2	50.94 ± 2.35 bc	7.15 ± 0.12 defghi	0.15 ± 0.01 fg	1.00 ± 0.06 de	41.92 ± 0.95 efghi
	‘Sicilian violet’ × 4	51.46 ± 0.91 bc	7.34 ± 0.14 cdefgh	0.17 ± 0.01 ef	1.19 ± 0.07 cd	45.10 ± 1.13 abcdef
	‘Sicilian violet’ × 6	52.25 ± 1.38 ab	8.18 ± 0.86 cdefgh	0.21 ± 0.01 e	1.21 ± 0.07 cd	48.31 ± 0.18 a
	‘Sicilian violet’ × 8	53.56 ± 1.38 ab	6.53 ± 0.36 defghij	0.28 ± 0.02 d	1.29 ± 0.08 bc	44.15 ± 0.89 cdefg
Soil	‘Macerata’ × 0	32.64 ± 0.82 jk	6.33 ± 0.05 fghijk	0.11 ± 0.01 hi	0.74 ± 0.04 ij	43.56 ± 0.18 efg
	‘Macerata’ × 2	40.48 ± 0.60 ghi	6.57 ± 0.16 defghijk	0.12 ± 0.01 gh	0.96 ± 0.06 ef	44.43 ± 0.12 cdefg
	‘Macerata’ × 4	40.6 ± 0.60 ghi	6.71 ± 0.16 defghijk	0.14 ± 0.01 fg	1.10 ± 0.07 cd	47.95 ± 0.42 ab
	‘Macerata’ × 6	43.10 ± 1.41 fgh	7.90 ± 0.19 abcde	0.17 ± 0.01 ef	1.17 ± 0.07 cd	48.23 ± 0.48 a
	‘Macerata’ × 8	46.63 ± 0.78 de	6.23 ± 0.08 ghijk	0.17 ± 0.01 ef	1.56 ± 0.09 ab	47.80 ± 0.30 abc
	‘Snowball’ × 0	32.12 ± 1.41 jk	7.06 ± 0.31 defghi	0.07 ± 0.01 jk	0.56 ± 0.03 mn	40.98 ± 0.48 ghij
	‘Snowball’ × 2	38.64 ± 1.38 i	7.64 ± 1.61 bcdef	0.08 ± 0.01 ij	0.68 ± 0.04 kl	42.72 ± 0.42 efgh
	‘Snowball’ × 4	38.78 ± 0.78 i	7.93 ± 0.44 abcd	0.11 ± 0.01 hi	0.71 ± 0.04 jk	45.06 ± 0.99 abcdef
	‘Snowball’ × 6	45.71 ± 0.99 def	8.71 ± 0.06 abc	0.13 ± 0.01 fg	0.91 ± 0.05 fg	47.16 ± 0.12 abcd
	‘Snowball’ × 8	41.53 ± 1.04 ghi	6.14 ± 0.09 hijk	0.13 ± 0.01 fg	1.23 ± 0.07 cd	44.74 ± 0.30 bcdef
	‘Sicilian violet’ × 0	48.72 ± 0.99 cd	6.64 ± 0.33 defghijk	0.33 ± 0.02 c	1.11 ± 0.07 cd	44.80 ± 0.18 bcdef
	‘Sicilian violet’ × 2	51.59 ± 0.99 bc	7.13 ± 0.14 defghi	0.34 ± 0.02 c	1.25 ± 0.08 bc	44.86 ± 0.07 abcdef
	‘Sicilian violet’ × 4	53.82 ± 0.23 ab	7.22 ± 0.22 defgh	0.41 ± 0.03 b	1.25 ± 0.08 bc	45.06 ± 0.07 abcdef
	‘Sicilian violet’ × 6	55.12 ± 1.38 a	7.47 ± 0.45 bcdefgh	0.43 ± 0.03 b	1.38 ± 0.08 bc	47.44 ± 1.08 abcd
	‘Sicilian violet’ × 8	55.25 ± 0.78 a	7.03 ± 0.35 defghijk	0.51 ± 0.04 a	1.71 ± 0.10 a	45.38 ± 2.26 abcdef
F statistics						
Growth system × variety × days		22.30 ***	4.35 ***	0.045 ***	1.241 ***	7.46 *** 7.40 ***

Values are presented as mean ± standard deviation (SD) (n = 4). Means followed by different lowercase letters within a column are significantly different according to Tukey’s Honest Significant Difference (HSD) test at $p < 0.05$. *** $p < 0.001$. The three-way interaction among production system, cultivar, and storage duration significantly affected all measured bioactive compounds and antioxidant parameters ($p < 0.001$). GAE = gallic acid equivalents; TE = Trolox equivalents; FRAP = ferric reducing antioxidant power; DPPH = 2,2-diphenyl-1-picrylhydrazyl radical scavenging activity; ABTS = 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical scavenging activity; GSL = glucosinolate content.

Under soil cultivation, glucosinolate concentrations in ‘Sicilian Violet’ varied only slightly throughout storage and were generally not significantly different among sampling dates, demonstrating greater stability than in the other cultivars. In contrast, soil-grown ‘Macerata’ exhibited a significant increase in glucosinolate concentration from 43.56 μg g⁻¹ at harvest to 47.95 μg g⁻¹ on day 4, after which concentrations remained statistically unchanged through days 6 and 8 (48.23 and 47.80 μg g⁻¹, respectively), indicating that glucosinolate accumulation had reached a plateau. A similar trend was observed in soil-grown ‘Snowball’, where glucosinolate concentrations increased progressively from 40.98 μg g⁻¹ at harvest to 47.16 μg g⁻¹ on day 6, and values recorded on days 6 and 8 (44.74 μg g⁻¹) did not differ significantly, suggesting stabilization during the later stages of storage. Overall, soil-grown curds generally maintained higher glucosinolate concentrations than

GFT-grown curds across cultivars and storage periods, indicating improved glucosinolate retention under soil cultivation.

The antioxidant capacity of cauliflower, as measured by FRAP, DPPH, and ABTS assays, was significantly influenced by the three-way interaction among production system, cultivar, and storage duration ($p < 0.001$). The significant production system $\times$ cultivar $\times$ storage duration interaction for FRAP ($F = 4.35$), DPPH ($F = 0.045$), and ABTS ($F = 1.241$) indicates that storage-related changes in antioxidant activity were dependent on the combined effects of cultivar and production system. The antioxidant capacity of cauliflower, measured using FRAP, DPPH and ABTS assays and expressed as mg TE g^{-1} DW, was significantly affected by the interaction among production system, cultivar, and storage duration ($p < 0.001$). Antioxidant activity generally increased during storage, although the magnitude of the response varied among cultivars and production systems.

For the FRAP assay, which measures ferric reducing antioxidant power, antioxidant capacity generally increased during refrigerated storage. In gravel-grown ‘Macerata’, FRAP increased from $5.61 \text{ mg TE g}^{-1}$ at harvest to $6.72 \text{ mg TE g}^{-1}$ on day 6, while ‘Snowball’ showed a greater increase from 7.25 to $9.26 \text{ mg TE g}^{-1}$ over the same period. Similarly, soil-grown ‘Snowball’ exhibited an increase from $7.06 \text{ mg TE g}^{-1}$ at day 0 to $8.71 \text{ mg TE g}^{-1}$ at day 6. These results indicate that refrigerated storage enhanced the reducing power of cauliflower, although the magnitude of increase varied among cultivars and production systems. The highest FRAP value was observed in gravel-grown Snowball on day 6, suggesting superior ferric reducing capacity under these conditions. FRAP values of ‘Sicilian Violet’ cauliflower remained relatively stable during postharvest storage in both GFT and soil production systems. In GFT-grown plants, FRAP increased from $7.07 \text{ mg TE g}^{-1}$ at harvest to $8.18 \text{ mg TE g}^{-1}$ on day 6 before declining to $6.53 \text{ mg TE g}^{-1}$ on day 8. A similar trend was observed in soil-grown plants, where FRAP increased from $6.64 \text{ mg TE g}^{-1}$ at harvest to $7.47 \text{ mg TE g}^{-1}$ on day 6 and subsequently decreased to $7.03 \text{ mg TE g}^{-1}$ on day 8. The significant three-way interaction among production system, cultivar, and storage duration for FRAP ($F = 4.35$, $p < 0.001$) confirms that changes in ferric reducing power were dependent on both cultivar and growing conditions during postharvest storage.

DPPH radical scavenging activity, expressed as mg TE g^{-1} DW, increased significantly during storage in all treatments. Among the cultivars, ‘Sicilian Violet’ consistently exhibited the highest DPPH values, indicating superior antioxidant capacity. Under soil cultivation, DPPH activity increased from $0.33 \text{ mg TE g}^{-1}$ DW at harvest to $0.51 \text{ mg TE g}^{-1}$ DW after 8 d of storage, representing the highest value recorded among all treatments. GFT-grown ‘Sicilian Violet’ also showed a substantial increase from 0.15 to $0.28 \text{ mg TE g}^{-1}$ DW. In comparison, DPPH activity in ‘Macerata’ increased from 0.08 to $0.17 \text{ mg TE g}^{-1}$ DW under GFT and from 0.11 to $0.17 \text{ mg TE g}^{-1}$ DW under soil cultivation. ‘Snowball’ exhibited lower values throughout storage, increasing from 0.06 to $0.14 \text{ mg TE g}^{-1}$ DW under GFT and from 0.07 to $0.13 \text{ mg TE g}^{-1}$ DW under soil cultivation.

ABTS radical scavenging activity showed trends similar to those observed for DPPH. Across all treatments, ABTS activity increased progressively during storage, indicating enhanced antioxidant capacity. ‘Sicilian Violet’ exhibited the highest ABTS values throughout storage under both production systems. Under soil cultivation, ABTS activity increased from $1.11 \text{ mg TE g}^{-1}$ DW at harvest to $1.71 \text{ mg TE g}^{-1}$ DW after 8 d of storage, representing the highest value among all treatments. GFT-grown ‘Sicilian Violet’ showed an increase from 0.60 to $1.29 \text{ mg TE g}^{-1}$ DW during storage. In contrast, ABTS activity in ‘Macerata’ increased from 0.43 to $1.24 \text{ mg TE g}^{-1}$ DW under GFT and from 0.74 to $1.56 \text{ mg TE g}^{-1}$ DW under soil cultivation. Corresponding values for ‘Snowball’ increased from 0.11 to $1.21 \text{ mg TE g}^{-1}$ DW under GFT and from 0.56 to $1.23 \text{ mg TE g}^{-1}$ DW under soil cultivation.

Overall, refrigerated storage enhanced antioxidant capacity, phenolic accumulation, and glucosinolate retention in cauliflower. Among the cultivars, ‘Sicilian Violet’ exhibited the greatest antioxidant capacity, reflected by its consistently higher TPC, DPPH, and ABTS values, particularly under soil cultivation. Soil-grown cauliflower generally maintained higher glucosinolate concentrations and antioxidant activity than GFT-grown cauliflower, demonstrating that preharvest production conditions strongly influenced postharvest nutraceutical quality. These findings suggest that postharvest storage enhanced antioxidant activity, with the magnitude of improvement being strongly dependent on cultivar and production system.

3.6. Interactive Effects of Growing System, Cultivar, and Storage Period on Pigments

Table 3 presents the interactive effects of growing system, cultivar, and storage period on the pigment composition of cauliflower.

Table 3. Interactive effects of gravel film technique (GFT) and soil production systems, cultivar, and storage duration on pigment contents of cauliflower.

Growth System	Variety	Days	Total Chlorophyll	β-Carotene Content	Total Anthocyanin	
Gravel	‘Macerata’		mg g ⁻¹	mg 100 g ⁻¹	mg g ⁻¹	
		0	1.93 ± 0.05 bcd	93.27 ± 1.49 d	49.54 ± 0.96 ij	
		2	1.69 ± 0.08 b	76.29 ± 1.33 f	48.20 ± 1.93 imn	
		4	1.47 ± 0.04 cdefg	58.81 ± 0.27 hi	47.31 ± 0.96 klm	
		6	1.45 ± 0.10 defgh	57.82 ± 1.01 hi	46.76 ± 0.00 klm	
		8	1.02 ± 0.05 kl	52.05 ± 0.54 j	36.74 ± 1.67 lm	
		‘Snowball’	0	0.73 ± 0.06 m	7.05 ± 0.27 r	48.43 ± 0.85 jklm
			2	0.63 ± 0.05 mn	10.84 ± 0.81 q	42.86 ± 1.72 no
			4	0.56 ± 0.02 mno	13.68 ± 0.14 pq	37.85 ± 0.94 p
			6	0.51 ± 0.02 no	26.33 ± 0.34 n	33.40 ± 1.31 q
			8	0.37 ± 0.06 o	32.68 ± 0.21 m	28.39 ± 0.68 r
		‘Sicilian violet’	0	1.58 ± 0.09 cdefg	69.98 ± 1.28 e	164.76 ± 1.88 c
			2	1.52 ± 0.01 bcdef	56.60 ± 0.92 g	155.30 ± 0.92 e
			4	1.41 ± 0.09 efghij	44.08 ± 0.14 h	146.39 ± 1.54 f
			6	1.31 ± 0.07 hij	37.10 ± 0.28 j	138.60 ± 0.77 g
8	1.25 ± 0.03hij		34.13 ± 0.51k	128.58 ± 1.26h		
Soil	‘Macerata’	0	2.01 ± 0.11 a	114.62 ± 0.14 a	52.32 ± 0.89 ij	
		2	1.72 ± 0.01 b	113.18 ± 0.08 a	50.65 ± 1.63 ijkl	
		4	1.68 ± 0.06 bc	107.46 ± 1.35 ab	48.43 ± 0.58 jklm	
		6	1.53 ± 0.03 bcde	101.51 ± 0.81 c	47.32 ± 1.17 klm	
		8	1.31 ± 0.01 fghij	75.34 ± 0.16 f	45.09 ± 0.96 mno	
	‘Snowball’	0	1.18 ± 0.14 jkl	15.61 ± 0.08 p	51.21 ± 0.74 i	
		2	0.97 ± 0.09 l	19.98 ± 0.95 o	49.54 ± 1.42 ij	
		4	0.71 ± 0.05 mn	21.87 ± 0.56 o	47.87 ± 0.45 klm	
		6	0.70 ± 0.12 mn	32.14 ± 0.61 m	47.31 ± 1.09 jklm	
		8	0.42 ± 0.02 o	34.08 ± 0.68 m	41.75 ± 0.83 o	
	‘Sicilian violet’	0	1.47 ± 0.07 cdefg	82.01 ± 2.50 g	179.23 ± 1.91 a	
		2	1.79.23 ± 1.91 a	70.12 ± 0.92 i	174.23 ± 0.99 b	
		4	1.29 ± 0.04 ghij	60.43 ± 0.36 k	173.44 ± 1.36 b	
		6	1.21 ± 0.01 ijk	50.84 ± 0.54 l	171.67 ± 0.71 c	
		8	0.54 ± 0.05 hij	41.87 ± 1.69 m	160.31 ± 1.24 d	
F statistics						
Growth system × variety × days			13.60 ***	110.30 ***	28.00 ***	

Values are presented as mean ± SD (n = 3). Means followed by different lowercase letters within a column differ significantly according to Tukey's HSD test ($p < 0.05$). *** $p < 0.001$. The production system × cultivar × storage duration interaction significantly affected total chlorophyll (F = 13.60, $p < 0.001$), total carotenoid content (F = 110.30, $p < 0.001$), and total anthocyanin content (F = 28.00, $p < 0.001$).

The total chlorophyll content was significantly influenced by the interaction of production system, cultivar, and storage duration ($F = 13.60$, $p < 0.001$), indicating that chlorophyll degradation during refrigerated storage varied among cultivars and growing systems. Overall, chlorophyll content declined progressively with storage time in all cauliflower cultivars, reflecting the natural degradation of photosynthetic pigments during postharvest storage.

For ‘Sicilian Violet’, total chlorophyll content decreased steadily throughout storage in both GFT and soil production systems. In GFT-grown cauliflower, chlorophyll declined from 1.58 mg g^{-1} at harvest to 1.25 mg g^{-1} after 8 days of storage, whereas soil-grown plants showed a decrease from 1.47 to 0.54 mg g^{-1} over the same period. These results indicate substantial chlorophyll degradation during storage, with a greater reduction observed under soil cultivation than in the GFT system. A similar declining trend was observed in ‘Macerata’ and ‘Snowball’ cultivars. ‘Macerata’ exhibited the highest chlorophyll content at harvest, particularly under soil cultivation (2.01 mg g^{-1} but values declined to 1.31 mg g^{-1} by day 8. ‘Snowball’ showed the lowest chlorophyll concentrations throughout storage, decreasing from 0.73 to 0.37 mg g^{-1} in GFT-grown plants and from 1.18 to 0.42 mg g^{-1} in soil-grown plants.

The β -carotene content was significantly affected by the interaction between production system, cultivar, and storage duration ($F = 110.30$, $p < 0.001$), indicating that accumulation of β -carotene and degradation during refrigerated storage depended on both cultivar and growth system. Overall, β -carotene content decreased during storage in ‘Macerata’ and ‘Sicilian Violet’, whereas an increasing trend was observed in ‘Snowball’, suggesting cultivar-specific responses to postharvest storage. Among the cultivars, ‘Macerata’ contained the highest β -carotene concentrations throughout storage, particularly under soil cultivation, whereas ‘Sicilian Violet’ maintained intermediate concentrations and ‘Snowball’ the lowest concentrations. In the GFT system, β -carotene content declined from $69.98 \text{ mg } 100 \text{ g}^{-1}$ at harvest to $34.13 \text{ mg } 100 \text{ g}^{-1}$ after 8 days of storage, representing a reduction of approximately 51%. Similarly, soil-grown ‘Sicilian Violet’ showed a decrease from 82.01 to $41.87 \text{ mg } 100 \text{ g}^{-1}$ during the same storage period. Despite storage-related declines, soil-grown ‘Macerata’ maintained the highest β -carotene concentrations among all treatments throughout storage. ‘Macerata’ also exhibited a progressive decline in β -carotene content during storage. In GFT-grown plants, β -carotene content decreased from 93.27 to $52.05 \text{ mg } 100 \text{ g}^{-1}$, while soil-grown plants showed a reduction from 114.62 to $75.34 \text{ mg } 100 \text{ g}^{-1}$ between harvest and day 8. The consistently higher values recorded in soil-grown ‘Macerata’ suggest that soil cultivation favoured β -carotene retention compared with the GFT system. In contrast, ‘Snowball’ showed an increase in β -carotene concentrations during storage. In the GFT system, β -carotene content increased from $7.05 \text{ mg } 100 \text{ g}^{-1}$ at harvest to $32.68 \text{ mg } 100 \text{ g}^{-1}$ after 8 days, while soil-grown ‘Snowball’ increased from 15.61 to $34.08 \text{ mg } 100 \text{ g}^{-1}$. This trend may reflect continued β -carotene biosynthesis or concentration effects associated with postharvest physiological changes during storage. Overall, refrigerated storage resulted in significant changes in β -carotene content, with the response strongly dependent on cultivar and production system. Soil-grown ‘Sicilian Violet’ exhibited the highest β -carotene concentration at harvest ($82.01 \text{ mg } 100 \text{ g}^{-1}$), whereas Sicilian Violet maintained the greatest β -carotene content throughout storage despite gradual declines. The significant three-way interaction confirms that stability of β -carotene content and retention were influenced by the combined effects of genotype, cultivation system, and storage duration. The total anthocyanin content was significantly affected by the interaction among production system, cultivar, and storage duration ($F = 28.00$, $p < 0.001$), indicating that changes in anthocyanin concentration during refrigerated storage depended on both cultivar and growing system. The β -carotene concentration of soil-grown

‘Macerata’ cauliflower at harvest ($113.18 \text{ mg } 100 \text{ g}^{-1} \text{ DW}$) corresponds to approximately 9432 μg retinol activity equivalents (RAE) per 100 g dry weight, based on the conversion factor of $12 \text{ } \mu\text{g}$ dietary β -carotene = 1 μg RAE. This amount would theoretically provide approximately 1048% and 1347% of the recommended daily vitamin A intake for adult men ($900 \text{ } \mu\text{g}$ RAE day^{-1}) and women ($700 \text{ } \mu\text{g}$ RAE day^{-1}), respectively. However, these estimates are expressed on a dry-weight basis. Since cauliflower is typically consumed as fresh tissue containing a high proportion of water, the actual contribution to dietary vitamin A intake from a typical serving would be considerably lower. Nevertheless, the results indicate that ‘Macerata’ cauliflower represents a rich source of provitamin A carotenoids and may contribute substantially to dietary vitamin A intake, particularly when compared with many commonly consumed vegetables.

Overall, anthocyanin content declined during storage in all cultivars; however, the magnitude of the decline differed among genotypes. ‘Sicilian Violet’ exhibited significantly higher anthocyanin concentrations than ‘Macerata’ and ‘Snowball’ throughout the storage period. In the GFT system, anthocyanin content in ‘Sicilian Violet’ decreased from 164.76 to 128.58 mg g^{-1} after 8 days of storage, while soil-grown ‘Sicilian Violet’ maintained the highest anthocyanin concentrations, declining only from 179.23 to 160.31 mg g^{-1} over the same period. Despite these storage-related losses, anthocyanin concentrations in ‘Sicilian Violet’ remained significantly greater than those of the other cultivars at all sampling times. In contrast, anthocyanin concentrations in ‘Macerata’ decreased from 49.54 to 36.74 mg g^{-1} in GFT-grown plants and from 52.32 to 45.09 mg g^{-1} in soil-grown plants between day 0 and day 8. Similarly, ‘Snowball’ exhibited the lowest anthocyanin concentrations, declining from 48.43 to 28.39 mg g^{-1} under GFT and from 51.21 to 41.75 mg g^{-1} under soil cultivation. The significant three-way interaction ($F = 28.00, p < 0.001$) further indicates that anthocyanin retention was strongly influenced by the combined effects of cultivar, production system, and storage duration.

3.7. Heat Map and Hierarchical Clustering Analysis

Heat map and hierarchical clustering analyses revealed that the postharvest performance of cauliflower was strongly influenced by the interaction among cultivar, production system, and storage duration (Figure 4). Hierarchical clustering grouped variables according to similarities in their response patterns, with traits connected by shorter branch lengths exhibiting stronger associations. Total phenolic content (TPC) and total anthocyanin content (TAC) clustered closely, indicating similar accumulation patterns during storage, whereas antioxidant power formed a distinct antioxidant-related cluster. Chlorophyll and β -carotene content were also closely associated, reflecting coordinated changes in pigment metabolism during postharvest storage. The heat maps further demonstrated clear treatment-dependent differences, where red and blue colours represented relatively higher and lower standardized values, respectively. Among the treatments, soil cultivation generally enhanced the retention of bioactive compounds, antioxidant capacity, pigments, and overall quality attributes compared with the gravel film production system. However, responses were cultivar-specific. Soil-grown ‘Sicilian Violet’ was characterized by elevated TPC, TAC, glucosinolate content, and antioxidant activity, indicating superior nutraceutical quality. In contrast, soil-grown ‘Macerata’ exhibited greater chlorophyll and β -carotene retention, suggesting enhanced physiological stability during storage. Although ‘Snowball’ contained comparatively lower concentrations of bioactive compounds, soil-grown curds maintained favourable quality characteristics during storage. Overall, the clustering patterns demonstrated that no single cultivar was superior across all measured attributes; rather, cultivar performance depended on the quality trait evaluated. These results highlight the importance of integrating cultivar selection with production system

management to optimize nutritional quality, physiological stability, and postharvest shelf life of cauliflower.

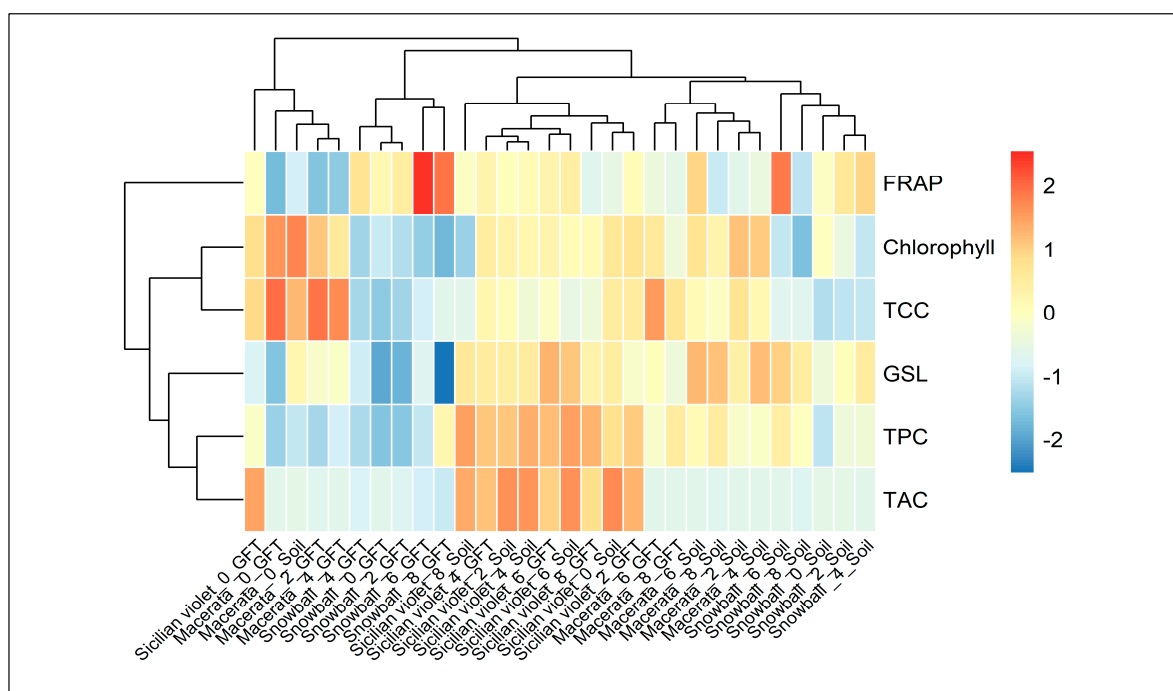


Figure 4. Hierarchical clustering heat map showing the distribution of total phenolics (TPC), chlorophyll, β -carotene content, glucosinolates (GSL), antioxidant activity (FRAP), and total anthocyanins (TAC) among cauliflower cultivars, production systems, and storage durations.

3.8. Influence of Production System, Cultivar, and Storage Duration on Sensory Evaluation of Cauliflower

Sensory attributes, including odour, texture, colour, taste, browning, and overall acceptability, were significantly affected by production system, cultivar, storage duration, and their interactions ($p < 0.05$; Figures 5 and 6). Regardless of cultivar or production system, all sensory attributes declined progressively during refrigerated storage, indicating a gradual loss of market quality (Figure 5).

The rate of sensory deterioration differed among cultivars and production systems. The effect of production system on overall acceptability was cultivar-dependent. Soil-grown ‘Macerata’ and ‘Sicilian Violet’ generally maintained higher overall quality scores during storage, whereas GFT-grown ‘Snowball’ retained higher overall acceptability than soil-grown ‘Snowball’ at 6 and 8 d of storage. For ‘Macerata’, overall acceptability decreased from 9.0 at harvest to 6.3 and 4.0 after 6 and 8 d of storage, respectively, under GFT cultivation, whereas soil-grown curds retained higher scores of 6.7 and 6.0 over the same storage period. Production system effects on sensory attributes varied among cultivars. Soil cultivation generally favored quality retention in ‘Macerata’ and ‘Sicilian Violet’, whereas ‘Snowball’ maintained comparable or higher sensory scores under GFT during later storage stages.

Similar trends were observed in ‘Sicilian Violet’, where overall acceptability declined from 9.0 to 6.3 and 4.0 in GFT-grown curds, compared with 6.3 and 5.0 in soil-grown curds after 6 and 8 d of storage, respectively. ‘Snowball’ exhibited the highest sensory stability, maintaining overall acceptability scores of 8.3, 6.0, and 3.7 after 4, 6, and 8 d of storage, respectively, under soil production, compared with 7.7, 7.0, and 5.7 in GFT-grown curds (Figure 5).

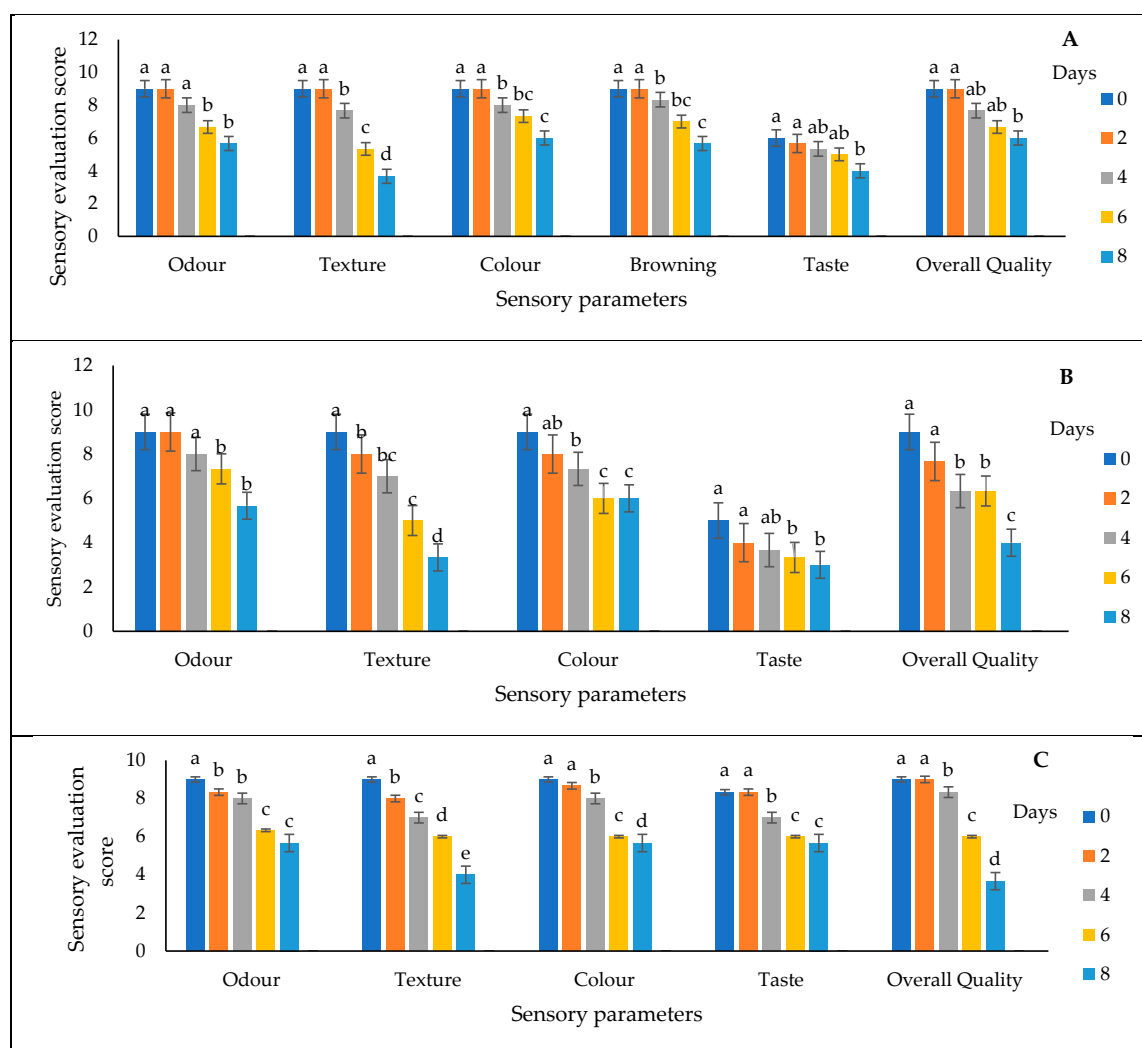


Figure 5. Interactive effects of production system, cultivar and storage duration on sensory attributes (odour, texture, colour, taste and overall acceptability) of cauliflower (A) ‘Macerata’ (B) ‘Sicilian violet’, (C) ‘Snowball’ during storage at 4 °C. Values are means $\pm$ SD. Means followed by the same letter are not significantly different according to Tukey’s HSD test ($p < 0.05$).

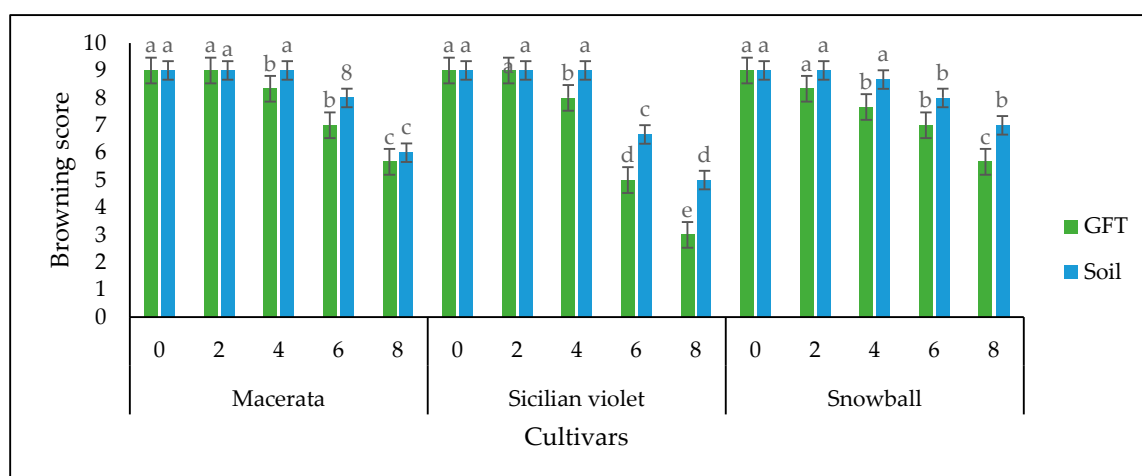


Figure 6. Browning scores of cauliflower cultivars grown under gravel flow technique (GFT) and soil cultivation during refrigerated storage at 4 °C. Values are means $\pm$ SE. Means followed by the same letter are not significantly different according to Tukey’s HSD test ($p < 0.05$).

Texture declined markedly during storage, particularly in ‘Sicilian Violet’, where scores decreased from 9.0 at harvest to 3.3 and 5.0 at day 8 under GFT and soil production, respectively. In contrast, ‘Snowball’ and ‘Macerata’ showed slower texture deterioration under soil cultivation. Odour and colour scores followed similar trends, with soil-grown curds consistently retaining higher ratings than GFT-grown curds throughout storage (Figure 5).

Sensory browning increased with storage duration in all cultivars, although the magnitude of browning was influenced by the production system. Soil-grown curds maintained higher browning scores (Figure 6), indicating less visible browning) than GFT-grown curds throughout storage. On day 8, browning scores were 6.0, 5.0, and 7.0 for soil-grown ‘Macerata’, ‘Sicilian Violet’, and ‘Snowball’, respectively, compared with corresponding values of 5.7, 3.0, and 5.7 in GFT-grown curds. Overall acceptability declined during storage in all treatments ($p < 0.05$; Figure 5). Soil-grown ‘Snowball’ maintained scores of 8.3, 6.0, and 3.7 after 4, 6, and 8 d of storage, respectively, whereas comparable scores for GFT-grown curds were 7.7, 7.0, and 5.7. Significant cultivar $\times$ production system $\times$ storage interactions were observed for all sensory attributes. Figure 7 (Top, Bottom) show the overall visual quality of cauliflower cultivars grown in both production systems after 4 to 8 days of cold storage.

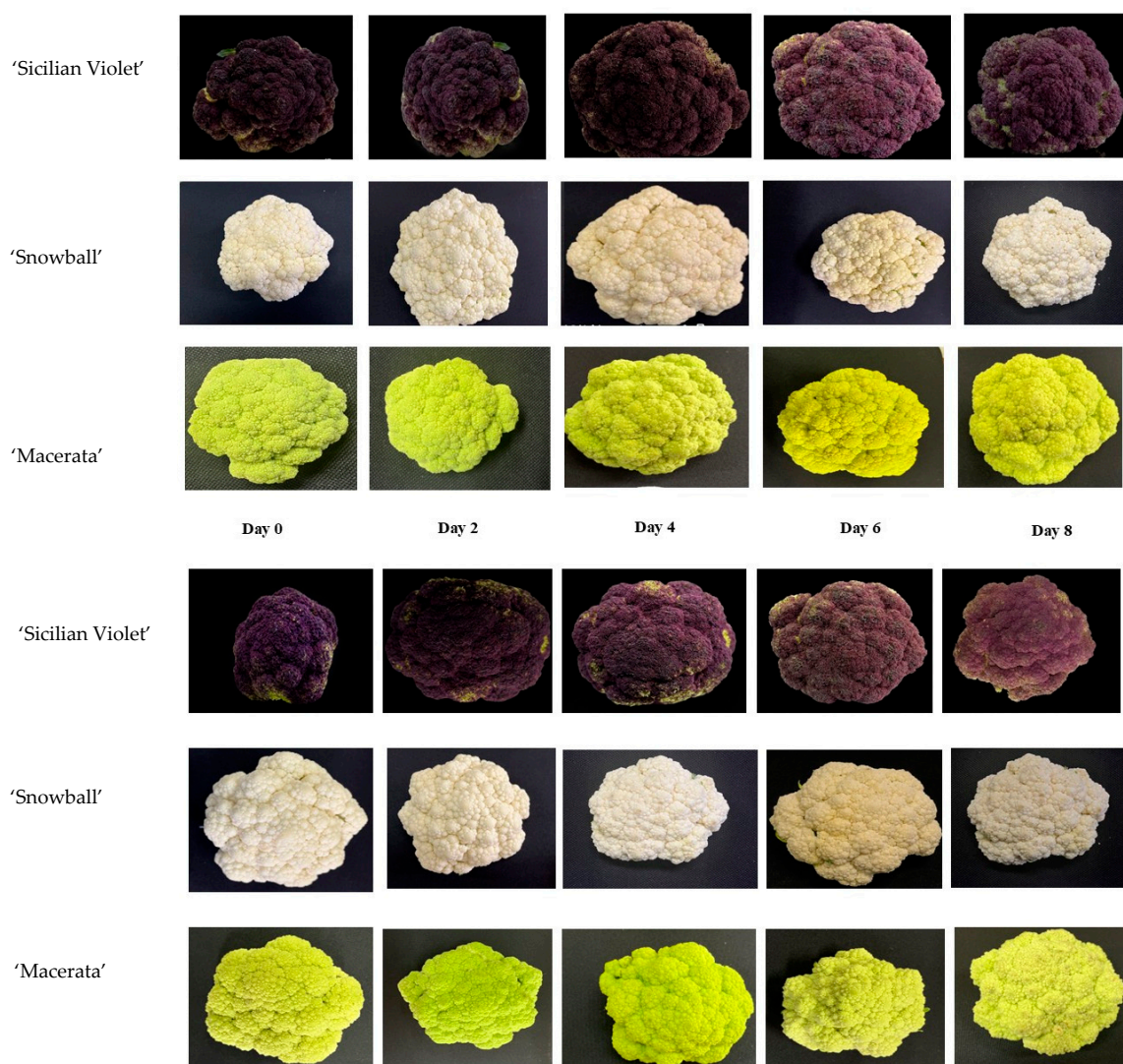


Figure 7. (Top) Interactive effects of soil production system, cultivar and postharvest storage duration on the overall visual quality of cauliflower. (Bottom) Interactive effects of GFT production system, cultivar and postharvest storage duration on the overall visual quality of cauliflower.

4. Discussion

4.1. Effects of Production System on Postharvest Physiology and Quality Retention

The present study demonstrated that postharvest performance of cauliflower was significantly influenced by the interaction between production system, cultivar, and storage duration. This suggests that preharvest production conditions influenced subsequent postharvest water-loss dynamics, supporting the view that preharvest environmental and crop management factors play a critical role in determining postharvest physiology, quality retention, and shelf life of horticultural produce [35]. The contrasting weight-loss patterns observed among production systems may therefore be associated with cultivation-induced differences in plant water status, tissue composition, and structural characteristics established before harvest [36]. Furthermore, the lower weight loss observed in ‘Sicilian Violet’, particularly under GFT production, and the greater cumulative weight loss recorded in ‘Snowball’ under soil cultivation indicate cultivar-dependent differences in water retention capacity that were further modified by the production system. Such responses may reflect inherent differences in tissue structure, cuticular properties, stomatal characteristics, and water relations among cultivar $\times$ production system combinations [37]. Similar cultivar-specific variations in postharvest behaviour have been reported for horticultural crops, where genotypic and preharvest factors interact to influence moisture loss and shelf-life potential [35]. Despite the significant increases observed during storage, weight loss remained below the commercially acceptable threshold of 5% for fresh cauliflower across all cultivar $\times$ production system combinations throughout the 8-d storage period, indicating that marketable quality was maintained under the storage conditions employed.

Soil-grown cauliflower generally maintained higher O_2 concentrations and lower CO_2 accumulation during refrigerated storage than GFT-grown cauliflower (Figure 3 (Top, Bottom)), indicating lower respiratory activity and delayed senescence. This enhanced physiological stability was accompanied by improved colour retention, reduced visual deterioration, and higher sensory quality scores throughout storage. The progressive decline in O_2 and increase in CO_2 observed across all treatments are typical consequences of respiratory metabolism in packaged fresh produce [38,39]. Although GFT-grown plants exhibited numerically higher stomatal conductance values, the differences between production systems were not significant (Table S1). Therefore, the superior maintenance of head space gas composition observed in soil-grown cauliflower cannot be attributed solely to differences in stomatal conductance. The more pronounced atmospheric modification in GFT-grown curds suggests greater respiratory demand and accelerated metabolic activity during storage. These findings indicate that preharvest cultivation conditions influenced postharvest behaviour through mechanisms beyond leaf gas exchange, potentially involving differences in tissue density, dry matter accumulation, carbohydrate reserves, nutrient composition, and plant stress responses established during crop growth [18,19]. We now identify dry matter concentration and carbohydrate reserves as key variables that should be quantified in future work to elucidate the mechanism underlying the observed differences in respiratory behaviour. Such factors may affect substrate availability for respiration and consequently influence storage performance. Previous studies have similarly demonstrated that preharvest environmental conditions can modify postharvest respiration rates and storage longevity by altering plant physiological status prior to harvest [5,8]. Future studies incorporating measurements of dry matter, tissue density, carbohydrate reserves, and mineral composition would provide greater insight into the physiological mechanisms underlying production system effects on postharvest quality retention. However, production system responses were cultivar-dependent, particularly for weight loss and sensory quality, where some cultivars performed similarly under both systems and GFT-grown ‘Snowball’ exhibited higher overall acceptability during later storage stages.

4.2. Pigment Degradation and Colour Stability During Storage

Changes in colour parameters were closely associated with the degradation of cultivar-specific pigments during storage. The increase in lightness (L^*) and reduction in positive a^* values observed in 'Sicilian Violet' were consistent with progressive anthocyanin degradation (Table 3), whereas maintenance of negative a^* values in 'Macerata' reflected greater preservation of chlorophyll pigments. Increases in b^* values in 'Macerata' and 'Snowball' further suggest chlorophyll breakdown and increased expression of underlying β -carotene pigments during senescence. Biochemical analyses supported these visual changes. Total chlorophyll declined progressively in all cultivars throughout storage, reflecting the degradation of photosynthetic pigments commonly associated with postharvest senescence. Chlorophyll degradation was accompanied by cultivar-specific changes in β -carotene content and anthocyanin concentrations [40]. β -carotene content decreased in 'Macerata' and 'Sicilian Violet' but increased in 'Snowball', indicating differential regulation of pigment metabolism among genotypes. Similarly, although anthocyanin content declined during storage, 'Sicilian Violet' consistently maintained substantially higher concentrations than 'Macerata' and 'Snowball'. This superior pigment retention likely contributed to the preservation of its characteristic purple colour during storage [41]. The observed pigment losses are consistent with previous reports indicating that chlorophylls and anthocyanins are highly susceptible to oxidative degradation following harvest [42–45]. The lower colour differences (ΔE) observed in soil-grown cauliflower further indicate enhanced preservation of visual quality and support the premise that preharvest growing conditions can influence pigment stability during storage. Although the pH differential method indicated measurable anthocyanin-equivalent concentrations in all cultivars, including the white cultivar 'Snowball', caution is warranted when interpreting these values. White cauliflower is generally not expected to accumulate substantial anthocyanin concentrations. The pH differential assay provides an estimate of total monomeric anthocyanins but may be influenced by co-extracted phenolic compounds, degradation products, or other interfering pigments present in the extract. Therefore, future studies should employ HPLC-based analyses to confirm anthocyanin profiles and quantify individual anthocyanin compounds in cauliflower cultivars.

4.3. Phytochemical Responses and Antioxidant Activity

Storage induced substantial changes in phytochemical composition and antioxidant activity. The accumulation of phenolic compounds and glucosinolates observed during refrigerated storage likely reflects activation of stress-responsive metabolic pathways [46] following harvest. Such responses are frequently associated with stimulation of the phenylpropanoid pathway and defence-related secondary metabolism under low-temperature and oxidative stress conditions [47–49].

Among the cultivars examined, 'Sicilian Violet' consistently displayed the highest concentrations of phenolics and anthocyanins together with the strongest antioxidant activity (Tables 1–3), whereas glucosinolate concentrations varied among cultivars and production systems, with the highest values recorded in soil-grown 'Macerata' and GFT-grown 'Sicilian Violet' during storage. Although anthocyanin concentrations gradually declined during storage, they remained substantially higher than those of the green and white cultivars. These findings are consistent with previous studies showing that purple Brassica vegetables contain elevated concentrations of phenolic compounds and anthocyanins, contributing significantly to their nutritional and antioxidant properties [2,50–52]. Antioxidant assays further demonstrated cultivar-dependent responses during storage. DPPH and ABTS antioxidant capacities generally increased during refrigerated storage, as indicated by the progressive increase in Trolox-equivalent values ($\text{mg TE g}^{-1} \text{ DW}$), whereas FRAP values

exhibited comparatively smaller changes. Among the cultivars, ‘Sicilian Violet’ consistently exhibited the highest DPPH and ABTS antioxidant capacities, suggesting a greater accumulation and retention of antioxidant compounds during storage.

Antioxidant assays further demonstrated cultivar-dependent responses during storage. DPPH and ABTS antioxidant capacities generally increased during refrigerated storage, as indicated by the progressive increase in Trolox-equivalent values ($\text{mg TE g}^{-1} \text{DW}$), whereas FRAP values exhibited comparatively smaller changes. Among the cultivars, ‘Sicilian Violet’ consistently exhibited the highest DPPH and ABTS antioxidant capacities, indicating greater accumulation and retention of antioxidant compounds during storage. Furthermore, soil-grown ‘Sicilian Violet’ maintained the greatest overall antioxidant capacity, suggesting that preharvest cultivation conditions influenced the synthesis and retention of antioxidant metabolites. This enhanced antioxidant performance is likely associated with the higher concentrations of phenolic compounds and anthocyanins observed in this cultivar. The superior retention of anthocyanins is consistent with the characteristic purple pigmentation of ‘Sicilian Violet’ and may have contributed substantially to its elevated antioxidant activity, as reflected by its higher DPPH and ABTS values throughout storage. Anthocyanins are recognised as important contributors to the antioxidant potential of purple Brassica vegetables and likely played a significant role in maintaining the strong antioxidant performance of ‘Sicilian Violet’ during refrigerated storage. Similar responses have been reported in Brassica species exposed to moderate environmental stress, where cultivation conditions altered secondary metabolism and enhanced antioxidant accumulation [53].

4.4. Linkages Between Physiological Stability, Antioxidant Capacity, and Sensory Quality

The results highlight a close relationship between physiological stability, antioxidant metabolism, and sensory quality retention during storage. Elevated respiration rates increase oxidative stress and accelerate senescence-associated processes, including pigment degradation, tissue deterioration, and quality losses [5,37]. The maintenance of higher O_2 concentrations and lower CO_2 levels in soil-grown cauliflower suggests reduced metabolic stress, which may have contributed to slower quality deterioration.

Phenolics, glucosinolates, and anthocyanins play important roles in protecting plant tissues against oxidative damage through reactive oxygen species scavenging, membrane stabilization, and stress-defence mechanisms [47,52]. The greater antioxidant activity observed in ‘Sicilian Violet’, particularly under soil cultivation, may therefore have contributed to improved pigment retention and delayed senescence during refrigerated storage. Nevertheless, postharvest quality is determined by multiple attributes, including appearance, colour, texture, and consumer acceptability. While ‘Sicilian Violet’ exhibited superior phytochemical and antioxidant characteristics, market acceptance ultimately depends on a balance between nutritional quality and sensory attributes [38].

4.5. Implications for Cultivar Selection and Production Management

The contrasting responses among cultivars highlight the importance of integrating cultivar selection with production practices to optimise both nutritional quality and postharvest performance. Sicilian Violet exhibited superior phytochemical composition, antioxidant activity, and bioactive compound retention, indicating strong potential for health-oriented and functional-food markets. Conversely, cultivars exhibiting greater visual stability and sensory acceptance may be more suitable for commercial supply chains where extended storage and distribution are priorities [54,55]. The superior overall performance of soil-grown cauliflower further emphasises the importance of preharvest management in determining postharvest outcomes. Preharvest environmental conditions strongly influence crop physiology, nutritional composition, and postharvest performance. Variations

in the growing environment can modify plant metabolism and stress responses, leading to differences in antioxidant accumulation, quality retention, and shelf life after harvest. Consequently, optimizing both cultivar selection and cultivation practices may provide an effective strategy for maximizing shelf life, maintaining product quality, and enhancing the nutritional value of cauliflower.

Thus, the results demonstrate that production system effects on cauliflower postharvest performance are strongly genotype-dependent, highlighting the importance of integrating cultivar selection with cultivation practices to optimize quality retention and nutraceutical value. Future research should focus on elucidating the molecular and physiological mechanisms governing pigment degradation, antioxidant metabolism, and stress adaptation under different production systems. Such knowledge will support the development of integrated cultivation and postharvest management strategies aimed at improving both marketability and nutraceutical quality of cauliflower.

5. Conclusions

This study demonstrated that cauliflower postharvest responses during refrigerated storage were strongly influenced by production system, cultivar, and storage duration. Soil cultivation generally enhanced the retention of phenolics, glucosinolates, pigments, antioxidant activity, colour quality, and browning resistance compared with the GFT. Soil-grown cauliflower also generally maintained higher O₂ concentrations and lower CO₂ accumulation than GFT-grown cauliflower, indicating reduced respiratory activity and slower physiological deterioration during storage. However, the magnitude and direction of production-system effects varied among cultivars, demonstrating strong genotype-dependent responses. For example, although soil cultivation generally favoured quality retention in ‘Macerata’ and ‘Sicilian Violet’, GFT-grown ‘Snowball’ maintained higher overall sensory acceptability during the later stages of storage.

Among the cultivars evaluated, ‘Sicilian Violet’ exhibited the greatest nutraceutical potential owing to its consistently high phenolic, glucosinolate, anthocyanin, and antioxidant levels throughout storage. In contrast, ‘Macerata’ showed superior retention of chlorophyll and β -carotene pigments, while ‘Snowball’ exhibited the highest weight loss and respiratory activity. These findings demonstrate that production-system effects on postharvest quality cannot be generalized across all cultivars and should be interpreted in conjunction with cultivar-specific responses.

Overall, the results highlight the importance of integrating cultivar selection with production practices to optimize shelf life, nutritional value, and postharvest quality of cauliflower. The findings provide practical guidance for growers and supply-chain stakeholders seeking to improve both quality retention and nutritional value during storage. Future research should focus on elucidating the physiological and molecular mechanisms underlying production system $\times$ cultivar interactions and on validating these responses under commercial storage and distribution conditions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/horticulturae12091133/s1>, Table S1: Effect of growing system and cauliflower variety on stomatal conductance at harvest.

Author Contributions: Conceptualization, D.S. and B.M.M.; methodology, S.M.; software, S.M.; validation, S.M. formal analysis, O.M.; investigation, O.M.; resources, D.S. and B.M.M.; data curation, D.S. and S.M.; writing—original draft preparation, O.M.; writing—review and editing, D.S.; visualization, D.S. and S.M.; supervision, D.S. and B.M.M.; project administration, D.S.; funding acquisition, D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Research Foundation, South Africa, grant number 98352 under the “Phytochemical Food Network to Improve Nutritional Quality for Consumers” initiative.

Data Availability Statement: The data presented in this study are available on reasonable request from the corresponding author. The data are not publicly available because they form part of an ongoing research project.

Acknowledgments: We thank Janet Mogwale for generating the images via RStudio. During the preparation of this manuscript, the author(s) used [Microsoft Copilot] for the purposes of [grammar and language editing]. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
FRAP	Ferric Reducing Antioxidant Power
TPC	Total Phenolic Content
GSL	Glucosinolate Content
TAC	Total Anthocyanin Content
DPPH	2,2-Diphenyl-1-picrylhydrazyl Radical Scavenging Activity
ABTS	2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulfonic Acid) Radical Scavenging Activity
GFT	Gravel Flow Technique
TE	Trolox Equivalents
GAE	Gallic Acid Equivalents
IC ₅₀	Concentration Required to Inhibit 50% of Free Radicals

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