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Correlations Between Kernel Quality and Soil Traits under Different Agricultural Practices in Hazelnut

Fındıkta Farklı Tarım Uygulamaları Altında Meyve Kalitesi ve Toprak Özellikleri Arasındaki Korelasyonlar

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CORRELATIONS BETWEEN KERNEL QUALITY AND SOIL TRAITS UNDER DIFFERENT AGRICULTURAL PRACTICES IN HAZELNUT

ABSTRACT

This study investigated the relationships between soil characteristics and hazelnut kernel quality under different production systems. The research was conducted in 2021 and 2022 in Ordu, Türkiye, in six orchards representing good agricultural practices (GAP) and conventional agricultural practices (CAP). Soil samples were analyzed for pH, saturation, total salinity, lime, organic matter, phosphorus (P), and potassium (K). Kernel samples were evaluated for moisture, ash, water activity, oil content, free fatty acid, peroxide value, oxidative stability (Rancimat), fatty acid composition, and α-tocopherol content. Multivariate correlation analysis and principal component analysis (PCA) were used to assess the relationships between soil properties and kernel physicochemical characteristics. The results showed that soil–kernel interactions differed markedly between the two production systems. In CAP orchards, kernel quality parameters were largely associated with stress-related soil factors, particularly soil salinity and saturation, which exhibited strong correlations with fatty acid composition, peroxide value, water activity, and oxidative stability. In contrast, in GAP orchards kernel quality was more strongly related to soil reaction (pH), lime content, and nutrient availability, especially P and K. Soil organic matter showed significant correlations with several kernel quality traits in both systems, highlighting its fundamental role in quality formation. Overall, CAP systems exhibited a stress-driven quality pattern, whereas GAP systems reflected a more balanced soil–nutrition relationship influencing hazelnut kernel quality.

Keywords: Bioactive Compounds, *Corylus Avellana*, Good Agriculture, Multivariate Analysis, Organic Matter.

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FINDIKTA FARKLI TARIM UYGULAMALARI ALTINDA MEYVE KALİTESİ VE TOPRAK ÖZELLİKLERİ ARASINDAKİ KORELASYONLAR

ÖZ

Bu çalışmada, farklı üretim sistemleri altında yetiştirilen fındıkta toprak özellikleri ile iç kalite özellikleri arasındaki ilişkiler araştırılmıştır. Araştırma 2021 ve 2022 yıllarında Ordu ilinde (Türkiye), iyi tarım uygulamaları (GAP) ve geleneksel tarım uygulamalarını (CAP) temsil eden toplam altı bahçede yürütülmüştür. Toprak örneklerinde pH, doygunluk, toplam tuzluluk, kireç, organik madde, fosfor

(P) ve potasyum (K) içerikleri analiz edilmiştir. Fındık içlerinde ise nem, kül, su aktivitesi, yağ oranı, serbest yağ asitliği, peroksit değeri, oksidatif stabilite (ransimat), yağ asidi bileşimi ve α-tokoferol içeriği belirlenmiştir. Toprak özellikleri ile iç fındığın fizikokimyasal özellikleri arasındaki ilişkileri değerlendirmek amacıyla çok değişkenli korelasyon analizi ve temel bileşen analizi (PCA) uygulanmıştır. Sonuçlar, iki üretim sistemi arasında toprak-ürün kalite ilişkilerinin belirgin şekilde farklılaştığını göstermiştir. CAP bahçelerinde iç kalite parametreleri büyük ölçüde stresle ilişkili toprak faktörleri, özellikle toprak tuzluluğu ve doygunluk düzeyi ile ilişkili bulunmuş; bu değişkenlerin yağ asidi bileşimi, peroksit değeri, su aktivitesi ve oksidatif stabilite ile güçlü korelasyonlar gösterdiği belirlenmiştir. Buna karşılık GAP bahçelerinde iç kalite özelliklerinin daha çok toprak reaksiyonu (pH), kireç içeriği ve besin elementleri, özellikle P ve K ile ilişkili olduğu saptanmıştır. Her iki üretim sisteminde de toprak organik maddesi birçok kalite özelliği ile anlamlı ilişkiler göstererek kalite oluşumunda temel bir rol oynamıştır. Genel olarak CAP sisteminde kalite oluşumu daha çok stres faktörleri tarafından yönlendirilirken, GAP sisteminde toprak beslenmesi ve denge ilişkileri fındık iç kalitesini belirleyen başlıca unsurlar olmuştur.

Anahtar Kelimeler: Biyoaktif Bileşikler, *Corylus Avellana*, Çok Değişkenli Analiz, İyi Tarım, Organik Madde.

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1. INTRODUCTION

Concerns about the negative effects of today's food systems on human health and ecosystems are increasing. At the same time, food production must ensure affordability, convenience, safety, nutritional value, and environmental sustainability (McClements, 2020). The definitional ambiguity surrounding the concept of "clean food" and the lack of a standardized regulatory framework, together with growing consumer demand for natural and healthy products, pose significant challenges for producers and ingredient developers (Inguglia et al., 2023). In this regard, different systems are being researched in agriculture for crop production, and one of them is good agricultural practices. Social livability, profitability, and productivity in the agricultural production system; protecting the health and well-being of all living beings, the environment, and natural resources; and ensuring traceability, sustainability, and safe products are the main objectives of good agricultural practices (Varol and Bostan, 2023).

In good agricultural practices, satisfactory results can be obtained, especially when cultural practices such as irrigation and fertilization are implemented. In this case, yield, pomological characteristics of fruits, and chemical properties increase, thereby improving nutritional value. For this reason, it is recommended that farmers be educated on this subject first (Bostan, 2023).

Hazelnut (*Corylus avellana*) is a nutritious food that has been cultivated since ancient times and has long been part of the human diet. Although annual production varies, they are commonly enjoyed as snacks, either shelled or kernel, and are also used in the confectionery industry.

According to FAO data for 2023, approximately 57.77% of the around 1.125.000 tons of in-shell hazelnuts produced globally were supplied by Türkiye, 9.13% by Italy, 7.59% by the United States, 6.70% by Azerbaijan, and 5.83% by Chile, totaling over 87% (FAO, 2025). In Türkiye, from 2007 to 2024, the number of producers using good agricultural practices increased 12-fold, the production area increased 73-fold, and the production volume increased 110-fold (Ministry of Agriculture and Forestry, 2024). While demand for good agricultural practices in hazelnut farming is increasing, the lack of research in this area results in insufficient knowledge among practitioners. This ultimately leads to the problem of expectations not being adequately met in this application.

Limited research exists on the relationships between soil properties and the physical and chemical characteristics of hazelnut fruit in conventional production systems (Bostan, 2003; Karadeniz and Bostan, 2004), soil microelements and fruit (Bektaş, 2019), leaf minerals and fruit traits, yield, and yield components (Balık et al., 2021), and soil properties and yield (Kızılkaya et al., 2022).

In addition, some studies have demonstrated significant interactions between soil nutrient reserves, organic materials, macro- and micronutrient elements, and yield and quality in hazelnuts (Özenç and Cayci, 2005; Tous et al., 2005; Özenç et al., 2014; Amini-Noori and Ziarati, 2015; Özenç and Bender Özenç, 2015a, b; Horuz et al., 2021; Ete Aydemir and Özkutlu, 2024). As these studies show, no research has demonstrated the direct relationships between soil properties and fruit characteristics in hazelnuts under conventional and good agricultural practices.

This study was conducted to determine comparatively the correlations between certain soil properties and key kernel physicochemical properties of the cv. 'Çakıldak' hazelnut, a major commercial variety, under conventional and good agricultural practices.

2. MATERIAL AND METHODS

2.1 Plant Material

This research was conducted in 2021 and 2022 in a total of 6 orchards located in the province of Ordu, Türkiye, where good agricultural practices were applied in 3 orchards and conventional agricultural methods were applied in the other 3. During orchard selection, attention was paid to ensuring that the orchards were

located in close proximity to minimize ecological variation, established in the same period, had similar slope conditions, and were managed in a comparable manner within each management system. The slope of the orchards ranged from 0% to 15%. Orchard establishment years were 55, 80, and 100 years in the GAP system and 60, 80, and 100 years in the CAP system.

In Türkiye, hazelnut cultivars are traditionally grown in the 'ocak' system, characterized by a multi-stemmed bush structure; therefore, the experimental unit in this study was defined as an ocak. The mean spacing between ocaks was approximately 3 m, with an average of nine stems per ocak.

In conventional orchards, weed control was performed once before harvest. Fertilization was generally based on farmers' experience, with predominant use of nitrogen fertilizers. Pruning was irregular or occasionally omitted, and pest and disease control was mainly applied when symptoms occurred, particularly against powdery mildew and the brown marmorated stink bug. Irrigation was not practiced, and production relied entirely on rainfall. In GAP-managed orchards, fertilization was based on soil and leaf analyses, with balanced and environmentally friendly inputs. Pruning was conducted regularly during the dormant and early spring periods to maintain adequate light and air circulation within the ocaks. Weed control was performed mechanically twice a year (May and pre-harvest), and pest and disease management followed integrated pest management (IPM) principles with full record keeping. Irrigation was generally not applied.

The trial area is located at an altitude of 150-190 m and is approximately 10 km from the Black Sea coast; therefore, the region is under the influence of a maritime climate, and temperatures in the summer months generally range between 25-30°C.

The study used the 'Çakıldak' hazelnut, an important commercial variety widely grown in Ordu and known for its late leafing characteristic. In hazelnut plantations in Türkiye, the 'Tombul' cultivar occupies 29.47% of the area, followed by the 'Çakıldak' cultivar with 20.63%, ranking second (Anonymous, 2024). In Ordu province, where the study was conducted, the 'Çakıldak' cultivar is the most widely grown, accounting for 42.16% of the total production area (Anonymous, 2025). In the orchards in the experimental area, the proportion of the 'Çakıldak' cv was 65%.

The 'Çakıldak' cultivar has an average nut weight of 2.08 g, nut size of 17.58 mm, kernel size of 13.82 mm, kernel weight of 1.18 g, shell thickness of 0.84 mm, kernel percentage of 55.8%, protein content of 17.55%, oil content of 59.4%, palmitic acid 10.011%, palmitoleic acid 0.135%, stearic acid 3.769%, oleic acid 72.691%, and linoleic acid 13.391% (Balık et al., 2016).

In both production systems, the experiment was arranged in a randomized block design with three replicates (orchards). Each orchard was considered as one replicate. For the analyses, three sampling groups were established within each orchard.

In both farming systems, harvesting was conducted on August 20, 2021, and August 15, 2022. The hazelnuts that reached harvest maturity in each orchard were hand-picked, dried in the sun in their husks, and then separated from the clusters using a husker. The in-shell nuts were subsequently dried again under sunlight.

2.2 Soil Analysis

In both years of the study, soil samples collected from the experimental orchards in September were analyzed. For this purpose, soil samples representative of the orchard were collected from a depth of 0-30 cm.

2.2.1 Soil Saturation Percentage

Soil saturation percentage was determined by the saturation paste method. Distilled water was gradually added to an air-dried soil sample until a saturated paste with a glistening surface was obtained. The amount of water required to reach saturation was recorded, and saturation percentage was calculated on a dry weight basis (Richards, 1954).

2.2.2 pH

Soil pH was measured in a 1:2.5 soil-water suspension using a calibrated pH meter according to Yurdakul (2018).

2.2.3 Total Salt Content (Electrical Conductivity)

Total soluble salt content of soil samples was determined by measuring the electrical conductivity (EC) of the saturated soil paste extract. The saturated paste was prepared, the extract was obtained by vacuum filtration, and EC was measured using a conductivity meter. Results were expressed as dS m^{-1} (Richards, 1954).

2.2.4 Carbonate Content (Volumetric Method)

Carbonate content of soil samples was determined by the volumetric method in accordance with ISO 10693 (ISO, 1995). Soil carbonates were reacted with hydrochloric acid, and the volume of carbon dioxide released was measured. Carbonate content was calculated based on the volume of CO_2 evolved and expressed as a percentage (%).

2.2.5 Soil Organic Matter

Soil organic matter content was determined by the Walkley-Black wet oxidation method. Organic carbon in the soil was oxidized with potassium dichromate in acidic medium, and the excess dichromate was titrated with ferrous sulfate solution. Organic matter content was calculated using an appropriate conversion factor and expressed as a percentage (%) (Walkley and Black, 1934).

2.2.6 Available Phosphorus (Olsen Method)

Available phosphorus was determined by the Olsen sodium bicarbonate extraction method (Olsen et al., 1954). Air-dried soil samples were extracted with 0.5 M sodium bicarbonate ($NaHCO_3$) solution adjusted to pH 8.5. The suspension was shaken for a fixed period and then filtered. Phosphorus concentration in the extract was determined colorimetrically using the molybdenum blue method with a spectrophotometer. Results were expressed as kg da^{-1}.

2.2.7 Available Potassium (Ammonium Acetate Method)

Available potassium was determined using the ammonium acetate extraction method. Soil samples were extracted with 1 Normal ammonium acetate solution at pH 7.0, and potassium concentration in the extract was measured using a flame photometer. Results were expressed as kg da^{-1} (Jackson, 1973).

2.3. Kernel Physicochemical Analysis

Dried nuts were cracked, and all physicochemical analyses were performed on the kernels.

2.3.1 Moisture Content

Moisture and volatile matter content of oil samples were determined in accordance with ISO 662 (ISO, 2016a). The samples were ground to <2mm flour in a grinder. Moisture content was determined with a rapid moisture determination device (Mettler Toledo HR73). A known amount of sample was weighed into a suitable container and heated in an oven at 103 ± 2 °C until constant mass was achieved. After heating, the samples were cooled in a desiccator and reweighed. The loss in mass was used to calculate the moisture and volatile matter content, and results were expressed as a percentage (%) of the sample.

Humidity (%) = (A0-A1x100) / A0 …….....…..... (1)

A0: Initial weight of the test specimen (g)

A1: Dry weight of the sample (g)

2.3.2 Ash Content

Ash content was determined by the direct ashing method in accordance with AOAC Official Method 940.26 (AOAC, 2000). Each sample was ground in a blender and weighed 3±0.1g with a 0.01g sensitive precision balance, and incinerated in a muffle furnace at 550 ± 25 °C until a light gray or white ash was obtained. After ashing, the crucibles were cooled to room temperature in a desiccator and weighed. Ash content was calculated gravimetrically and expressed as a percentage (%) of the sample.

Ash (%) = (A0x100) / A1 ……..…….... (2)

A0: Ash content (g)

A1: Dry weight of the sample (g)

2.3.3 Water Activity (aw)

Water activity was measured at 25 °C using a calibrated water activity meter according to ISO 18787 (ISO, 2017a). The instrument (Novasina AW Sprint Series Operating Instructions Manual Water Activity Analyzers. Novasina AG, Switzerland) was calibrated with certified saturated salt standards before analysis. The samples were ground in a grinder and then placed in ziplock bags and prepared for water activity measurement. Approximately 5 g of the sample was filled to cover 2/3 of the sample container with <2 mm of the pulverized sample. Samples were transferred into sealed sample cups and equilibrated in the measurement chamber until equilibrium was reached and a stable value was obtained. The result of the analysis was read from the screen on the device and noted.

2.3.4 Peroxide Value

The peroxide value of oil samples was determined according to ISO 3960 (ISO, 2017b). Peroxide number was calculated by peroxide analysis (Potentiometric titration). An appropriate amount of oil sample was dissolved in a mixture of acetic acid and chloroform and reacted with a saturated potassium iodide solution. The iodine liberated from potassium iodide by peroxides present in the sample was titrated with standardized sodium thiosulfate solution using starch as an indicator, and thus the peroxide number was found. The peroxide value was expressed as milliequivalents of active oxygen per kilogram of oil (meq O_2 kg^{-1}).

The following materials were added to a beaker.

- 2-2.5 g sample (oil)

- 10 ml acetic acid/Isooctane (3/2) (v/v) was used to dissolve the oil.

- 0.2 ml of saturated KI (potassium iodide) solution was added and kept in the dark for 5 min.

- 50 ml of pure water

- A magnetic stirrer (Metrohm 801 Stirrer) and electrode (Metrohm 907 Titrando) were installed.

- Titrated with 0.01N sodium thiosulfate ($Na_2S_2O_3$).

At the end of the process, the result was seen as meqO2/kg.

Peroxide Number = (V-v) x F x 10 / m …….. (3)

V: Amount of 0.01N $Na_2S_2O_3$ solution spent in the titration (ml)

v: Amount of 0.01N $Na_2S_2O_3$ Solution spent in the blind sample (ml)

F: 0.01N $Na_2S_2O_3$ Solution Factor

m: Sample weight (g)

2.3.5 Rancimat Test

Approximately 2.5-3.0 g of hazelnut oils obtained from cold pressed hazelnut kernel samples were weighed. The oxidative stability of oil samples was determined by an accelerated oxidation test using a Rancimat apparatus (Metrohm 743) at 130 °C with an air flow rate of 20 L h^{-1}, and the induction period was recorded in accordance with ISO 6886 (ISO, 2016b).

2.3.6 Oil Content

Crude fat content was determined according to AOAC Official Method 920.39 (AOAC, 2005). The analysis samples were ground in the grinder and the samples were measured in maximum 30 minutes. 2-3 g of the ground samples were weighed and placed in the cartridges of the device (BUCHI/B-811). The cartridges were placed in the extraction column. Oil collection containers were placed on the heaters. Approximately 120-150 ml of petroleum ether was poured into the extraction column for each sample. The analysis was started by selecting the program used. When the extraction, solvent collection and oil drying were finished, the oil in the oil collection container was placed in an oven set at 103±2°C for 1 h. Then, the samples were cooled in a desiccator for 30 min and weighed on a precision balance. Drying and desiccator cooling continued until a constant weight was obtained. The final weight of the glass container was recorded and the oil content in % oil was calculated (AOAC, 2005).

% Oil (g / 100 g) = ((M2-M1) / M0) x 100 …….. (4)

M0: Weight of the dried test sample (g)

M1: Extraction device oil collection container weight (g)

M2: Weight of oil collection container after drying (g)

2.3.7 Free Fatty Acid

Free fatty acid content was determined by alkali titration. Oil samples were dissolved in a mixture of ethanol and diethyl ether and titrated with 0.1 Normal NaOH using phenolphthalein as an indicator. Results were expressed as a percentage of oleic acid (AOAC, 1990).

The following materials were used in this analysis:

- Ethyl alcohol/Diethyl ether 1/1

- 0.1N NaOH Solution

The following materials were added to a beaker.

- 2.5-5 g sample (oil)

- 60 ml Ethyl alcohol/Diethyl ether: 1/1

- Magnetic stirrer (Metrohm 801 Stirrer) and electrode (Metrohm 907 Titrando) were installed.

- Titration was performed with 0.1N NaOH solution.

At the end of the process, the result was %FFA.

% FFA= (V-v) x F x 2.82 / m ……..…… (5)

- V: Amount of 0.1N NaOH solution spent in titration (ml)

- v: Amount of 0.1N NaOH solution spent in the blind sample (ml)

- F: 0.1N NaOH Solution Factor

- m: Sample weight (g)

2.3.8 Fatty Acid Composition

The crude oil samples were obtained by pressing the kernels with a cold press oil extraction device were then esterified (IUPAC, 1987). For esterification, 1 ml of 2 N methanolic KOH solution and 7 ml n-hexane were added to 0.5 g of crude oil sample in a 10 ml screw cap test tube and centrifuged at 7000 rpm for 30 min.

As a result of this process, the supernatant containing fatty acid metal esters was clarified and this supernatant was placed in special glass bottles without mixing with the other phase and made ready for gas chromatography (Agilent Technologies 6890N, CA, USA) injection. With an automatic sampling apparatus (HP7683 B), 1 µl of the samples was automatically taken and injected into the device. A 60 m long 'Spelco 2380' capillary clone (60 m x 0.25 mm i.d., 0.20 µm film thickness; Supelco, Bellefonte, PA, USA) was used for the analysis. The peaks formed during the analysis were identified using the fatty acid standard (SupelcoTM 37 Component FAME mix, Supelco, Bellefonte, PA, USA) and fractions were determined by calculating the time and area of the peak and the results were presented as % fatty acid. In the determination of fatty acids, a mixture of methyl esters of 37 different fatty acids was tested as a standard with the samples. When the chromatograms obtained from the samples and standards were compared with each other, the fatty acid types in the samples and their relative proportions were determined.

2.3.9 α-Tocopherol Content

The kernels were pressed with a cold press oil extraction device to obtain oil. The α-tocopherol content of the samples was determined by high-performance liquid chromatography (HPLC) according to the EN 12822 standard (CEN, 2014). An appropriate amount of sample was subjected to extraction using a suitable organic solvent system. The extract was filtered and injected into the HPLC system for analysis. Tocopherols were separated on a suitable chromatographic column and detected using a fluorescence detector. Individual tocopherols were identified by comparing their retention times with those of authentic standards, and quantification was performed using external calibration. To find the results of the samples, calculations were made with standard curves prepared using standard substances and the results were expressed as mg kg^{-1} of sample.

2.4. Statistical Analysis

Multivariate correlation, Pairwise correlation, and principal component analysis (PCA) based on the kernel physicochemical parameters of hazelnut and soil traits were conducted using the SAS JMP (version 13.2.0, USA) statistical software. Data were normalized for the analyses.

3. RESULTS AND DISCUSSIONS

The soil characteristics of the orchards showed clear distinctions between good agricultural practices (GAP) and conventional agricultural practices (CAP). In GAP orchards, soil texture varied between clayey and clayey-loamy, with saturation levels ranging from 75.4% to 88.6%. The pH values fluctuated from slightly

acidic to slightly alkaline, and organic matter content ranged from 1.88% to 3.71%. Lime content demonstrated a wide variation (0.52-10.62%), while phosphorus and potassium concentrations ranged from 0.73 to 2.15 kg da^{-1} and 31.53 to 46.04 kg da^{-1}, respectively. Conversely, CAP orchards exhibited predominantly clayey soils with higher saturation levels (92.4-98.5%) and pH values mostly near neutral to slightly alkaline. Organic matter, lime, phosphorus, and potassium contents showed ranges similar to or slightly narrower than those recorded in GAP orchards. Organic matter varied between 2.08-3.67%, lime between 4.64-9.72%, phosphorus between 0.73-2.67 kg da^{-1}, and potassium between 31.50-37.80 kg da^{-1} in GAP orchards.

The chemical and quality properties of hazelnut samples obtained from GAP and CAP production systems showed generally similar results, although some parameters exhibited notable differences. Moisture, ash, and water activity values were close in both systems, measured as 5.86%, 2.75%, and 0.69 aw in GAP and 5.76%, 2.77%, and 0.70 aw in CAP, respectively. Free fatty acid and peroxide values were slightly higher in CAP samples (GAP: 0.12% and 0.02 meqO_2 kg^{-1}; CAP: 0.16% and 0.04 meqO_2 kg^{-1}). The rancimat oxidation stability value was 4.79 h in GAP and 5.18 h in CAP. Oil content and free fatty acid were slightly lower in GAP (52.48% and 0.12%, respectively) than in CAP (53.58% and 0.16%, respectively). Oleic acid was the predominant fatty acid in both systems, measured at 85.08% in GAP and 84.96% in CAP. Palmitic, stearic, and linoleic acid levels also showed only minor differences (GAP: 5.45%, 2.65%, 6.34%; CAP: 5.38%, 2.69%, 6.51%, respectively). In contrast, the amount of α-tocopherol, an important antioxidant component, was considerably higher in GAP samples (280.79 mg kg^{-1}) compared to CAP (255.39 mg kg^{-1}). Overall, although GAP and CAP hazelnuts displayed largely similar quality characteristics, certain parameters such as oxidative stability and antioxidant content demonstrated meaningful differences.

3.1 Correlation Analysis

The comparative evaluation of the relationships between soil properties and the physicochemical parameters of the kernel reveals that the nature of soil-plant interactions differs substantially across production systems (Table 1 and 2). In conventional agricultural practices (CAP), soil total salt content and saturation showed strong positive or negative correlations with a wide range of kernel quality attributes. In particular, the extremely strong associations between total salt content and several quality parameters-such as linoleic (0.963), oleic (-0.902) and palmitic acids (-0.744), water activity (0.765), peroxide value (-0.960), and rancimat stability (-0.761)-indicate that salinity and soil moisture dynamics play a decisive role in shaping kernel composition under CAP conditions. Organic matter also showed significant correlations with both fatty acid profile and oxidative stability indicators, highlighting its importance as a key soil determinant of quality within CAP.

In contrast, soil pH was associated with only a limited subset of fatty acid fractions (notably linoleic and palmitic acids), suggesting a narrower influence range in this system (Table 1).

Table 1. Significant Pairwise Correlations between kernel physicochemical parameters and soil traits in conventional agricultural practices

Variable$_{Kernel}$	**by Variable$_{Soil}$**	**Correlation**	**Signif Prob**
Ash	Organic matter	-0.707	0.0102*
	Saturation	0.731	0.0069*
	Total salt	-0.920	<.0001*
Free fatty acid	K	0.623	0.0305*
	P	0.592	0.0428*
Linoleic acid	Organic matter	0.843	0.0006*
	pH	-0.641	0.0246*
	Saturation	-0.805	0.0016*
	Total salt	0.963	<.0001*
Moisture	Saturation	-0.601	0.0389*
	Total salt	0.675	0.0159*
Oil	Organic matter	0.601	0.0386*
Oleic acid	Organic matter	-0.758	0.0043*
	Saturation	0.710	0.0097*
	Total salt	-0.902	<.0001*
Palmitic acid	Organic matter	-0.836	0.0007*
	pH	0.714	0.0090*
	Saturation	0.707	0.0101*
	Total salt	-0.744	0.0055*
Peroxide	Organic matter	-0.738	0.0062*
	Saturation	0.773	0.0032*
	Total salt	-0.960	<.0001*
Rancimat	Saturation	0.847	0.0005*
	Total salt	-0.761	0.0041*
Stearic acid	Saturation	0.696	0.0119*
	Total salt	-0.861	0.0003*
Water activity	Saturation	-0.723	0.0079*
	Total salt	0.765	0.0037*
α-tocopherol	Organic matter	0.828	0.0009*
	pH	-0.619	0.0319*
	Saturation	-0.846	0.0005*
	Total salt	0.969	<.0001*

In good agricultural practices (GAP), however, the correlation structure shifted markedly, with relationships becoming more strongly associated with soil reaction, lime content, and nutrient elements. Under GAP conditions, lime, pH, phosphorus (P), and potassium (K) exhibited significant correlations with essential quality traits such as moisture content, water activity, peroxide value, oil content, and fatty acid composition. The strong negative correlations of moisture-pH (-0.893), α-tocopherol-saturation (-0.877), moisture-lime (-0.857), water activity-lime (-0.856), palmitic acid-total salt (-0.810) and water activity-pH (-0.807) indicate that the physicochemical attributes of the kernel are primarily influenced by soil reaction, saturation, calcium, and salt content in GAP. Additionally, the associations observed between oil and specific fatty acids with P and K suggest that nutrient availability plays a more pronounced role in determining kernel chemistry under GAP compared to CAP. Despite these system-specific differences, an important common finding is that organic matter showed strong correlations with numerous quality attributes in both systems, confirming its role as a fundamental determinant of kernel quality, irrespective of the production method (Table 2).

Taken together, these comparative results demonstrate that, in CAP, kernel quality is predominantly influenced by environmental stress factors associated with salinity and moisture regime, whereas in GAP, quality is governed mainly by soil reaction, lime content, and nutrient balance. Thus, the two production systems rely on distinct dominant mechanisms in soil-kernel quality interactions: stress-based processes (salt-saturation) in CAP and nutrition- and chemical balance-driven processes in GAP.

Table 2. Significant Pairwise Correlations between kernel physicochemical parameters and soil traits in good agricultural practices

Variable$_{Kernel}$	**by Variable$_{Soil}$**	**Correlation**	**Signif Prob**
Ash	Saturation	0.700	0.0112*
	Total salt	-0.625	0.0297*
Free fatty acid	Organic matter	0.816	0.0012*
	pH	-0.775	0.0030*
	Saturation	-0.582	0.0474*
	Total salt	0.742	0.0058*
Linoleic acid	Organic matter	0.651	0.0219*
	P	-0.605	0.0370*
	Saturation	-0.798	0.0019*
	Total salt	0.697	0.0118*
Moisture	Lime	-0.857	0.0004*
	Organic matter	0.690	0.0131*
	pH	-0.893	<.0001*

Variable$_{Kernel}$	by Variable$_{Soil}$	Correlation	Signif Prob
Oil	K	0.690	0.0130*
	P	-0.622	0.0308*
	Saturation	-0.650	0.0222*
Oleic acid	P	0.726	0.0076*
	Saturation	0.623	0.0305*
	Total salt	-0.707	0.0101*
Palmitic acid	Organic matter	-0.720	0.0083*
	P	0.662	0.0190*
	Saturation	0.788	0.0024*
	Total salt	-0.810	0.0014*
Peroxide	Lime	-0.608	0.0360*
	P	0.778	0.0029*
Stearic acid	Organic matter	-0.733	0.0067*
	P	0.715	0.0089*
	Saturation	0.658	0.0200*
	Total salt	-0.759	0.0042*
Water activity	Lime	-0.856	0.0004*
	Organic matter	0.581	0.0474*
	pH	-0.807	0.0015*
α-tocopherol	K	0.604	0.0374*
	Organic matter	0.659	0.0198*
	P	-0.607	0.0365*
	Saturation	-0.877	0.0002*
	Total salt	0.754	0.0046*

3.2 Principal Component Analysis

The PCA analysis in both production systems revealed the multivariate relationships between soil properties and kernel chemical and quality parameters. However, the contributions of variables to principal components (PCs) and the variance explained differed markedly between conventional agricultural practices (CAP) and good agricultural practices (GAP). Overall, in CAP, the first three components explained 87.47% of the total variance, with PC1 being highly dominant (57.91%).

Table 3. The principal component for soil traits and kernel physicochemical parameters in conventional agricultural practices

Parameter	PC1	PC2	PC3	PC4
Peroxide	**0.965680**	-0.052109	0.093329	-0.131940
Oleic acid	**0.957857**	-0.030227	-0.029056	-0.244601
Stearic acid	**0.899184**	-0.365306	0.215426	-0.048836
Ash	**0.889331**	-0.024499	0.010408	-0.041682
Palmitic acid	**0.856347**	0.140057	-0.354921	0.035739
Saturation	**0.850652**	0.281566	0.244191	0.363057
Rancimat	**0.738604**	-0.173887	0.314428	0.537150
Lime	-0.151986	**0.934622**	0.115832	0.232063
pH	**0.584136**	**0.769354**	-0.234094	-0.033101
Moisture	-0.756197	0.569655	-0.154745	-0.192523
Water activity	**-0.857413**	0.390113	-0.077948	-0.196411
K	-0.163595	0.531636	**0.801017**	0.094807
P	-0.035411	-0.325613	**0.780597**	-0.529054
Free fatty acid	0.213937	0.476299	**0.633160**	-0.482940
Oil	-0.523959	-0.063453	**0.594083**	**0.576816**
Organic matter	**-0.811294**	-0.507663	0.263259	-0.012490
Linoleic acid	**-0.977002**	-0.087565	-0.025203	0.145018
Total salt	**-0.968019**	-0.042950	-0.042798	-0.046895
α-tocopherol	**-0.990673**	-0.058271	-0.051728	0.065011
Eigenvalue	11.00	3.10	2.52	1.52
Variance	57.91	16.31	13.25	7.98
Cumulative variance	57.91	74.22	87.47	95.45

Factor loading ≥|0.55| are marked in bold

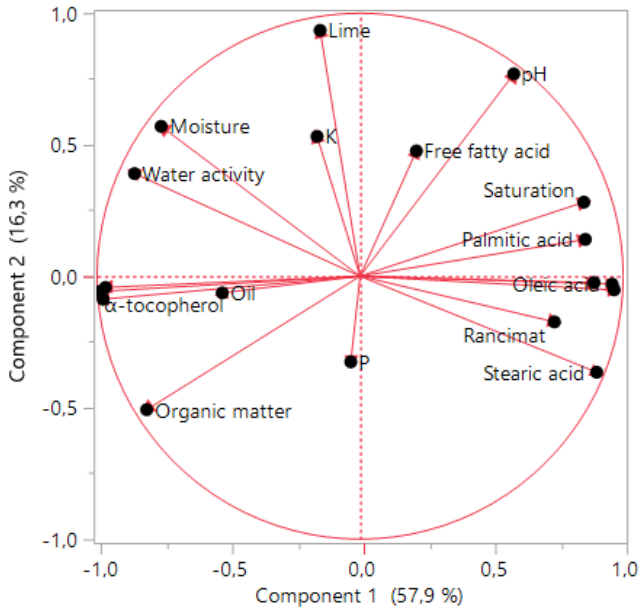


Figure 1. Biplot graph of the first two principal components for soil traits and physicochemical parameters of hazelnut kernels in conventional agricultural practices

This indicates that most variables cluster in the same direction (Table 3 and Figure 1). In GAP, the first three components accounted for 86.06% of the variance; however, unlike CAP, the variance was more evenly distributed, with PC1 contributing 47.85% and PC2 showing a notably high contribution (28.98%) (Table 4 and Figure 2). Consequently, while CAP exhibited a more centralized structure in which soil and quality variables were clustered together, GAP demonstrated a more balanced distribution of variance across two main components, indicating a more heterogeneous variable structure.

Table 4. The principal component for soil traits and kernel physicochemical parameters in good agricultural practices

Parameter	PC1	PC2	PC3	PC4
Palmitic acid	**0.938985**	0.111455	0.154569	0.143169
Saturation	**0.912263**	-0.285383	-0.253330	0.061432
Stearic acid	**0.839624**	-0.067738	0.489150	-0.021169
Oleic acid	**0.828340**	0.284980	0.213269	-0.050407
P	**0.753721**	0.358354	0.068187	-0.358028
Ash	**0.697819**	-0.049593	-0.434171	-0.206916

Parameter	PC1	PC2	PC3	PC4
Peroxide	**0.579176**	0.455868	0.471030	-0.337530
pH	0.532344	**-0.803108**	0.026894	0.115481
Moisture	-0.234841	**0.964223**	0.074608	0.071002
Water activity	-0.126108	**0.954806**	0.208699	0.119978
Free fatty acid	-0.583524	0.628819	-0.445150	0.144351
Organic matter	**-0.833241**	0.524856	-0.026402	-0.118376
K	-0.390509	**-0.636713**	**0.553890**	0.327355
α-tocopherol	**-0.885414**	-0.166448	0.374072	-0.130417
Oil	**-0.737799**	-0.450323	0.358456	-0.285914
Linoleic acid	**-0.893968**	-0.253206	0.151778	-0.300420
Rancimat	0.339361	0.513707	0.305157	**0.681332**
Lime	-0.099043	**-0.912659**	-0.148426	0.272723
Total salt	**-0.895636**	0.182803	-0.060900	0.264221
Eigenvalue	9.09	5.51	1.75	1.28
Variance	47.85	28.98	9.23	6.76
Cumulative variance	47.85	76.83	86.06	92.82

Factor loading ≥|0.55| are marked in bold

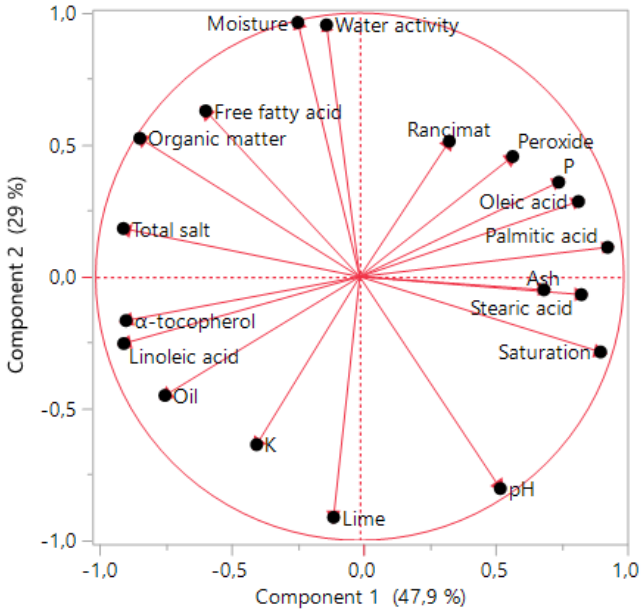


Figure 2. Biplot graph of the first two principal components for soil traits and physicochemical parameters of hazelnut kernels in good agricultural practices

3.2.1 Fatty Acids and Oxidative Parameters

In CAP, PC1 showed high positive loadings for oleic, stearic, and palmitic acids, as well as peroxide value, Rancimat, and ash. In contrast, linoleic acid, total salt, and α-tocopherol exhibited high negative loadings (Table 3). In GAP, PC1 was mainly associated with saturated and monounsaturated fatty acids (palmitic, stearic, oleic), while linoleic acid and α-tocopherol showed negative loadings (Table 4). Therefore, in both systems, PC1 represented fatty acid composition and oxidative quality. However, in CAP, soil-related variables like total salt and α-tocopherol had a stronger impact on this axis, whereas in GAP, PC1 was mainly influenced by biochemical and quality parameters rather than soil characteristics.

3.2.2 Moisture, Water Activity, and pH Relationship

In CAP, PC2 was characterized by lime, pH, and moisture/water activity moving together, indicating that this component represented soil alkalinity and kernel moisture status. Moisture and water activity showed strong positive loadings, while pH and lime exhibited strong negative loadings (Table 3). In both systems, PC2 reflected the relationship between moisture-water activity and pH-lime; however, this association was more pronounced under GAP conditions. Moisture and water activity emerged as more dominant variables in GAP (Table 4).

In CAP, PC3 was mainly influenced by K, P, and free fatty acid, representing mineral nutrition and hydrolytic lipid oxidation. In PC4, rancimat, oil content, and P were the most significant variables (Table 3). In GAP, PC3 was characterized by K, stearic acid, and peroxide value, while PC4 was dominated by rancimat, indicating oxidative stability (Table 4). Consequently, soil nutrients formed a clearer component under CAP, whereas oxidative stability appeared as a more independent axis under GAP.

3.2.3 Soil Nutrients and Oxidative Stability

These results show that variables in CAP tend to cluster more centrally, with fatty acids, mineral content, and oxidative quality grouped along the same axis. This indicates a more uniform yet more interconnected variable structure. In contrast, GAP displayed a more evenly spread distribution across two main components (PC1 and PC2), suggesting a broader system response to environmental and biochemical factors. Moisture and water activity, in particular, played a more prominent role under GAP conditions. Although fatty acid profile and oxidative quality were important factors in both systems, soil salinity and α-tocopherol had a stronger influence in CAP compared to GAP.

Previous studies have reported that high salinity disrupts membrane integrity, increases lipid peroxidation, and alters fatty acid biosynthesis (Chartzoulakis, 2005; Kacar and Katkat, 2009). This supports the interpretation that the extremely strong correlations ($|r| \geq 0.90$) observed between total soil salinity and basic chemical quality traits under conventional agricultural practices (CAP) are stress-induced. In the literature, there are only a few findings indicating significant relationships between certain soil properties of hazelnut orchards and some physical characteristics. These studies reported strong negative correlations between pH and shell thickness, pH and good kernel ratio, organic matter and shell thickness, and organic matter and good kernel ratio (Bostan, 2003); strong negative correlations between pH and kernel weight and kernel ratio, and significant positive correlations between pH and shrivelled kernel ratio and between organic matter and internal cavity size (Karadeniz and Bostan, 2004); significant positive correlations have been reported between yield and pH, EC (salinity), and Cmic (microbial biomass carbon) values (Kızılkaya et al., 2022). On the other hand, similar studies conducted on different fruit species have also reported significant correlations between soil properties and fruit quality attributes (Lu et al., 2011; Zhou et al., 2016; Chen et al., 2021; Sun et al., 2022; Xu et al., 2023; Tong et al., 2024; Wu et al., 2024; Yu et al., 2024; Zhuo et al., 2024). These studies also clearly demonstrated, through multivariate analyses, that the physical and chemical properties of soils play a decisive role in determining fruit quality parameters. In particular, soil pH, organic matter content, and macronutrients (N, P, K, Ca, and Mg) showed statistically significant and directional correlations with the physical properties, chemical composition, and biochemical quality indicators of the fruits. All of this reveals that soil-plant interactions significantly shape not only yield but also the commercial and nutritional quality of the fruit.

4. CONCLUSION

The comparative evaluation of GAP and CAP production systems demonstrated that soil-kernel interactions differ fundamentally between the two management approaches. In CAP, kernel quality was predominantly governed by salinity- and moisture-related stress factors, which strongly influenced fatty acid composition, oxidative stability, and several quality attributes. In contrast, GAP exhibited a more balanced and heterogeneous structure in which soil reaction, lime content, and nutrient elements (P and K) played a central role in determining kernel physicochemical properties. Despite these system-specific differences, soil organic matter consistently emerged as a key determinant of kernel quality in both systems. Overall, CAP is characterized by a more stress-driven quality pattern, whereas GAP supports a more nutritionally regulated and quality-stabilizing soil environment.

In conclusion, reducing soil salinity and improving water management under CAP conditions have the potential to mitigate stress-related adverse effects on oil composition and oxidative stability. In the GAP system, optimizing soil pH and lime levels may contribute to improvements in moisture-related quality parameters. Strengthening phosphorus and potassium management in GAP also appears to be an effective approach for regulating oil content and fatty acid profiles. Increasing soil organic matter emerges as a common and critical strategy for enhancing kernel quality in both production systems. Additionally, the adoption of GAP-like practices in CAP orchards may provide substantial benefits, particularly in areas where salinity and drainage issues limit overall quality.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Ethics

This study does not require ethics committee approval.

Author Contribution Rates

Investigations: DV (75%), SZB (25%)

Methodology: DV (50%), SZB (50%)

Laboratory analyses: DV (75%), SZB (25%)

Data collections: DV (75%), SZB (25%)

Data analysis: DV (20%), SZB (80%)

Supervision: SZB (100%)

Writing: DV (20%), SZB (80%)

Review and Editing: SZB (100%)

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