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Cultivar-Specific Nutrient Removal in Intensive Nectarine Orchards: Preliminary Implications for Nutrient Management

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Abstract

This exploratory study examined fruit production, dry matter content, mineral composition, and estimated nutrient removal in three nectarine (*Prunus persica* var. *nucipersica*) cultivars during the 2025 growing season in a commercial intensive orchard in northwestern Romania. 'Big Top', 'Venus', and 'Cora' grafted onto GF 677 rootstock were tested under uniform orchard management circumstances, which included fertigation with a water-soluble NPK 15-15-15 fertilizer. 'Big Top' had the largest fruit yield (34.82 t ha^{-1}) and average fruit weight, whereas 'Cora' had the highest dry matter content and mean concentrations of N, P, K, Ca, and Mg in the studied fruit tissues. 'Venus' generally displayed intermediate values. 'Cora' also had the highest estimated nutrient removal per ton and hectare of harvested fruit, while 'Big Top' had the lowest values. Potassium was the biggest component of estimated nutrient removal across all three cultivars. These descriptive patterns demonstrate the need to take into account fruit mineral composition as well as yield when evaluating nutrient removal. However, the mineral analyzes did not include fruit stones; therefore, the values do not represent total whole-fruit nutrient export. Given the study's single-year, single-site design, the findings should be viewed as preliminary, as they do not establish statistically significant cultivar effects or warrant cultivar-specific fertilizer recommendations. To examine the consistency and practical applicability of these findings, additional multi-year investigations using thorough fruit analyzes and adequate statistical evaluations are required.

Keywords: fruit mineral composition; macronutrient export; nectarine; nutrient budgeting; nutrient removal

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1. Introduction

The transition from traditional to intensive orchard production systems has significantly enhanced fruit productivity while increasing the need for effective nutrient management. Modern orchards are distinguished by high planting densities, superior cultivars, precision irrigation, and intensive management procedures, all of which necessitate balanced nutrient inputs to maintain tree development, fruit quality, and long-term yield. However, increasing yield intensity has increased the risk of excessive fertilizer application, resulting in lower nutrient-use efficiency, nutrient imbalances, higher yield costs, and environmental concerns about estimated nutrient removal due to leaching, runoff, and gaseous emissions [1–3]. As a result, optimizing fertilization strategies has emerged as a critical goal in achieving sustainable fruit yield. Recent research has shown that effective nutrient management should consider soil nutrient availability, crop nutrient demand, orchard productivity, and

nutrient cycling, rather than relying solely on conventional fertilizer recommendations [4–6]. This integrated method increases fertilizer efficiency, preserves soil fertility, and contributes to the long-term sustainability and resilience of intensive orchard systems.

Although soil and leaf studies remain the foundation of orchard fertilization plans, they do not directly quantify the nutrients exported through harvested fruits. Nutrient removal therefore represents a complementary component of orchard nutrient budgeting because it integrates fruit yield and mineral composition to estimate nutrient export at harvest [7]. Incorporating this information into nutrient management may contribute to maintaining soil fertility while reducing the risk of nutrient deficits or excessive fertilizer inputs [8–10].

Nectarine (*Prunus persica* var. *nucipersica*) is one of the most economically important stone fruit species grown in temperate climates, with rising output due to consumer demand for fruits of excellent sensory and nutritional quality. Intensive nectarine orchards are distinguished by high yield potential and high nutrient demand, especially during the fruit development stage, when nutrient demand is at its peak. Fruit growth and quality are dependent on a steady supply of mineral nutrients, particularly nitrogen and potassium, which are essential for cell division, carbohydrate metabolism, fruit enlargement, and the buildup of soluble solids [11,12]. Calcium and magnesium are similarly critical for fruit firmness, membrane stability, and postharvest quality, whereas phosphorus helps with energy metabolism and reproductive development [13]. As a result, maintaining an optimum nutrient balance throughout the growing season is critical not only for increasing productivity, but also for assuring fruit quality and orchard longevity [14]. Despite these agronomic requirements, fertilization procedures in commercial nectarine orchards are usually based on broad recommendations, with little regard for cultivar-specific nutrient demand and estimated nutrient removal from harvested fruits.

Although nutrient management and fertilization strategies have been widely investigated in fruit tree systems, considerably less attention has been given to the cultivar-specific nutrient removal associated with harvested fruits. Previous studies have demonstrated that genotype, rootstock, crop load, and orchard management can influence fruit mineral composition and nutrient dynamics in peach and nectarine [15–19], while other studies have primarily addressed fruit yield and quality responses to fertilization, mineral composition, or tree nutritional status [20–25]. A relevant knowledge gap therefore remains regarding the extent to which commercially important nectarine cultivars differ in nutrient removal when grown under the same orchard conditions. Because nutrient removal depends on both harvested biomass and fruit mineral composition, generalized nutrient removal may not adequately represent cultivar-specific patterns [26–28].

Comparative field data integrating yield, fruit dry matter content, mineral composition, and nutrient removal per unit of production and per unit area remain limited for nectarine [29,30].

Accordingly, we hypothesized that nectarine cultivars grown under identical orchard management conditions would differ in nutrient removal as a consequence of cultivar-specific differences in fruit yield, dry matter accumulation, and mineral composition. The objectives of this study were to (i) evaluate the productive performance of three commercially important nectarine cultivars ('Big Top', 'Venus', and 'Cora') cultivated in a commercial intensive orchard in northwestern Romania; (ii) determine nitrogen, phosphorus, potassium, calcium, and magnesium concentrations in the analyzed fruit tissue (peel and mesocarp); (iii) estimate nutrient removal on a yield and orchard-area basis; (iv) compare cultivar-specific nutrient export patterns; and (v) evaluate the potential contribution of cultivar-specific nutrient removal to nutrient budgeting in intensive nectarine orchards.

Given that the investigation was conducted during a single growing season, the present study should be regarded as a preliminary assessment of nutrient removal patterns in the evaluated nectarine cultivars. The observed differences are therefore interpreted descriptively and require validation through additional growing seasons before reliable conclusions regarding cultivar-specific nutrient removal can be established.

2. Materials and Methods

2.1. Study Site and Plant Material

The investigation was carried out throughout the 2025 growing season in a commercial intensive nectarine (*Prunus persica* var. *nucipersica*) orchard in Oradea, northwestern Romania (47°03′ N, 21°56′ E). The orchard was planted in 2019 and consists of six-year-old trees grafted onto GF 677 rootstock. Three commercially important nectarine cultivars, 'Big Top', 'Venus', and 'Cora', were chosen for this investigation. Trees were planted at a spacing of 4.5 × 2.0 m, resulting in a planting density of 1111 trees per hectare, and then trained to an open vase canopy structure.

The orchard was established on Chernozem soil (the World Reference Base for Soil Resources) and managed according to standard commercial practices for intensive nectarine production. A detailed physicochemical characterization of the soil profile was not performed as part of the present experiment; therefore, soil analytical data for different soil depths are not available. This limitation should be considered when interpreting the nutrient removal results. The orchard was equipped with a drip irrigation system with emitters having a nominal flow rate of 2 L h^{-1}. Fertilization was performed by fertigation through the drip irrigation system using a water-soluble compound NPK fertilizer (15-15-15; DIAFILLON NPK 15.15.15., Nuova Sunchemical, Valsamoggia, Italy). The fertilizer was applied at a total seasonal rate of 600 kg ha^{-1}, corresponding to 90 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1}. The total amount was divided into three applications of approximately 200 kg ha^{-1} each, scheduled according to the main phenological stages of the crop: at the beginning of the growing season, before flowering, and during the fruit growth period. The same fertilizer formulation, application rate, and fertigation schedule were applied uniformly to all experimental plots, ensuring comparable nutrient supply conditions among cultivars.

Trees were pruned annually to maintain the open-vase canopy structure and adequate canopy development. Weed management and routine pest and disease control were carried out according to the standard commercial management practices of the orchard and were applied uniformly across all experimental plots. Throughout the experimental period, the trees showed uniform vigor and canopy development, with no visible symptoms of nutrient deficiency or substantial pest or disease damage. Thus, all three cultivars were evaluated under comparable orchard management conditions.

2.2. Climatic Conditions During the Experimental Period

Meteorological data from the Oradea Meteorological Station, which is around 15 km from the experimental orchard, were used to assess climatic conditions for the 2025 growing season. Monthly mean air temperature, mean minimum and maximum air temperatures, and cumulative precipitation were taken into account for the primary vegetative and reproductive phase of nectarine production (March–September 2025). Table 1 shows the meteorological conditions that existed in the study area during the trial season.

Table 1. Climatic conditions recorded in the Oradea area during the 2025 nectarine growing season.

Month	Mean Temperature (°C)	Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Precipitation (mm)
March	9.2	13.9	4.2	84.0
April	12.7	17.8	7.3	9.1
May	13.9	19.3	8.5	35.5
June	23.0	29.8	16.1	8.6
July	23.8	30.3	17.3	44.4
August	23.1	29.8	16.2	21.1
September	19.9	25.0	14.7	30.5

2.3. Experimental Design

The experiment was set up as a randomized complete block design (RCBD), with cultivar serving as the experimental factor. Three nectarine cultivars ('Big Top', 'Venus', and 'Cora') were assessed under the same orchard management conditions. Each cultivar was represented by four biological replicates, resulting in a total of 12 experimental plots. Each experimental plot comprised five adjacent trees; thus, 20 trees per cultivar (60 trees in total) were included in the experimental plots. The two outer trees of each plot were considered border trees and were excluded from sampling to minimize edge effects, while all measurements were performed on the three central trees. Consequently, 12 trees per cultivar (36 trees in total) were used for data collection. Fruit samples were collected at commercial maturity during the 2025 harvest season. To ensure representative sampling, fruits were randomly collected within each replicate from all canopy orientations (north, south, east, and west) and canopy heights. Only healthy, undamaged fruits with uniform commercial maturity were used in the analyses.

2.4. Determination of Fruit Yield and Physical Characteristics

Fruit yield was calculated separately for each experimental tree at commercial maturity. Fruits taken from each experimental unit's three central trees were weighed on a digital platform scale (KERN& SOHN GmbH, Balingen, Germany), and yield was expressed as kg tree^{-1}. The yield per hectare was calculated based on a planting density of 1111 trees per hectare and expressed as t ha^{-1}.

To determine physical fruit characteristics, twenty fruits were randomly selected from each biological replication, yielding a total of eighty fruits per cultivar. Fruits were collected from all canopy orientations and heights to guarantee representative sampling. Only healthy, undamaged fruits with uniform market maturity were included in the analyses.

A digital analytical balance (AS 220.R2, Radwag, Radom, Poland) was used to determine the weight of each individual fruit (±0.01 g). Fruit length and equatorial diameter were measured using a digital caliper (CD-6", Mitutoyo, Corporation, Kawasaki, Japan; ±0.01 mm). Fruit dry matter content was measured using the AOAC Official Method 920.151 [31]. Homogenized fruit samples were dried in a forced-air oven at 65 °C until consistent weight. The method is based on a gravimetric determination of the mass remaining after moisture removal, and dry matter content was expressed as a percentage of the initial fresh sample mass. Dry matter (%) was computed as follows (1):

$$\text{Dry matter (\%)} = \frac{\text{Dry weight}}{\text{Fresh weight}} \times 100 \quad (1)$$

The average fruit weight obtained from each replication was then combined with fruit yield to determine the number of fruits per tree and calculate nutrient removal.

2.5. Determination of Fruit Mineral Composition

For mineral composition analysis, 20 fruits from each biological replicate were used to prepare a composite fruit sample. Fruit samples from each biological replicate were prepared separately for mineral analysis to preserve the independence of the experimental replicates. Before analysis, fruits were thoroughly washed with distilled water to remove any surface contaminants that could interfere with mineral determination. The stones were removed before sample preparation, and mineral analyses were performed on the remaining fruit tissue, comprising the peel and mesocarp. Therefore, the mineral concentrations reported in this study refer specifically to the analyzed fruit tissue and do not include the mineral content of the stone. The peel and mesocarp were subsequently cut into small pieces and homogenized to obtain a representative sample of the analyzed fruit tissue. The homogenized samples were dried in a forced-air oven (Binder GmbH, Tuttlingen, Germany) at 65 °C until constant weight, allowing mineral concentrations to be expressed on a dry-weight basis. After drying, the samples were cooled and ground using a laboratory mill (Grindomix GM 200, Retsch GmbH, Haan, Germany) to obtain a fine, homogeneous powder. The powdered material from each biological replicate was stored separately in clean, sealed containers under dry conditions and analyzed within one week after sample preparation. Aliquots of the homogenized dry material were subsequently used for the determination of total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg).

Total nitrogen (N) concentration was determined using the Kjeldahl method according to AOAC Official Method 978.04 [32]. The method is based on acid digestion of the organic sample with concentrated sulfuric acid (H_2SO_4), converting organic nitrogen into ammonium, followed by alkalization with sodium hydroxide (NaOH) to release ammonia (NH_3). The liberated ammonia was distilled, collected in a boric acid (H_3BO_3) solution, and quantitatively determined by acid titration. The resulting nitrogen content was expressed on a dry-weight basis. To determine phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), 0.50 g of dried sample was microwave-assisted acid digested using a mixture of concentrated nitric acid (HNO_3, 65%) and hydrogen peroxide (H_2O_2, 30%) in closed Teflon vessels according to EPA Method 3052 [33]. Following digestion, the solutions were quantitatively transferred to volumetric flasks and diluted to 50 mL with ultrapure deionized water.

The concentrations of P, K, Ca, and Mg were measured by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (Agilent 5110 ICP-OES, Agilent Technologies Inc., Santa Clara, CA, USA). The analytical principle of ICP-OES is based on the excitation of atoms and ions in an inductively coupled argon plasma, followed by measurement of the characteristic optical emission at element-specific wavelengths. The emission intensity is proportional to the concentration of each element in the sample, and quantitative determination was performed using calibration with certified multi-element standard solutions. Analytical quality was confirmed using reagent blanks, duplicate samples, and certified reference materials evaluated alongside the experimental samples. Mineral concentrations were indicated in grams per kilogram of dry weight (g/kg DW).

All assays were done in triplicate, and the mean value from each biological replicate was used in subsequent descriptive evaluations.

The analytical precision of the determinations was evaluated by calculating the relative standard deviation (RSD), which remained less than 5% for all investigated elements, demonstrating excellent repeatability of the analytical method.

2.6. Calculation of Nutrient Removal

Nutrient removal was estimated using the mineral composition of the analyzed fruit tissue (peel and mesocarp), dry fruit matter content, and marketable yield, following an approach similar to that used in nutrient budgeting studies in perennial fruit crops [34,35]. Nutrient removal was expressed both on a yield basis (kg t^{-1} fresh fruit) and on an orchard basis (kg ha^{-1}), allowing comparisons among cultivars differing in fruit yield and mineral composition.

Because the stones were not included in the mineral analysis, the calculated nutrient removal should be interpreted as estimates based on the analyzed fruit fraction rather than as measurements of the total mineral content of the entire harvested fruit. This methodological limitation was considered when interpreting the results.

The amount of each nutrient removed per tonne of harvested fruit was estimated using Equation (2):

$$NRt = C \times DMf \quad (2)$$

where C is nutrient concentration in fruit dry matter (g kg^{-1} DW) and DMf is the dry matter fraction of the fruit (kg kg^{-1} fresh weight).

Total nutrient removal per hectare was subsequently estimated using Equation (3):

$$NRha = NRt \times Y \quad (3)$$

where NRha is nutrient removal per hectare (kg ha^{-1}) and NR is nutrient removal per tonne of harvested fruit (kg t^{-1}); Y is marketable fruit yield (t ha^{-1}).

Individual calculations were made for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). The resulting nutrient removal values were used to compare cultivar-specific nutrient removal patterns and to explore their potential contribution to nutrient budgeting in intensive nectarine orchards [35,36].

2.7. Statistical Analysis

The experimental data for each of the three nectarine cultivars were summarized using descriptive statistics, such as means and standard deviations. The experiment was set up as a randomized complete block design, with four blocks and one experimental plot for each cultivar. The experimental plot was designated as the unit of replication, and measurements from the three central trees were aggregated at the plot level. The findings were interpreted descriptively to describe the observed patterns in fruit output, fruit weight, dry matter content, mineral composition, and estimated nutrient removal throughout the course of the growing season. No inferential statistical comparisons between cultivars are offered. As a result, the observed variations are interpreted as preliminary descriptive patterns rather than statistically established cultivar effects. Descriptive statistical analyses were performed using Microsoft Excel (Microsoft Excel 365, Microsoft Corporation, Redmond, WA, USA).

2.8. Use of Generative Artificial Intelligence

During the preparation of this manuscript, a generative artificial intelligence tool was used to assist with linguistic refinement and to improve the clarity and readability of the text.

3. Results

3.1. Fruit Yield, Fruit Weight, and Dry Matter Content

Table 2 presents the fruit yield, average fruit weight, and dry matter content of the three nectarine cultivars tested during the 2025 growing season. These measures were utilized to characterize fruit output and specific quality features in the orchard settings studied.

Table 2. Fruit yield, fruit weight, and dry matter content of the three nectarine cultivars.

Cultivar	Yield (t ha^{-1})	Fruit Weight (g)	Dry Matter (%)
Big Top	34.82 ± 1.21	182.6 ± 5.4	13.84 ± 0.36
Venus	31.45 ± 1.08	171.3 ± 4.8	14.91 ± 0.41
Cora	29.74 ± 0.96	163.8 ± 4.5	16.27 ± 0.39

Values are presented as mean ± standard deviation (n = 4 experimental plots per cultivar).

'Big Top' had the highest mean fruit output (34.82 t ha^{-1}) and average fruit weight (182.6 g), whereas 'Cora' had the highest dry matter content (16.27%). 'Venus' displayed intermediate values for all three parameters. Fruit yield and dry matter content showed an inverse relationship among the three cultivars, with higher-yielding cultivars having lower mean dry matter percentages. This trend should be considered as an observation unique to the analyzed growing season, rather than evidence of a statistically established link.

3.2. Fruit Mineral Composition

The mineral composition of the tested nectarine fruit tissues (peel and mesocarp) was distinguished by differences in mean nutrient concentrations across the three cultivars during the 2025 growing season (Table 3).

Table 3. Mineral composition of the analyzed fruit tissue (peel and mesocarp) of the evaluated nectarine cultivars (g kg^{-1} DW).

Cultivar	N	P	K	Ca	Mg
Big Top	10.42 ± 0.24	1.48 ± 0.05	18.74 ± 0.42	1.12 ± 0.04	0.86 ± 0.03
Venus	11.36 ± 0.28	1.63 ± 0.06	20.15 ± 0.48	1.18 ± 0.05	0.92 ± 0.03
Cora	12.61 ± 0.31	1.81 ± 0.07	22.43 ± 0.51	1.36 ± 0.05	1.04 ± 0.04

Values are presented as mean ± standard deviation (n = 4 experimental plots per cultivar). Nutrient concentrations refer to the analyzed fruit tissue on a dry-weight basis.

Potassium was the most abundant macronutrient in the studied fruit tissues of all three cultivars, followed by nitrogen, with phosphorus, calcium, and magnesium in lower amounts. The mean concentrations of all five macronutrients were highest in 'Cora', lowest in 'Big Top', and intermediate in 'Venus'. This descriptive pattern demonstrates differences in fruit mineral composition between the evaluated cultivars under the environmental and orchard management circumstances of the examined growing season. However, these findings do not support independent cultivar effects.

3.3. Nutrient Removal per Tonne of Harvested Fruit

The estimated nutrient removal per ton of harvested fruit was computed for each nectarine cultivar using the mineral concentrations and dry matter content of the studied fruit tissues. The results are shown in Table 4, and they give a descriptive comparison of nutrient quantities linked with fruit output during the investigated growing season.

The estimated nutrient removal per ton of harvested fruit varied across the three assessed cultivars (Table 4). Potassium was the highest estimated nutrient removal component, ranging from 2.59 kg t^{-1} in 'Big Top' to 3.65 kg t^{-1} in 'Cora'. Nitrogen was the second greatest component, estimated at 1.44 to 2.05 kg t^{-1}. 'Cora' had the highest mean estimated removal values for all five macronutrients, followed by 'Big Top' with the lowest and 'Venus' with intermediate amounts. These findings show cultivar-specific trends in estimated nutrient removal per unit of harvested yield, without proving statistically independent cultivar effects.

Table 4. Estimated nutrient removal per tonne of harvested fruit (kg t^{-1} fresh fruit).

Cultivar	N	P	K	Ca	Mg
Big Top	1.44 ± 0.05	0.20 ± 0.01	2.59 ± 0.08	0.15 ± 0.01	0.12 ± 0.01
Venus	1.69 ± 0.06	0.24 ± 0.01	3.00 ± 0.09	0.18 ± 0.01	0.14 ± 0.01
Cora	2.05 ± 0.07	0.29 ± 0.01	3.65 ± 0.11	0.22 ± 0.01	0.17 ± 0.01

Values are presented as mean ± standard deviation (n = 4 experimental plots per cultivar). Nutrient removal values are estimated based on the mineral concentrations and dry matter content of the analyzed fruit tissues.

3.4. Nutrient Removal per Hectare

The estimated nutrient removal per hectare was computed by multiplying the nutrient removal values per ton of harvested fruit by the corresponding fruit yield of each cultivar. Table 5 shows the derived estimations for nitrogen, phosphate, potassium, calcium, and magnesium. These results provide a descriptive assessment of the nutrient quantities related to harvested fruit production under the orchard circumstances studied.

Table 5. Estimated nutrient removal based on the analyzed fruit tissue (kg ha^{-1}).

Cultivar	N	P	K	Ca	Mg
Big Top	50.13 ± 2.08	6.96 ± 0.28	90.16 ± 3.41	5.22 ± 0.24	4.18 ± 0.19
Venus	53.15 ± 1.96	7.55 ± 0.31	94.35 ± 3.26	5.66 ± 0.22	4.40 ± 0.17
Cora	60.97 ± 2.15	8.62 ± 0.33	108.55 ± 3.87	6.54 ± 0.26	5.06 ± 0.21

Values are presented as mean ± standard deviation (n = 4 experimental plots per cultivar). Nutrient removal values represent estimates based on fruit yield and the mineral composition of the analyzed fruit tissues.

The estimated nutrient removal per hectare showed descriptive variation among the three nectarine varieties (Table 5). 'Cora' had the highest mean estimated removal values for all five macronutrients: 60.97 kg N ha^{-1}, 8.62 kg P ha^{-1}, and 108.55 kg K ha^{-1}. In contrast, 'Big Top' had the lowest estimated nutrient removal values despite having the largest fruit yield, while 'Venus' had mostly intermediate values. Potassium was the most significant nutrient removal component across all cultivars, with estimates ranging from 90.16 to 108.55 kg/ha.

4. Discussion

The current study presents a preliminary assessment of fruit yield, dry matter content, mineral composition, and estimated nutrient removal in three nectarine cultivars cultivated under identical orchard management circumstances over a single growing season. The descriptive results revealed varied trends among the cultivars tested. 'Big Top' had the highest mean fruit output and average fruit weight, as well as lower dry matter content and mineral concentrations, whereas 'Cora' had lower productivity but greater dry matter content and macronutrient concentrations. 'Venus' generally displayed intermediate values. Peach and nectarine genotypes vary similarly in terms of productivity and physicochemical features [37]. Previous research on 'Big Top' has also shown the effect of rootstock and growing season on fruit attributes [38]. However, the differences revealed in the current study should not be attributed solely to cultivar, as their expression may be influenced by environmental circumstances, crop load, and fruit ripeness at harvest.

Fruit mineral composition is a significant factor in calculating estimated nutrient removal throughout harvested production. Potassium was the most abundant macronutrient in the studied nectarine fruit tissues, followed by nitrogen, which was consistent with earlier studies of peach and nectarine mineral composition [39,40]. The comparatively

higher mean mineral concentrations observed in 'Cora' may be due to changes in fruit dry matter accumulation and other physiological or environmental variables. However, nutrient buildup in fruit is influenced by a number of interconnected processes, including nutrient availability in the soil, root uptake, transit within the plant, and allocation to developing fruits. Soil physicochemical parameters, particularly pH and other chemical variables, might influence nutrient availability and plant absorption [41]. Furthermore, interactions between potassium, calcium, and magnesium may impact their relative concentrations in plant tissues [42]. Because comprehensive soil nutrient availability, leaf mineral composition, and whole-tree nutrient uptake were not examined in the current investigation, these pathways remain plausible explanations rather than experimentally confirmed causes. Similarly, the observed relationship between increased fruit yield and lower mineral concentrations in 'Big Top' may be consistent with a dilution-related pattern, but the available measurements do not allow for confirmation of a physiological dilution process.

Estimating nutrient removal per ton of harvested fruit provides a consistent depiction of the nutrient quantities involved in fruit production. These estimations include the dry matter content and mineral concentrations used in the calculation; therefore, they differ between cultivars based on the observed parameters of the investigated fruit tissues. In the current study, 'Cora' had the highest estimated removal per ton for all five macronutrients, including about 42% more nitrogen removal and 41% more potassium removal than 'Big Top'. A previous study on peach production has indicated nitrogen removal values of roughly 2.7 kg t^{-1} of harvested fruit [43], which exceed the range estimated in this analysis. Such discrepancies could be attributed to cultivar traits, growing conditions, crop load, analytical methodologies, and the fruit components used in nutritional assays. Research on nutrient fluxes in perennial orchard systems has also highlighted the importance of harvested biomass as a nutrient export channel [44].

When estimated nutrient removal was reported per hectare, the observed trends mirrored a mix of nutrient removal per ton and total harvested yield. Although 'Big Top' had the highest mean fruit output, it also had the lowest estimated nutrient removal per hectare for the five macronutrients studied. In contrast, 'Cora' had the highest estimated nutrient removal per hectare despite its lower yield. These differences are due to the yield and fruit composition values employed in the calculation, and should not be regarded as proof of statistically established cultivar impacts. Previous research has investigated the impact of orchard management and fruit characteristics on nutrient-related processes in peach production [45], whereas nutrient-flow assessments in apple orchards have demonstrated the importance of considering harvested products as part of the larger orchard nutrient system [46]. In this context, the current data indicate the descriptive utility of assessing fruit composition and yield, even though they do not establish independent contributions or causal linkages.

The differing productive and compositional traits revealed among the three cultivars can also be viewed in the context of multivariate variation reported for peach and nectarine germplasm [47,48]. However, the current dataset is analyzed descriptively, with no reliance on multivariate statistical separation to identify unique cultivar groups. The observed connections between yield, dry matter content, mineral concentration, and estimated nutrient elimination should be viewed as early patterns that must be confirmed through additional experimental observations. The estimated nutrient removal, for example, incorporates fruit composition and collected biomass, and this quantitative link should not be given as an independently established physiological mechanism.

From an orchard nutrient management standpoint, the estimated quantities of nutrients linked with harvested fruit may provide further information for analyzing nutrient exports. However, nutrient removal by fruit harvest does not equate to fertilizer consump-

tion. A perennial orchard's nutrient balance includes soil nutrient reserves, fertilizer inputs, nutrient uptake and buildup in vegetative and perennial organs, internal nutrient remobilization, and nutrient recycling via non-harvested plant material.

Studies on nutrient inputs and outputs in orchard systems have highlighted the complexities of nutrient budgeting [49]. Isotopic nitrogen tracing studies in peach trees have also shown that fertilizer-derived nitrogen accounts for just a portion of the nitrogen recovered by trees, emphasizing the relevance of both internal and external nutrient sources [50]. These factors highlight the importance of integrating harvested fruit nutrient removal with soil and leaf analysis, fertilizer efficiency, and nutrient cycling for establishing complete orchard nutrient-management plans.

Several limitations should be acknowledged when interpreting the present findings. First, this investigation represents a preliminary study conducted during a single growing season at one commercial orchard site. Consequently, the observed patterns are specific to the meteorological, agronomic, and physiological conditions of the 2025 season and cannot be generalized across years or production environments without further validation. Second, crop load and fruit maturity at harvest were not independently quantified as explanatory variables, limiting the ability to distinguish cultivar-associated differences from the potential effects of fruit developmental stage or crop load. Third, although the experiment was organized into four blocks, the original plot-level observations required for a retrospective statistical analysis incorporating block effects were not recoverable. Therefore, the results are presented descriptively, without inferential conclusions regarding cultivar differences. Furthermore, comprehensive soil nutrient availability, leaf mineral status, irrigation water nutrient contributions, and nutrient accumulation in perennial tree organs were not assessed.

An additional methodological limitation concerns the estimation of nutrient removal through harvested fruit. Mineral concentrations were determined in the peel and mesocarp, whereas fruit stones were excluded from chemical analysis. Consequently, the reported estimates are based on the mineral composition of the analyzed fruit tissues and do not represent complete whole-fruit nutrient removal. The absence of separate measurements of stone biomass and mineral composition further limits the accuracy of these estimates. Importantly, the observed patterns cannot be used to establish cultivar-specific fertilizer requirements or to optimize fertilization rates, since harvested fruit nutrient removal represents only one component of the overall orchard nutrient balance.

Future research should therefore include multiple growing seasons, comprehensive fruit mineral analyses, detailed soil and leaf nutrient assessments, and statistical analyses appropriate to the experimental design. Such investigations are necessary to validate the preliminary findings and provide a more reliable scientific basis for developing sustainable nutrient-management strategies in intensive nectarine orchards.

5. Conclusions

The current preliminary investigation found descriptive variations in fruit yield, dry matter content, mineral composition, and estimated nutrient removal across three nectarine cultivars tested throughout a single growing season. 'Big Top' had the highest mean fruit yield and average fruit weight, but comparatively lower dry matter content and mineral concentrations, whereas 'Cora' had lower productivity but higher dry matter content and concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). 'Venus' generally displayed intermediate values. These trends were also evident in the estimated nutrient removal per ton and per hectare of harvested fruit, with 'Cora' having the highest mean estimations for all five macronutrients.

The findings illustrate the relevance of considering both fruit mineral composition and yield when estimating nutrient removal from nectarine orchards. However, these results should be interpreted strictly as preliminary observations obtained during a single growing season at one commercial orchard site and do not establish statistically significant cultivar effects or support cultivar-specific fertilization optimization. Furthermore, the nutrient removal estimates were based on mineral analyses of the peel and mesocarp, excluding fruit stones, and therefore do not represent complete whole-fruit nutrient removal. Additional investigations conducted over multiple growing seasons, incorporating comprehensive fruit, soil, and plant nutrient assessments and appropriate plot-level statistical analyses, are necessary to validate the observed patterns and determine their potential contribution to sustainable nutrient management in intensive nectarine orchards.

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