# Dynamic Interplay: Seasonal Variation and Growth Stage-Dependent Nutrient Dynamics in Grapevine Physiology and Their Implications for Fruit Quality and Yield Optimisation

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**This study investigated the variation in nutrient content in grape petioles and berries throughout the growing season. Seasonal variation and stage-wise changes in grape fruit yield and quality were correlated with a corresponding nutrient concentration in the plants and berries. The results show that, among medium vines, Perlette exhibited lower plant and fruit characteristics than Anab-e-Shahi. Among the growth stages, the highest was noticed in D9 and the lowest in $D_1$. The study of grapevine development and nutrient dynamics provides a comprehensive understanding of the intricate relationship between vegetative growth and fruit development, offering crucial insights into factors that significantly affect grape quality and yield. The analysis of key parameters such as shoot length, trunk girth, and fruit dimensions, along with the dynamics of fruit weight and number, emphasises the importance of early-season growth and its overarching influence on overall vine productivity. Varietal distinctions, notably between Anab-e-Shahi and Perlette, manifest in unique growth patterns and fruit characteristics. In addition, the investigation delves into the temporal progression of sugar content, identifying a pivotal phase marked by rapid escalation followed by a subsequent decline. The study extends its scope to nutrient dynamics, exemplified by alterations in nitrogen, phosphorus and potassium concentrations in leaf petioles, further enriching the holistic comprehension of grapevine physiology. The cumulative findings offer valuable insights for vineyard management practices aiming to optimise grape quality and yield.**

## INTRODUCTION

Grapes, scientifically known as *Vitis vinifera* L., are a significant commercial fruit crop in temperate and tropical regions (Arrobas *et al*., 2014). Their importance in agriculture is evident, as they rank among the most widely cultivated fruits alongside citrus and banana. Viticulture is a highly profitable agricultural venture, and its long-term success hinges on achieving consistent yields and high-quality harvests. Vine reproductive development processes are sensitive to environmental factors, such as light and temperature, which significantly influence inflorescence initiation and vary by cultivar (Buttrose, 1970; Sánchez & Dokoozlian, 2005).

Several factors influence vine performance, with soil fertilisation and maintaining balanced plant nutrition being crucial among them. Globally, the assessment of soil nutrients through analysis serves as a key indicator, with documented values primarily linked to the growth and yield of the cultivated crops (Biddoccu *et al*., 2016). However, for perennial plants like grapevines, it is essential to go beyond soil analysis alone and include leaf and fruit analysis. This necessity arises because grapevines exhibit higher rates of dry matter and nutrient accumulation and occupy a larger volume of soil than annual crops (Brunetto *et al*., 2016; Kumar *et al*., 2022). As a result, fruit-bearing plants achieve a degree of nutritional stability during their mature phase, which allows for the utilisation of leaf and fruit composition to adjust and optimise fertilisation.

The changes in growth and yield based on phenology relate to all the alterations in plant development and productivity across different growth stages. Understanding the relationship between phenological variations and nutrients involves recognising how changes in the growth stages of plants affect their nutrient needs and usage. As plants go through different phenological phases, their nutritional requirements can change, affecting the efficiency of nutrient uptake and utilisation.

## MATERIALS AND METHODS

The experiment was conducted on two grape varieties, Perlette and Anab-e-Shahi, at the experimental vineyards of the Division of Fruit Science, SKUAST-K. The farm is situated at an elevation of 1 570 meters above mean sea level, located between 34° 75' North latitude and 74° 50' East longitude (see Fig. 1). The cultural operations for the

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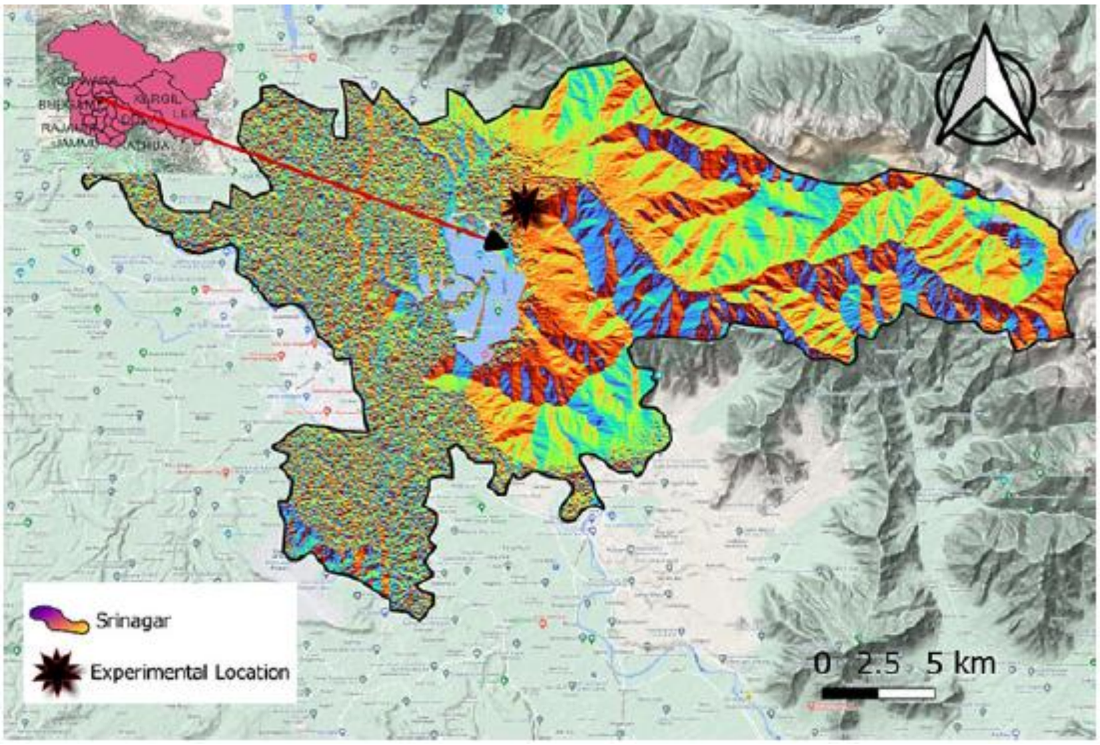


FIGURE 1
Map of study area

experimental trees were performed following the standard recommended practices, including a recommended fertilisation programme. The preliminary analysis of orchard soil indicated an optimum status of all the nutrients. The pH of the soil was 6.7, measured with the help of a pH meter using soil to water in the ratio of 1:2, while electrical conductivity (EC) and soil organic carbon (OC) were 0.27 ds $m^{-1}$ and 0.75 %, respectively. For fruit analysis, a composite sample of 25 g of berries per treatment was collected at 15-day intervals from 15 June until maturity and evaluated for various characteristics accordingly. The nitrogen content of the berries and leaves was quantified using the Kjeldahl method, as described by Subbaih and Asija (1956). To assess the concentrations of phosphorus (P) and potassium (K), a 0.5 g sample of both fruit and leaves was subjected to digestion in a 10 ml di-acid mixture composed of nitric acid and perchloric acid in a 9:4 ratio. The digestion process was conducted on a hot plate, maintaining a temperature between 115°C and 118°C. Following digestion, the resultant sample was filtered and subsequently diluted with double-distilled water to achieve a final volume of 50 ml. The phosphorus concentration was determined through the use of ammonium molybdate and ammonium metavanadate, with transmittance and absorbance measured at a wavelength of 420 nm, employing a blue filter for clarity. The potassium concentration of the berries and petiole was determined with flame photometry using a flame photometer (UK).

Shoot length, trunk girth, fruit length and breadth were measured using measuring tapes and Vernier callipers, respectively. The TSS was measured with a hand refractometer. Total titratable acidity and total sugars were determined as per the methodology given by the AOAC (1980) (Khalil *et al*., 2023). The statistical methods described by Gomez and Gomez (1976) were followed to analyse and interpret the data using corrplot with factor-wise correlation coefficients, scatterplots, and principal component analysis. The test of significance was done with a 5% level of significance. Statistical analysis and plotting was done in R software.

## RESULTS AND DISCUSSION

### Vegetative growth and fruit development grapevines during the growing season

Table 1 illustrates the evolving shoot length of medium- and low-yielding vines. The progression in shoot length exhibited a characteristic single sigmoidal growth pattern. During the early season, encompassing the fruit set period until 1 June, medium vines saw this phase contributing 59.96% to the total shoot growth. In contrast, low-yielding vines experienced a higher contribution of 76.50%. This resulted in low-yielding vines exhibiting approximately 17% more growth in the early season than their medium-yielding counterparts, ultimately reducing fruit set.

Examining the data in the table further, it is evident that, in medium-yielding vines of the Perlette variety, 63.56% of total shoot growth occurred until 1 June, corresponding to the bloom and fruit-set period. In contrast, low-yielding vines of the same variety recorded 80.53% of total shoot growth during this season. For the Anab-e-Shahi cultivar, 56.71% of total shoot growth took place until fruit set in medium-yielding vines, while low-yielding vines of the same cultivar exhibited 73.63% of total shoot growth during


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the corresponding growth period.

Upon careful examination of Tables 1 and 6, a distinct inverse relationship becomes apparent between vegetative growth and the number of fruits per cluster. Furthermore, Anab-e-Shahi demonstrated a higher growth rate compared to Perlette in the latter part of the season, contributing to a more significant drop in berries in Anab-e-Shahi. Both grape cultivars under study exhibited a single sigmoidal growth pattern.

The data provided in Table 2 show no significant change in incremental growth over the growing season of the grapevines. However, noteworthy growth in trunk girth was observed only after fruit set in both cultivars. A close examination of the data reveals that medium-yielding vines

TABLE 1
Periodical variation in shoot growth (cm) in grapevines during the growing season

| Sampling dates | Medium vines | | | Low-yielding vines | | |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_1$ | 8.91 | 7.05 | 7.98 | 5.83 | 5.07 | 5.45 |
| $D_2$ | 34.32 | 37.68 | 36.00 | 50.60 | 47.69 | 49.15 |
| $D_3$ | 190.46 | 188.21 | 189.34 | 272.35 | 256.16 | 264.26 |
| $D_4$ | 275.45 | 277.37 | 276.41 | 293.60 | 298.65 | 296.13 |
| $D_5$ | 288.19 | 317.05 | 302.62 | 307.84 | 314.71 | 311.28 |
| $D_6$ | 294.40 | 325.52 | 309.96 | 322.16 | 324.18 | 323.17 |
| $D_7$ | 296.09 | 327.61 | 311.85 | 332.74 | 332.14 | 332.48 |
| $D_8$ | 297.69 | 330.55 | 314.12 | 335.17 | 340.12 | 337.65 |
| $D_9$ | 299.61 | 331.84 | 315.73 | 338.16 | 352.65 | 345.41 |
| Mean | 226.10 | 237.70 | 231.90 | 250.90 | 252.40 | 251.70 |
| CD $_{(P \leq 0.05)}$ | Dates = 7.52<br>Varieties = 6.59<br>Dates × varieties = 8.32 | | | Dates = 9.52<br>Varieties = 8.23<br>Dates × varieties = 10.32 | | |

CD = critical difference
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

TABLE 2
Periodical variation of trunk girth (cm) in grapevines during growing season

| Sampling dates | Medium vines | | | Low-yielding vines | | |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_1$ | 40.21 | 42.59 | 41.40 | 29.92 | 30.12 | 30.02 |
| $D_2$ | 40.21 | 42.59 | 41.40 | 29.92 | 30.12 | 30.02 |
| $D_3$ | 40.21 | 42.59 | 41.40 | 29.92 | 30.12 | 30.02 |
| $D_4$ | 40.33 | 42.66 | 41.50 | 30.03 | 30.21 | 30.12 |
| $D_5$ | 40.43 | 42.79 | 41.61 | 30.11 | 30.31 | 30.21 |
| $D_6$ | 40.57 | 43.01 | 41.79 | 30.21 | 30.42 | 30.32 |
| $D_7$ | 40.84 | 43.25 | 42.05 | 30.44 | 30.70 | 30.57 |
| $D_8$ | 40.86 | 43.31 | 42.09 | 30.45 | 30.73 | 30.59 |
| $D_9$ | 40.86 | 43.31 | 42.09 | 30.45 | 30.73 | 30.59 |
| Mean | 40.50 | 42.90 | 41.70 | 30.16 | 30.38 | 30.27 |
| CD $_{(P \leq 0.05)}$ | Dates = NS<br>Varieties = NS<br>Dates × varieties = NS | | | Dates = NS<br>Varieties = NS<br>Dates × varieties = NS | | |

CD = critical difference; NS = not significant
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

consistently exhibited higher trunk girth throughout the growing season than low-yielding vines.

Table 3 and Fig. 2 present the periodic variation in fruit length (cm) during grape berry development in the growing season. The data indicate a rapid increase in fruit length for both medium- and low-yielding vines until 1 July. Notably, low-yielding vines had a higher rate of increase compared to medium-yielding vines. However, there was a significant decline in the rate of increase for low-yielding vines after 1 July, continuing until 15 July. In contrast, medium-yielding vines experienced a less pronounced decrease in their rate of increase during this period. Subsequently, fruit length continued to increase until harvest, although the rate of increase gradually declined. In July, we observe a significant drop in the rate of fruit length growth, creating a characteristic double sigmoidal pattern. This intriguing pattern, illustrated in Fig. 3, highlights the complex dynamics of fruit development during this period, showcasing the fluctuations in growth rates as they respond to environmental factors. Medium-yielding vines showed 91.75% of total fruit length growth until véraison (1 August), while low-yielding vines showed 94.93%. Although the growth pattern was

TABLE 3
Periodical variation in fruit length (cm) of grape berries during fruit development in the growing season

| Sampling dates | Medium vines | | | Low-yielding vines | | |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_4$ | 0.38 | 0.34 | 0.36 | 0.24 | 0.17 | 0.21 |
| $D_5$ | 1.13 | 1.16 | 1.16 | 0.97 | 0.90 | 0.94 |
| $D_6$ | 1.21 | 1.27 | 1.27 | 1.05 | 1.09 | 1.07 |
| $D_7$ | 1.62 | 1.67 | 1.67 | 1.36 | 1.63 | 1.50 |
| $D_8$ | 1.65 | 1.74 | 1.74 | 1.41 | 1.69 | 1.55 |
| $D_9$ | 1.70 | 1.82 | 1.82 | 1.43 | 1.72 | 1.58 |
| Mean | 1.28 | 1.33 | 1.33 | 1.07 | 1.20 | 1.14 |
| CD $_{(P \leq 0.05)}$ | Dates = 0.083<br>Varieties = 0.042<br>Dates × varieties = 0.091 | | | Dates = 0.081<br>Varieties = 0.063<br>Dates × varieties = 0.072 | | |

CD = critical difference

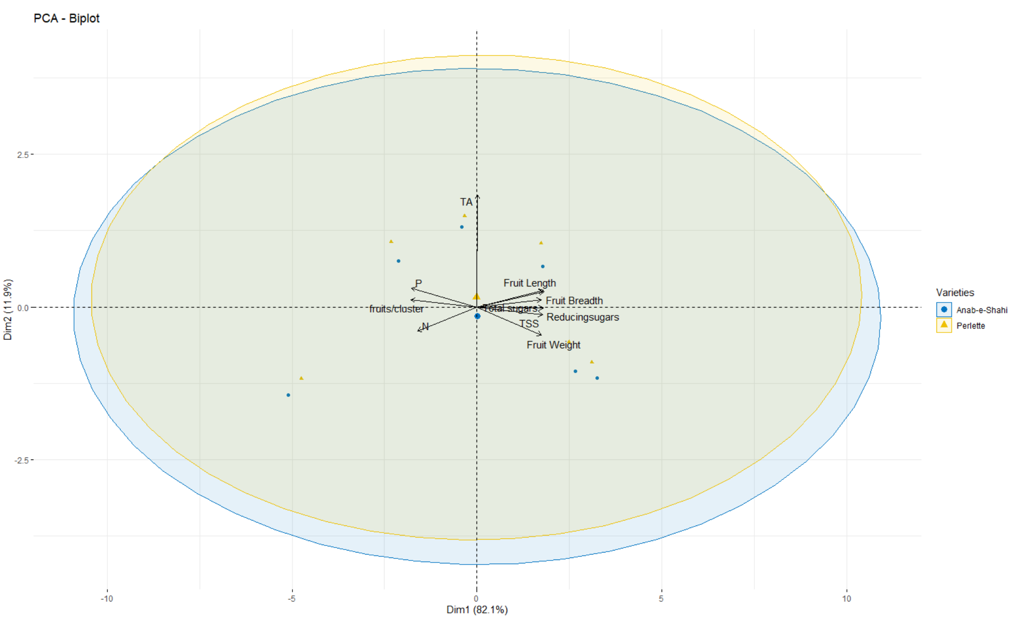


FIGURE 2
Fruit quality parameters and PCA analysis

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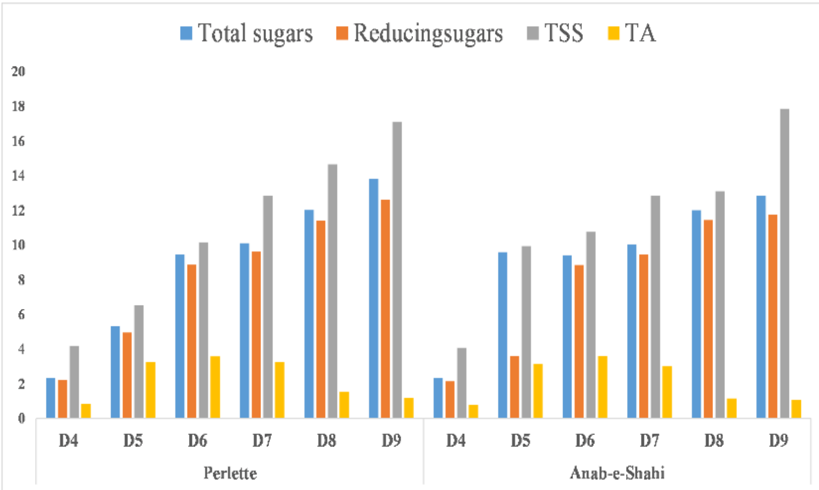


FIGURE 3
Correlation between fruit growth and quality, and plant nutrition

similar in both grape cultivars, the decline in the growth rate was less marked in Perlette compared to Anab-e-Shahi. The growth in fruit length observed until 1 August was 95.29% for medium-yielding vines of Perlette and 88.29% for Anab-e-Shahi. For low-yielding vines, the corresponding growth rates were 94.10% for Perlette and 94.70% for Anab-e-Shahi. At the time of harvest, the total fruit length was greater for Anab-e-Shahi, measuring 1.93 cm, in contrast to 1.70 cm for Perlette.

Table 4 illustrates the dynamics of berry fruit breadth, demonstrating a double sigmoidal growth pattern. Initially, the rate of increase in berry fruit breadth accelerated, but then showed signs of slowdown between 1 July and 15 July. Following this period, the growth rate increased again, stabilising as harvest approached for both medium- and low-yielding vines. Medium-yielding vines achieved a 91.18% increase in fruit breadth, while low-yielding vines reached a 97.29% increase by véraison (1 August/D7), with gradual growth continuing thereafter. Earlier in the season, low-yielding vines showed a higher rate of increase compared to medium vines. However, in the later part of the season, medium vines exhibited a higher rate of increase than low-yielding vines. The interaction effects of the varieties and sampling dates indicated a similar double sigmoidal growth pattern for both varieties. Notably, in medium vines, Perlette recorded a greater fruit breadth (1.60 cm) than Anab-e-Shahi (1.57 cm). The double sigmoidal growth pattern was more pronounced in Anab-e-Shahi compared to Perlette. Before véraison, the increase in fruit breadth was 90.62% for medium-yielding vines of Perlette and 97.88% for Anab-e-Shahi. For low-yielding vines, the growth in fruit breadth until 1 August (D7) reached 93.63% for Perlette and 96.63% for Anab-e-Shahi.

The growth of berries is illustrated quantitatively in Table 5, showcasing the increase in average fruit weight over time. This increase follows a characteristic double sigmoidal curve pattern. Notably, fruit weight accumulation prior to véraison (1 August/D7) accounted for 82.35% in medium-yielding vines and 81.70% in low-yielding vines. The initial phase of growth exhibited the highest rate of increase, which began to decline from 1 July to 15 July. However, a resurgence in growth was observed between 15 July and 1 August, followed by another decline thereafter.

In terms of specific cultivars, Perlette and Anab-e-Shahi displayed similar fruit weight growth patterns. Nevertheless, Anab-e-Shahi achieved a greater final fruit weight, measuring 1.81 grams, compared to Perlette, which reached 1.58 grams. The period from 1 August to 15 August was particularly crucial for Anab-e-Shahi, as it experienced a significant weight gain, leading to a higher total fruit weight at harvest. While Perlette accounted for 84.81% of its total weight by véraison across both medium- and low-yielding vines, Anab-e-Shahi accumulated slightly less, at 80.11%, during the same timeframe in similar vine categories. Table 6 reveals that low-yielding vines consistently produced fewer fruits per cluster than medium-yielding vines during the sampling period. The decline in fruit count was similar for both cultivars in the medium- and low-yielding vines. However, post-fruit set counts were notably lower in low-yielding vines. Anab-e-Shahi had more fruits (166.67 in medium- and 143.17 in low-yielding vines) after fruit set, but fewer at harvest (154.61 in medium- and 135.27 in low-yielding vines) compared to Perlette. The highest berry drop occurred in July, and the variation in fruit numbers is linked to differences in vegetative growth.

The fruit set in medium-yielding grapevines was 38.42%, with Perlette and Anab-e-Shahi showing values of 38.50% and 38.58%, respectively. Low-yielding vines had a mean fruit set of 33.41%, with Perlette and Anab-e-Shahi at 33.75% and 33.10%, respectively. The sugar content increased most significantly between 15 June and 1 July, reaching a concentration of 13.33% at maturity. Perlette had the highest sugar content, of 13.81% at maturity, while Anab-e-Shahi reached 12.85%. Reducing sugar content in berries rose rapidly until véraison and peaked from 1 to 15 July. Perlette's reducing sugar content grew from 2.21% on 1 June to 12.60% by the last sampling date, while Anab-e-Shahi showed a similar pattern, with a maximum of 11%.

TABLE 4
Periodical variation in fruit breadth (cm) of grape berries during fruit development in the growing season

| Sampling dates | Medium vines | | | Low-yielding vines | | |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_4$ | 0.41 | 0.32 | 0.37 | 0.20 | 0.25 | 0.23 |
| $D_5$ | 1.01 | 1.00 | 1.01 | 0.94 | 0.97 | 0.96 |
| $D_6$ | 1.12 | 1.15 | 1.14 | 1.00 | 1.09 | 1.05 |
| $D_7$ | 1.45 | 1.47 | 1.46 | 1.39 | 1.49 | 1.44 |
| $D_8$ | 1.54 | 1.53 | 1.53 | 1.42 | 1.52 | 1.47 |
| $D_9$ | 1.60 | 1.57 | 1.59 | 1.42 | 1.54 | 1.48 |
| Mean | 1.19 | 1.17 | 1.18 | 1.06 | 1.14 | 1.10 |
| CD $_{(P \leq 0.05)}$ | Dates = 0.072<br>Varieties = 0.012<br>Dates × varieties = 0.073 | | | Dates = 0.063<br>Varieties = 0.015<br>Dates × varieties = 0.065 | | |

CD = critical difference
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

TABLE 5
Periodical variation in fruit weight (g) of grape berries during fruit development in the growing season

| Sampling dates | Medium vines | | | Low-yielding vines | | |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_4$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $D_5$ | 0.32 | 0.32 | 0.32 | 0.29 | 0.25 | 0.27 |
| $D_6$ | 0.41 | 0.40 | 0.41 | 0.38 | 0.30 | 0.34 |
| $D_7$ | 1.34 | 1.45 | 1.40 | 1.31 | 1.38 | 1.34 |
| $D_8$ | 1.53 | 1.72 | 1.63 | 1.46 | 1.66 | 1.56 |
| $D_9$ | 1.58 | 1.81 | 1.70 | 1.53 | 1.74 | 1.64 |
| Mean | 0.86 | 0.95 | 0.91 | 0.83 | 0.89 | 0.86 |
| CD $_{(P \leq 0.05)}$ | Dates = 0.147<br>Varieties = 0.093<br>Dates × varieties = 0.148 | | | Dates = 0.149<br>Varieties = 0.052<br>Dates × varieties = 0.152 | | |

CD = critical difference
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

The study indicated significant variations in plant growth metrics across different stages and vine types.

**Periodic variation in fruit quality parameters of developing berries of grapes during the growing season**

The information regarding the change in total soluble solids (TSS) is detailed in Table 8 and Fig. 3. The data illustrate that, during the rapid enlargement phase of berries, which extends up to 60 days after flowering, there was a slight increase in TSS. Following this initial period, the TSS content in the berries experienced a sudden increase, reaching 17.48 °Brix at the mature stage. The rate of TSS increase persisted throughout the sampling period, with a minor decline observed between 45 to 60 days after flowering (corresponding to D6 to D7, 15 July to 1 August). The peak rate of TSS elevation occurred from D8 to D9, representing the maturity stage.

In addition, the cultivar Perlette demonstrated a TSS content of 17.10 °Brix at the mature stage on D9 (30 August), following a pattern similar to Anab-e-Shahi regarding the increase in TSS content throughout the season. However, Anab-e-Shahi showed a slightly higher TSS content at the mature stage, i.e., 17.85 °Brix on 30 August (D9). Regarding the titratable acidity of the grape berries, acidity showed a rapid increase up to 60 to 65 days after flowering, aligning with the period of rapid berry growth (as presented in Table 8 and Fig. 3). Maturity was linked to a significant decrease in acidity levels. The highest total acidity percentage, measured

TABLE 6
Periodical variation in number of fruits/cluster in grapevines during growing season

| Sampling dates | Medium vines | | | Low-yielding vines | | |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_4$ | 154.61 | 166.67 | 160.64 | 135.27 | 143.17 | 139.22 |
| $D_5$ | 142.49 | 159.73 | 151.11 | 130.52 | 129.73 | 130.13 |
| $D_6$ | 115.13 | 119.21 | 117.17 | 103.64 | 106.21 | 104.93 |
| $D_7$ | 96.28 | 96.72 | 96.50 | 78.33 | 79.72 | 79.03 |
| $D_8$ | 89.23 | 86.72 | 87.98 | 74.23 | 73.72 | 73.98 |
| $D_9$ | 87.18 | 81.18 | 84.18 | 71.68 | 67.18 | 69.43 |
| Mean | 114.20 | 118.40 | 116.30 | 98.90 | 100.00 | 99.50 |
| CD $_{(P \leq 0.05)}$ | Dates = 5.701<br>Varieties = 4.102<br>Dates × varieties = 6.405 | | | Dates = 3.701<br>Varieties = 3.102<br>Dates × varieties = 4.405 | | |

CD = critical difference
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

TABLE 7
Periodical variation in total sugars and reducing sugars in developing berries of grapes during the growing season

| Sampling dates | Total sugars (%) | | | Reducing sugars (%) | | |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_4$ | 2.35 | 2.33 | 2.34 | 2.21 | 2.15 | 2.18 |
| $D_5$ | 5.32 | 9.59 | 7.46 | 4.96 | 3.61 | 4.29 |
| $D_6$ | 9.44 | 9.40 | 9.42 | 8.87 | 8.85 | 8.86 |
| $D_7$ | 10.11 | 10.03 | 10.07 | 9.63 | 9.45 | 9.54 |
| $D_8$ | 12.02 | 12.01 | 12.02 | 11.41 | 11.45 | 11.43 |
| $D_9$ | 13.81 | 12.85 | 13.33 | 12.60 | 11.76 | 12.18 |
| Mean | 8.84 | 9.37 | 9.11 | 8.28 | 7.88 | 8.08 |
| CD $_{(P \leq 0.05)}$ | Dates = 1.523<br>Varieties = 1.032<br>Dates × varieties = 1.592 | | | Dates = 0.901<br>Varieties = 1.012<br>Dates × varieties = 0.923 | | |

CD = critical difference
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

at 3.60%, was recorded on 15 July (D6), while the lowest, at 0.83%, was observed on 15 June (D4).

In Perlette grapes, the acid content increased rapidly until 20 days after fruit set (D4/15 June), similarly to what was seen in Anab-e-Shahi grapes. Following this initial increase, a gradual rise in acidity was noted until 15 July (D6), after which there was a sharp decline leading up to maturity. At maturity, Perlette had a higher titratable acidity of 1.21%, compared to Anab-e-Shahi's 1.09%. Total and reducing sugars in the berries started to increase about 45 days after anthesis and continued until harvest. Fruit quality parameters are recorded during the growing season, and different types of vines conform to total sugars (Muñoz-Robredo et al., 2011), reducing sugars (Fernández-Novales et al., 2009), and total soluble solids (Torchio et al., 2010).

**Periodic variation in primary nutrients in leaf petioles of grapevines during the growing season**

The data presented in Table 9 demonstrate a consistent decline in the average nitrogen (N) content of grape petioles throughout the leaf-sampling period, with a decrease from 1.37% on 1 May (D1) to 0.76% on the final sampling date of 30 August. Notably, stability in the mean N content was observed from 1 June to 15 June (D3 to D4), 15 July to 1 August (D6 to D7), and during the month of August. Both grape cultivars exhibited a downward trend in N content throughout the sampling period, with the highest N levels recorded on the initial sampling date (1.35% in Perlette and 1.38% in Anab-e-Shahi). A slight, yet non-significant, increase in petiole N was noted on 15 August and 30 August for both cultivars. The lowest N content was documented at

0.74% for Perlette and 0.77% for Anab-e-Shahi on 30 August (D9). Cultivar Perlette demonstrated stability in petiole N content from 1 June to 15 June and from 15 August to 30 August.

An analysis of the data in Table 9 reveals a distinct pattern in the mean phosphorus (P) content of the grape petioles. During the initial growth period, the petiole P content increased from 1 May to 15 May (D1 to D2), reaching a peak of 0.34% on 15 May (D2). Thereafter, a non-significant decrease in mean P content was observed between 1 June and 15 June, 1 July and 15 July, and throughout the month of August. No change in petiole P content was detected from 15 August to 30 August (D8 to D9). In terms of periodic variation in petiole P content across grape cultivars, the highest P content occurred on 15 May, recording values of 0.35% in Perlette and 0.32% in Anab-e-Shahi. However, petiole P content experienced a continuous decline from 15 May onward, reaching its lowest point on 30 August (D9). Cultivar Perlette exhibited stability in petiole P content from 1 June to 15 June, 1 July to 15 July, and throughout August,

TABLE 8
Periodical variation in total soluble solids and titratable acidity in developing berries of grapes during the growing season

| Sampling dates | Total soluble solids ($^o$ Brix) | | Mean ($^o$Brix) | Titratable Acidity (% Tartaric acid) | | Mean (% Tartaric acid) |
|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | | Perlette | Anab-e-Shahi | |
| $D_4$ | 4.18 | 4.08 | 4.13 | 0.86 | 0.80 | 0.83 |
| $D_5$ | 6.52 | 9.94 | 8.23 | 3.25 | 3.15 | 3.20 |
| $D_6$ | 10.15 | 10.76 | 10.45 | 3.58 | 3.61 | 3.60 |
| $D_7$ | 12.84 | 12.86 | 12.84 | 3.25 | 3.01 | 3.13 |
| $D_8$ | 14.65 | 13.10 | 13.87 | 1.56 | 1.16 | 1.34 |
| $D_9$ | 17.10 | 17.85 | 17.48 | 1.21 | 1.09 | 1.20 |
| Mean | 10.90 | 11.43 | 10.66 | 2.28 | 2.13 | 2.21 |
| CD $_{(P \leq 0.05)}$ | Dates = 0.412<br>Varieties = 0.324<br>Dates × varieties = 0.456 | | | Dates = 0.162<br>Varieties = 0.132<br>Dates × varieties = 0.169 | | |

CD = critical difference
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

TABLE 9
Periodical variation in primary nutrients in leaf petioles of grapevines during the growing season

| Sampling dates | N (%) | | | P (%) | | | K (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean | Perlette | Anab-e-Shahi | Mean |
| $D_1$ | 1.35 | 1.38 | 1.37 | 0.31 | 0.29 | 0.30 | 2.35 | 2.28 | 2.32 |
| $D_2$ | 1.25 | 1.32 | 1.29 | 0.35 | 0.32 | 0.34 | 2.75 | 2.68 | 2.72 |
| $D_3$ | 1.13 | 1.27 | 1.20 | 0.29 | 0.29 | 0.29 | 2.84 | 2.88 | 2.86 |
| $D_4$ | 1.05 | 1.18 | 1.12 | 0.27 | 0.25 | 0.26 | 2.28 | 2.25 | 2.27 |
| $D_5$ | 0.94 | 1.13 | 1.03 | 0.23 | 0.20 | 0.22 | 2.23 | 2.15 | 2.19 |
| $D_6$ | 0.74 | 0.89 | 0.82 | 0.21 | 0.19 | 0.20 | 2.13 | 2.08 | 2.11 |
| $D_7$ | 0.62 | 0.71 | 0.67 | 0.16 | 0.14 | 0.15 | 1.94 | 1.90 | 1.92 |
| $D_8$ | 0.72 | 0.76 | 0.74 | 0.13 | 0.10 | 0.12 | 1.77 | 1.63 | 1.70 |
| $D_9$ | 0.74 | 0.77 | 0.76 | 0.12 | 0.11 | 0.12 | 1.63 | 1.53 | 1.58 |
| Mean | 0.95 | 1.04 | 1.00 | 0.23 | 0.21 | 0.22 | 2.21 | 2.15 | 2.18 |
| CD $_{(P \leq 0.05)}$ | Dates = 0.078<br>Varieties = 0.069<br>Dates × varieties = 0.089 | | | Dates = 0.031<br>Varieties = 0.024<br>Dates × varieties = 0.032 | | | Dates = 0.078<br>Varieties = 0.064<br>Dates × varieties = 0.082 | | |

CD = critical difference
D1 – 1 May; D2 – 15 May; D3 – 1 June; D4 – 15 June; D5 – 1 July; D6 – 15 July; D7 – 1 August; D8 – 15 August; D9 – 30 August

whereas Anab-e-Shahi displayed minimal variation from 1 July to 15 July and from 15 August to 30 August.

The data illustrated in Table 9 indicate that the concentration of potassium (K) in petioles increased from 2.32% on 1 May (D1) to 2.86% on 15 June. Following this period, a gradual decrease was observed until the final sampling date on 30 August (D9), when the lowest petiole K content of 1.58% was recorded. The periods of least variation in mean petiole potassium concentrations were noted from 15 June to 1 July and from 1 July to 15 July.

The data on the interaction effect between varieties and sampling dates suggest that petiole K content increased until 1 June for both Perlette and Anab-e-Shahi, rising from 2.35% on 1 May to 2.84% for Perlette and from 2.28% on 15 June to 2.88% for Anab-e-Shahi. However, a gradual decrease was noted from 15 June until the last sampling date for both grape cultivars. The lowest concentrations of petiole K were recorded on the final sampling date, measuring 1.63% for Perlette and 1.53% for Anab-e-Shahi. A comprehensive analysis of the data reveals a stable period from 15 June to 1 July for Perlette and from 1 July to 15 July for Anab-e-Shahi. Variations in plant nutrition among grape leaf petioles differed across growth stages, with results aligning with the trends observed for nitrogen, phosphorus and potassium.

**PCA and Correlation of Fruit quality and nutritional dynamics**

A correlation was drawn between nutritional profiling and plant growth and fruit development and fruit quality parameters using corrplot, with factor-wise correlation coefficients and scatterplots (Figs 4 and 5), while principal component analysis was performed between different growth and quality parameters.

## CONCLUSIONS

In conclusion, this study on grapevine development and nutrient dynamics reveals a nuanced interplay between vegetative growth and fruit development, shedding light on critical factors influencing grape quality and yield. The observed patterns of shoot length, trunk girth and fruit dimensions, coupled with the dynamics of fruit weight and number, underscore the significance of early season growth and its impact on overall vine productivity. Varietal differences, particularly between Anab-e-Shahi and Perlette, contribute to distinct growth patterns and fruit characteristics. Furthermore, the study elucidates the temporal evolution of sugar content, indicating a crucial period of rapid increase and a subsequent decline. Nutrient dynamics, as evidenced by changes in nitrogen, phosphorus, and potassium concentrations in leaf petioles, further contribute to the comprehensive understanding of grapevine physiology. These findings collectively contribute valuable insights for vineyard management practices aimed at optimising grape quality and yield.

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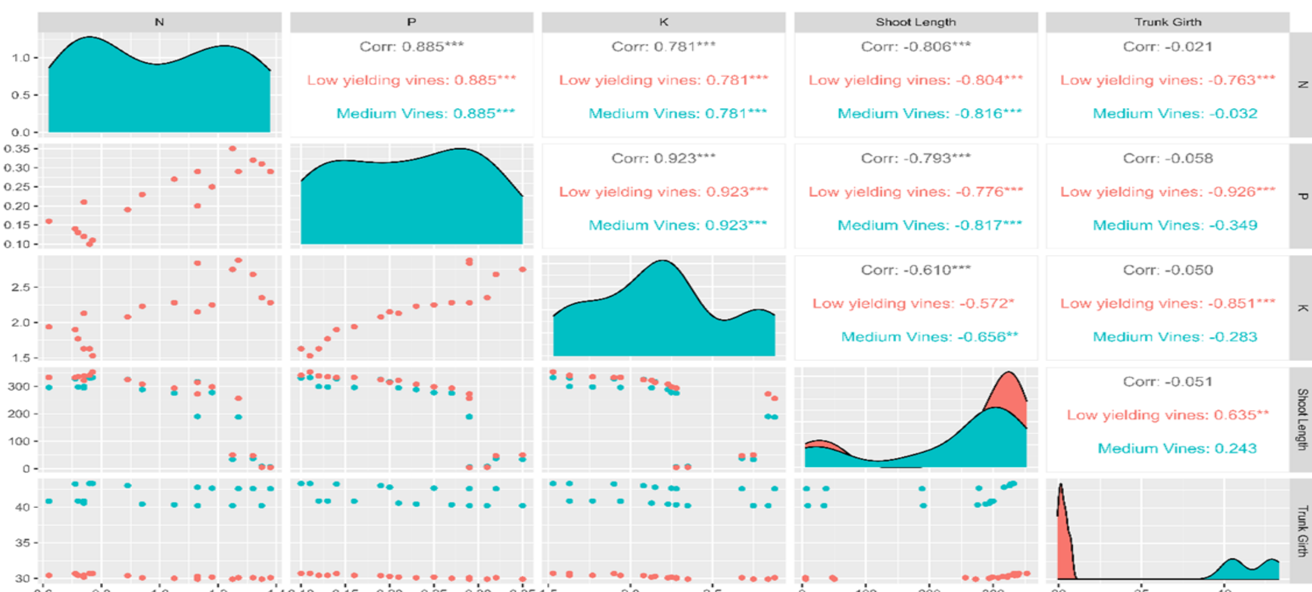


FIGURE 4
Factorial Coreelogram between nutrients and plant growth parameters

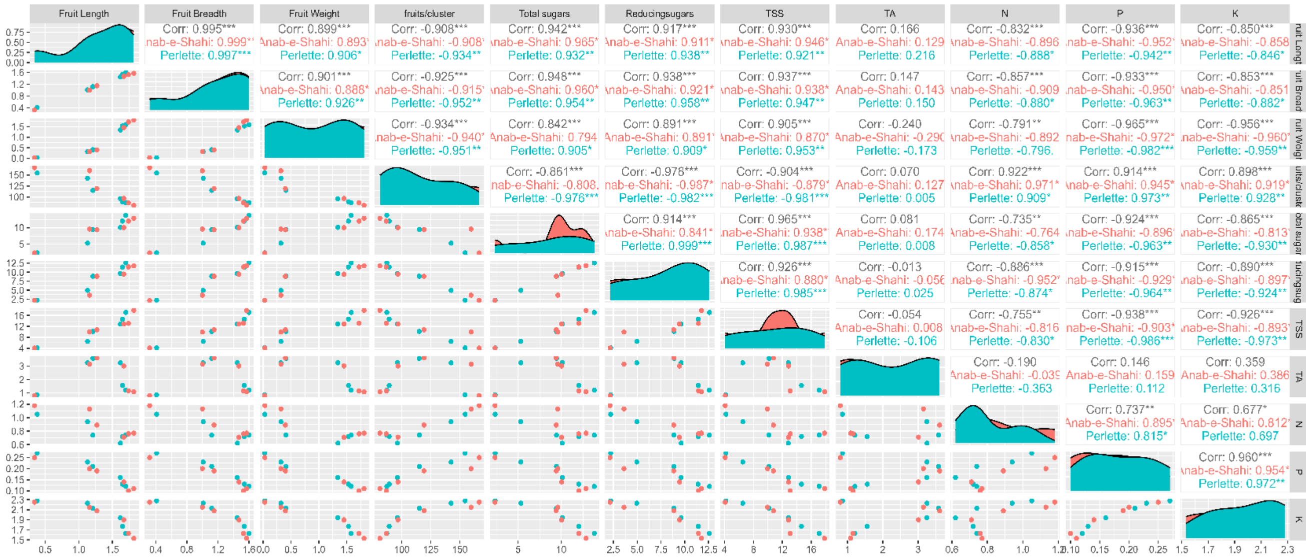


FIGURE 5
Correlation between plant growth and nutrients among different varieties

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