

Synthetic Indices and Multivariate Analysis for Explaining Apple Fruit Quality in Relation to Foliar Fertilization and Nutritional Status

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Abstract. The study evaluated the differential response of five apple varieties ('Generos', 'Florina', 'Delicios de Voinești', 'Jonathan' and 'Pionier') to eight foliar fertilization options and an unfertilized control. The experiment was placed in a semi-intensive non-irrigated plantation, located in flat terrain conditions, with chernozem soil, within the DER (Didactic and Experimental Resort) of ULS "King Mihai I" from Timișoara – Fruit Center. Foliar concentrations of N, P, K, Fe, Cu and Zn were analyzed, as well as fruit quality indicators, titratable acidity (Ac) and soluble sugar content (SUG). To integrate the information, three synthetic indices were proposed: Nutrition Status Index (NSI), Fruit Quality Index (FQI) and Fertilization Efficiency Index (FEI). The data were analyzed by additive factorial ANOVA, Pearson correlations, PCA, interaction heatmaps and regression models. The results indicated a clear differentiation of the varieties in terms of the capacity to capitalize on foliar inputs, with higher average NSI values in Pionier and Florina, while the qualitative response of the fruits did not always follow the same direction with mineral nutrition. Multivariate analysis (PCA) separated the nutritional variables from the quality indicators and demonstrated that the nutrition-quality relationship is dependent on the genotype and the fertilizer combination. The proposed approach facilitated the identification of technological variants with high integrated efficiency and provides a reproducible framework for the evaluation of foliar fertilization in apple.

Keywords: foliar fertilization, fruit quality, *Malus domestica*, mineral nutrition, multivariate analysis, synthetic indices

INTRODUCTION

Apple fertilization is an essential technological element for maintaining the balance between vegetative growth, fruiting and production quality (Scudellari et al., 1993; Milošević et al., 2022). In modern and semi-intensive orchards, mineral nutrition must be analyzed not only in terms of elemental input, but also through the ability of varieties to convert these inputs into commercial and nutritional quality of fruits (Fallahi et al., 2010). The literature has shown that fertilization can modify apple productivity and quality, but the intensity of the response is frequently dependent on the cultivar, rootstock, tree biology and age, water regime, and initial soil status (Jackson, 2003; Cheng and Raba, 2009; Marschner, 2012; Neilsen et al., 2010; Ljavić et al., 2023).

Foliar fertilization has been considered a rapid intervention to correct nutritional imbalances, especially in situations where root absorption is limited by soil moisture, pH, temperature or element availability (Wójcik, 2004; Banyal et al., 2016; Shrestha et al., 2025). Fallahi (2013) emphasized that foliar applications can increase nutrient use efficiency, but their effectiveness depends on the timing of application, concentration, product compatibility, leaf area, and specific species requirements. In the case of apple, this approach is relevant because differences between varieties can determine contrasting responses to the same fertilization scheme. The influence of foliar treatments on apple has been reported in various studies, which have highlighted the influence of secondary macroelements (e.g. Ca), microelements (e.g. B, Zn), or biostimulants on physiological indices, agronomic parameters, yield and quality in apple (Kadir, 2004; Ljavić et al., 2023; Xu et al., 2025).

Nitrogen influences vegetative growth, leaf development, photosynthesis and biomass accumulation potential, but excess can reduce firmness and post-harvest quality (Tagliavini et al., 1995; Marschner, 2012). Phosphorus is involved in energy transfer and root system development, and potassium is correlated with carbohydrate transport, fruit size and sugar accumulation. Microelements (e.g. Fe, Cu, Zn, B) participate in enzymatic processes, photosynthesis, oxidative metabolism and synthesis of growth regulators (Mengel and Kirkby, 2001; Wójcik and Wójcik, 2007; Fageria, 2009; Marschner, 2012).

Fruit quality in apple is a complex trait, dependent on both genotype and technological conditions. Acidity and sugar content are important indicators of taste, maturity and commercial acceptability. Fertilization studies have shown that fruit quality response can be more strongly influenced by variety than by fertilizer treatment, especially when data are obtained from mature plantations, under relatively stable pedoclimatic conditions (Milošević and Milošević, 2015; Ljavić et al., 2023). The temperate zone is highly favorable for the cultivation of fruit trees, in various plantation systems, where apple is one of the species with high frequency in plantations (Robinson, 2003; Tromp et al., 2005). For the proper management of fruit plantations, with regard to nutrients and fertilizers, different evaluation methods are used through soil analysis, foliar diagnosis or floral diagnosis (Stilles et al., 1991; Sanz et al., 1994; Tanou et al., 2017).

In recent years, multivariate analysis has become an important tool in the interpretation of horticultural experiments. PCA allows for dimensionality reduction and the identification of groups of variables that explain the differentiation of experimental variants. In addition, standardized synthetic indices can transform multinutrient and multiquality data sets into comparable scores, useful in technological recommendations. In the present study, this approach is applied to quantify differentially tree nutrition, fruit quality and integrated foliar fertilization efficiency in five apple cultivars grown under non-irrigated conditions on chernozem.

MATERIAL AND METHODS

Study location and biological material

The experiment was carried out within the SDE of USVT Timișoara, Fruit Center, Figure 1. The plantation was located on flat land, with chernozem soil, in a non-irrigated system. The biological material was represented by five apple varieties: 'Generos' (G), 'Florina' (F), 'Delicios de Voinești' (D), 'Jonathan' (J) and 'Pionier' (P).

The plantation was in a semi-intensive system, with 10-year-old trees. The analyzed data represent average values based on previous studies (Jivan and Sala, 2014).

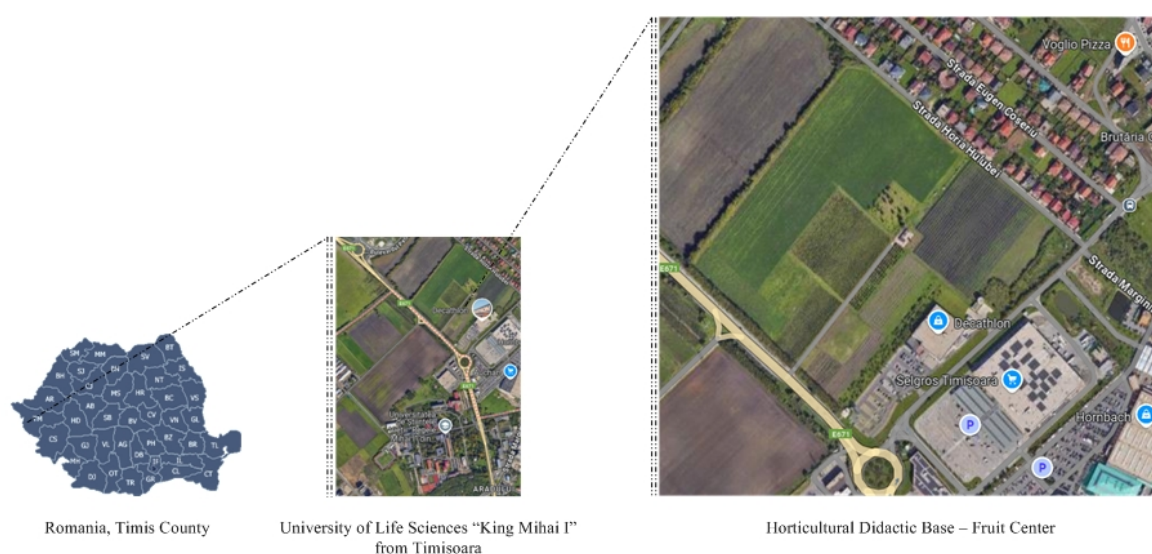


Figure 1. Study location (Google maps)

Fertilization variants

Eight fertilization options were provided, along with a control option, according to Table 1. The fertilizer products were used in the following concentrations: Uwafol 0.4%, Foliarel 0.1%, Calcio Plus 0.2%, Biocomplex900 0.2%, Megafol 0.2%. Three foliar treatments were applied with an atomizer device.

Table 1. Experimental matrix

Fertilization variant component	No	'Generos'	'Florina'	'Delicios de Voinești'	'Jonathan'	'Pionier'
Control	0	G0	F0	D0	J0	P0
Uwafol&Foliarel	1	G1	F1	D1	J1	P1
Uwafol&Foliarel&Calcio Plus	2	G2	F2	D2	J2	P2
Waterfert&Foliarel	3	G3	F3	D3	J3	P3
Waterfert&Foliarel&Calcio Plus	4	G4	F4	D4	J4	P4
Biocomplex900&Foliarel	5	G5	F5	D5	J5	P5
Biocomplex900&Foliarel&Calcio Plus	6	G6	F6	D6	J6	P6
Megafol&Foliarel	7	G7	F7	D7	J7	P7
Megafol&Foliarel&Calcio Plus	8	G8	F8	D8	J8	P8

To quantify nutritional status, leaf samples were taken in the third decade of July, after the application of the third treatment. Leaf samples were taken randomly, under similar conditions for each apple variety (crown

height, crown exposure, shoot type). Fruits were sampled at harvest maturity.

Determined indicators

To assess the nutritional status of the trees, the content of N, P, K, Fe, Cu and Zn in the leaves was determined. The quality of the fruits was evaluated by determining the acidity (Ac) and the content of soluble sugars (SUG).

Synthetic indices considered

For each numerical variable, the standardized score was calculated, Equation (1).

$$Z_i = (x_i - \bar{x}_i) / s_i \quad (1)$$

where: Z_i – standardized score for variable "i"; x_i – variable "i"; $\bar{x}$ – arithmetic mean of variable "i"; s_i – standard deviation of variable "i"

The nutrition synthetic index (NSI) was calculated as the average of the standardized scores for the six nutrients, Equation (2).

$$NSI = (Z_N + Z_P + Z_K + Z_{Fe} + Z_{Cu} + Z_{Zn}) / 6 \quad (2)$$

where: NSI – nutrition synthetic index; Z_N , Z_P , Z_K , Z_{Fe} , Z_{Cu} , Z_{Zn} – standardized nutrient scores

The synthetic fruit quality index (FQI) was calculated as the average of the standardized scores for acidity and sugars, Equation (3).

$$FQI = (Z_{Ac} + Z_{SUG}) / 2 \quad (3)$$

where: FQI – fruit quality index; Z_{Ac} , Z_{SUG} – standardized score for quality indicators

The synthetic fruit quality index (FQI) was calculated as the average of the standardized scores for acidity and sugars, Equation (3).

$$FEI = FQI / (FQI - NSI_{min} + 0.1) \quad (4)$$

where: FEI – fertilization efficiency index; FQI – fruit quality index; NSI_{min} – nutrition synthetic index minimum value

The term 0.1 was introduced to stabilize the ratio and avoid division at values very close to zero.

Statistical analyses

The data were analyzed using descriptive statistics, Pearson correlations, PCA and additive factorial ANOVA with the factors variety and fertilization. Based on the mean values for the combination variety × fertilization, the interaction effect variety × fertilization was interpreted graphically and multivariately. PAST software v.4.14 (Hammer et al., 2001) and JASP software v.0.16.2 (2022) were used for data analysis and generation of graphical representations.

RESULTS AND DISCUSSIONS

Statistical analysis of the data led to the average values of the mineral element content in leaves and of the quality indices, in relation to the apple variety, Table 2, and in relation to the fertilization variants, Table 3. The data series (N=45) presented a normal distribution, with $r = 0.973$ (N), $r = 0.992$ (P), $r = 0.988$ (K), $r = 0.947$ (Fe), $r = 0.981$ (Cu), $r = 0.984$ (Zn), $r = 0.956$ (Ac), $r = 0.959$ (SUG). Outlier test (Grubs test) indicated that the data series (N=45) did not present outlier values, Table 4 ($p > 0.05$).

Table 2. Plant nutrition and fruit quality – average values in relation to the studied varieties

Apple Cultivar	N	P	K	Fe	Cu	Zn	Ac	SUG
		(%)			(ppm)			
'Delicios de Voinești'	2.261	0.178	1.456	128.444	11.600	19.678	0.297	20.981
'Florina'	1.977	0.180	1.551	97.000	12.622	19.478	0.417	18.307
'Generos'	1.928	0.174	1.392	62.444	11.300	18.656	0.449	7.584
'Jonathan'	2.583	0.174	1.478	139.111	12.067	18.544	0.610	12.715
'Pionier'	2.645	0.178	1.550	150.889	12.133	19.978	0.579	13.023

Table 3. Plant nutrition and fruit quality – in relation to experimental variants

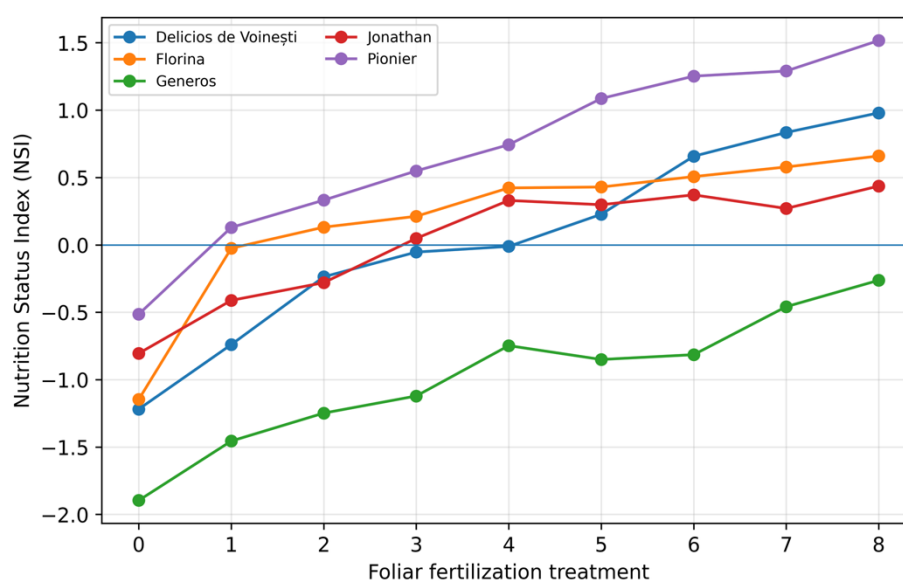
Fertilization variant number	N	P	K	Fe	Cu	Zn	Ac	SUG
		(%)			(ppm)			
0 (Ct)	1.873	0.167	1.414	99.600	10.800	18.500	0.423	14.940
1	2.219	0.172	1.446	109.600	11.380	18.820	0.464	14.449
2	2.280	0.175	1.456	113.200	11.620	19.000	0.489	14.256
3	2.280	0.176	1.472	116.200	11.880	19.180	0.482	14.791
4	2.349	0.179	1.496	118.400	11.920	19.360	0.464	14.337
5	2.340	0.179	1.496	119.600	12.220	19.480	0.466	14.352
6	2.444	0.180	1.511	119.800	12.340	19.600	0.484	14.292
7	2.372	0.182	1.531	120.400	12.500	19.600	0.483	14.503
8	2.353	0.182	1.547	123.400	12.840	19.860	0.479	14.778

Table 4. Outlier test results

Statistical parameters	N	P	K	Fe	Cu	Zn	Ac	SUG
Grubbs test								
G:	2.961	2.154	2.033	1.755	2.077	2.754	1.778	1.599
p(no outlier):	0.083	1.000	1.000	1.000	1.000	0.184	1.000	1.000

Apple varieties specifically capitalized on the applied foliar fertilization. In relation to the values of the Nutrition status index (NSI), the apple varieties were positioned differently, as a specific response to the experimental variants, Figure 2. With a low response, across the entire series of experimental variants, the 'Generos' variety was positioned.

The other apple varieties presented a differentiated position in relation to the fertilization variants, based on the NSI values, Figure 2. The 'Pionier' variety presented relevant NSI values starting with fertilization variant 1, with an increasing trend in relation to the other fertilization variants. The 'Florina' variety presented relevant NSI values starting with fertilization variant 2, with an increasing trend in relation to the other fertilization variants. The 'Jonathan' variety presented relevant NSI values starting with fertilization variant 3, and the 'Delicios de Voinești' variety starting with fertilization variant 5, Figure 2.

**Figure 2.** Cultivar-specific nutritional response to foliar fertilization, based on NSI values

In general, the variants with complex products and the addition of Calcio Plus showed a tendency to modify the mineral profile of the leaves, but the direction of the response depended on the apple variety. For this reason, the technological recommendation should not be formulated exclusively on the average of all varieties, but differentiated by genotype. The curves showed that foliar fertilization produced different responses depending on the variety. Some combinations increased the NSI (nutrition status index) values, while others determined moderate, or even negative, responses, compared to the general average (represented in the graph at position 0.0).

The "genotype $\times$ fertilization" interaction was expressed through the interaction matrix, in Figure 3. In relation to the NSI value scale, the most pronounced positive effect was quantified in the variety 'Pionier' with fertilization variant 8 (in descending order, of the other fertilization variants), followed by the variety 'Delicios de Voinești' with fertilization variant 8 (in descending order of the other variants), 'Florina' and 'Jonathan'.

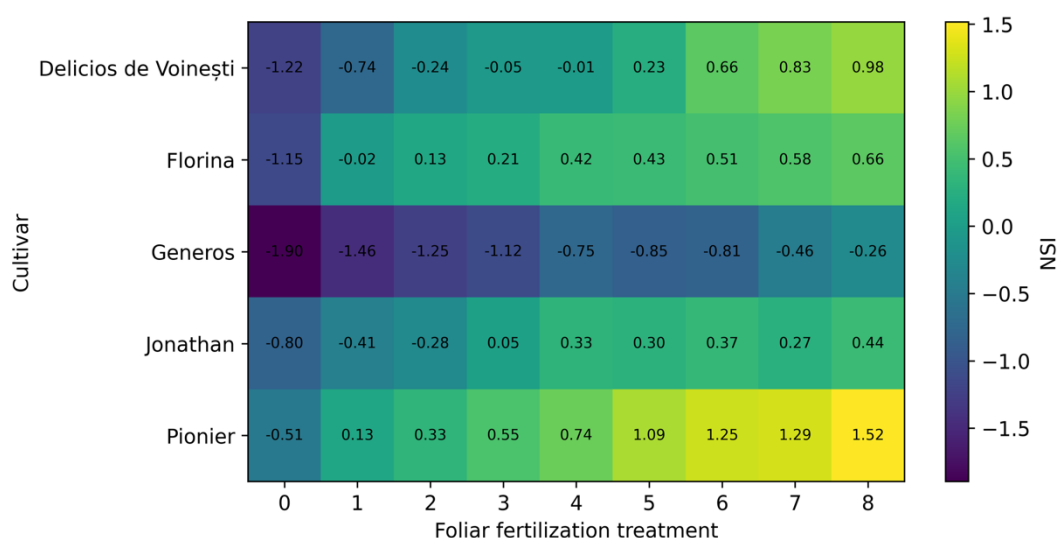


Figure 3. "Genotype $\times$ fertilization" interaction matrix for nutritional status based on NSI values

Regarding the potential of genotypes to capitalize on inputs through fertilization, the average values indicated clear genetic differences between varieties, Figure 4.

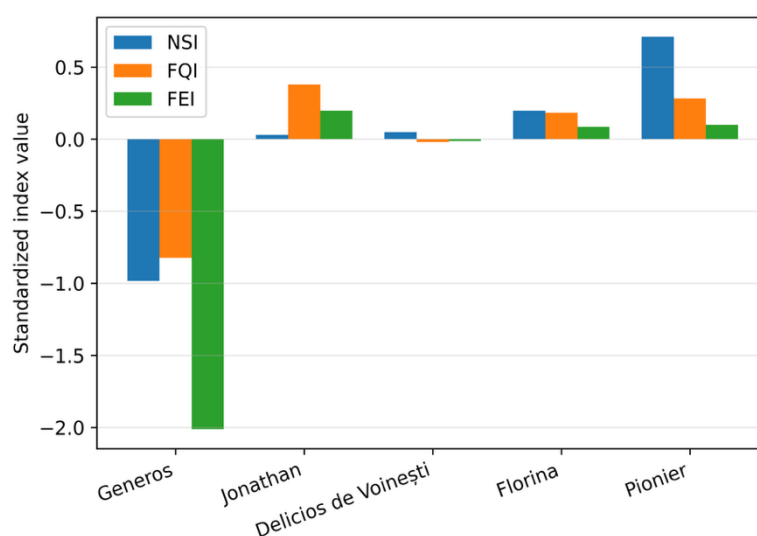


Figure 4. Graphical representation of the potential of apple genotypes to capitalize on inputs through fertilization

The 'Pionier' variety presented the highest average value of the NSI index, suggesting a greater capacity to accumulate or maintain a superior mineral status. The 'Florina' variety also had positive NSI values, while the 'Generos' variety remained in the negative zone, indicating a relatively lower nutritional profile compared to the fertilization variants.

The bars in the graphical representation compared NSI, FQI and FEI at the variety level. Figure 4 suggests that a high nutritional status does not automatically guarantee the best qualitative response, which justifies the simultaneous use of synthetic indices.

From the perspective of fruit quality, the fertilization response was less linear than in the case of nutritional status, Figure 5. This confirmed the hypothesis that the mechanisms of accumulation of sugars and organic acids depend not only on foliar mineral concentration, but also on ripening, carbohydrate metabolism, fruit load and variety characteristics.

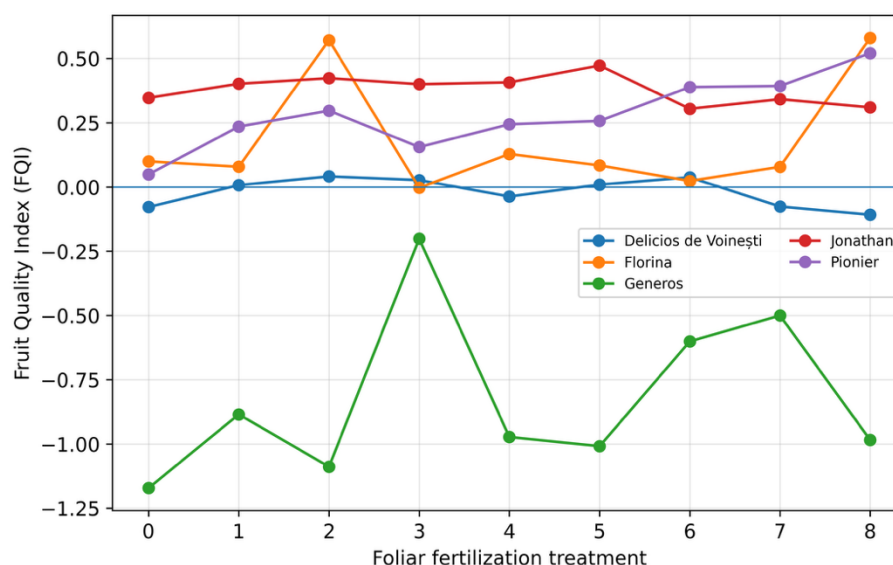


Figure 5. Cultivar-specific fruit quality response to foliar fertilization

Fruit quality, expressed by FQI (fruit quality index), has important variations between varieties and treatments, confirming that acidity and sugars must be interpreted together. In this sense, linear regression analysis was applied to describe the relationship between apple fruit quality indices (SUG, Ac), with the values of statistical safety parameters in Table 5, and the graphical representation, on a logarithmic scale, in Figure 6.

Table 5. The values of the statistical parameters resulting from the linear regression of fruit quality indices

Statistical parameters		Statistical parameters values	
Slope a	-0.5996	Std. error a:	0.1696
t	3.5364	p (slope):	0.0010
Intercept b	0.9304	Std. error b:	0.0618
95% bootstrapped confidence intervals (N=1999)			
Slope a	(-0.88716, -0.39987)		
Intercept b	(0.85143, 1.0066)		
Correlation			
r	-0.4747		
r ²	0.2253		
t	-3.5364		
p (uncorr.)	0.0010		
Permutation p	0.0011		

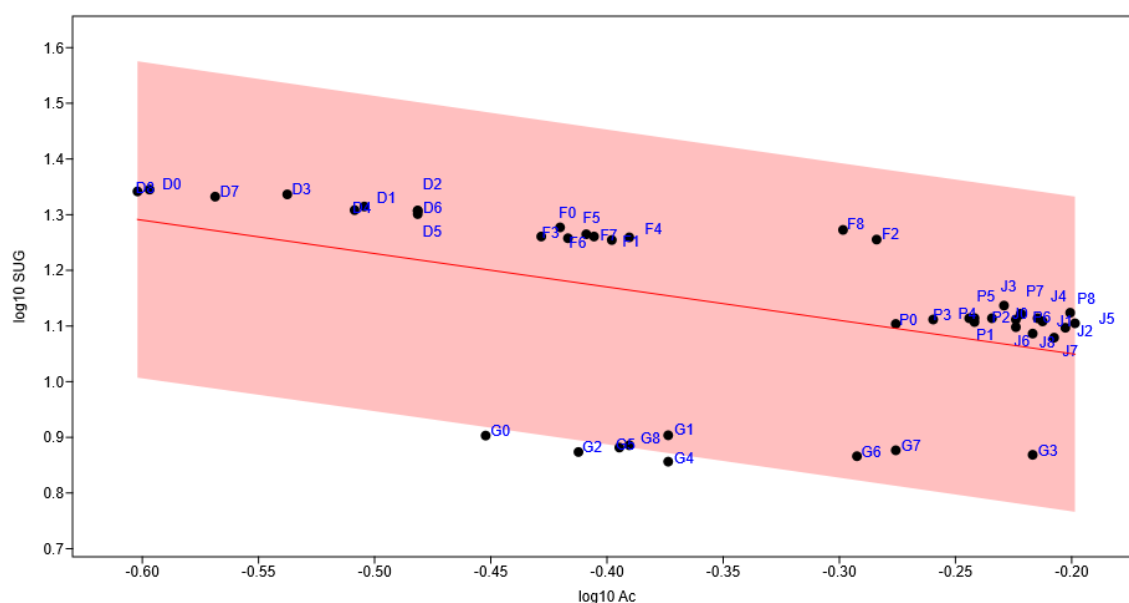


Figure 6. Linear fit plot between SUG and Ac quality indices in apple (log-log scale)

The relationship between nutrition status index (NSI) and fruit quality index (FQI) is presented in Figure 7. The regression model indicated the intensity of the relationship between NSI and FQI, in statistical safety conditions, $R^2 = 0.42$, $p = 0$. The points grouped by variety showed that the effect was genetically mediated.

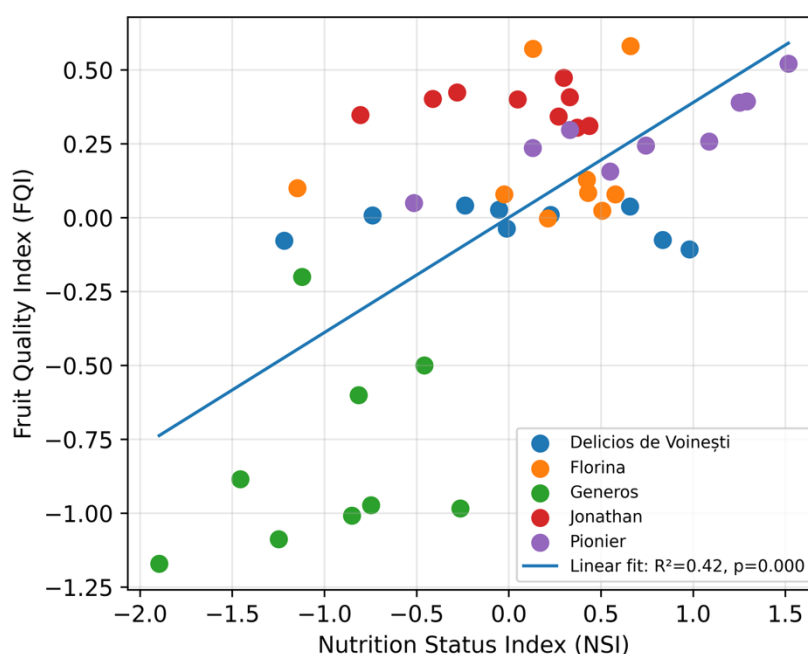


Figure 7. Relationship between nutritional status and fruit quality

Correlation analysis, Pearson's r indicated the level of interdependence between leaf mineral elements, quality parameters (SUG, Ac) and indices that reflected nutritional (NSI) and fruit quality (FQI), Figure 8. The correlations between nutrients and quality indicators support the interpretation of an integrated, but not strictly proportional relationship. Some nutrients may be positively associated with FQI, while others rather reflect vegetative status or general metabolic capacity.

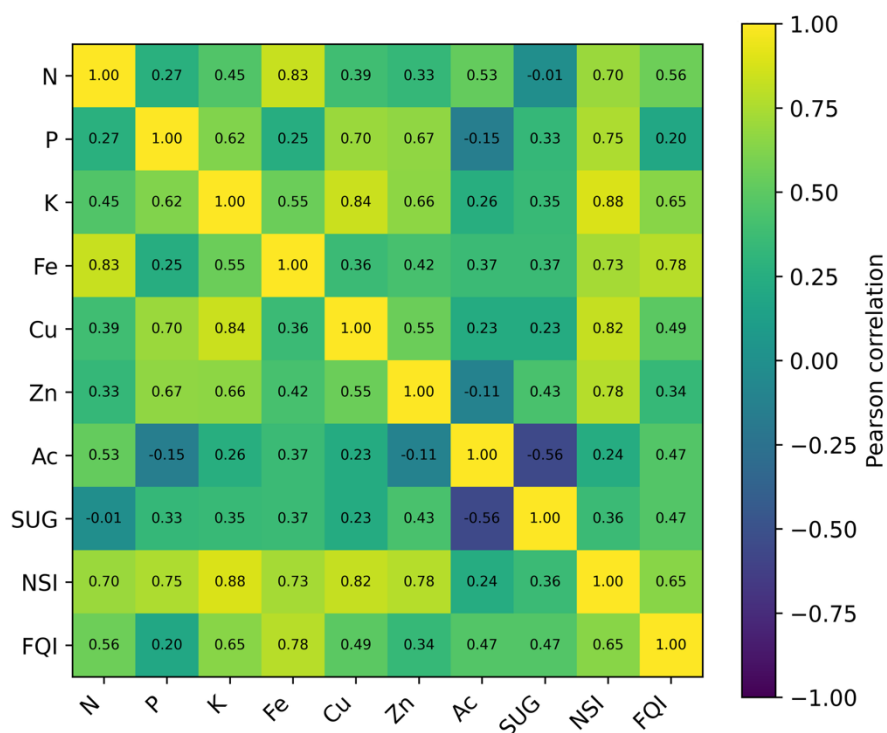


Figure 8. Correlation matrix among nutrition and quality variables in apple

The multivariate analysis resulted in the PCA plot in Figure 9. PC1 explained 48.3% of the variance, and PC2 explained 24.7% of the total variance. Together, the first two components synthesize 73.0% of the total variability. PCA confirmed that the nutritional and quality variables are not redundant.

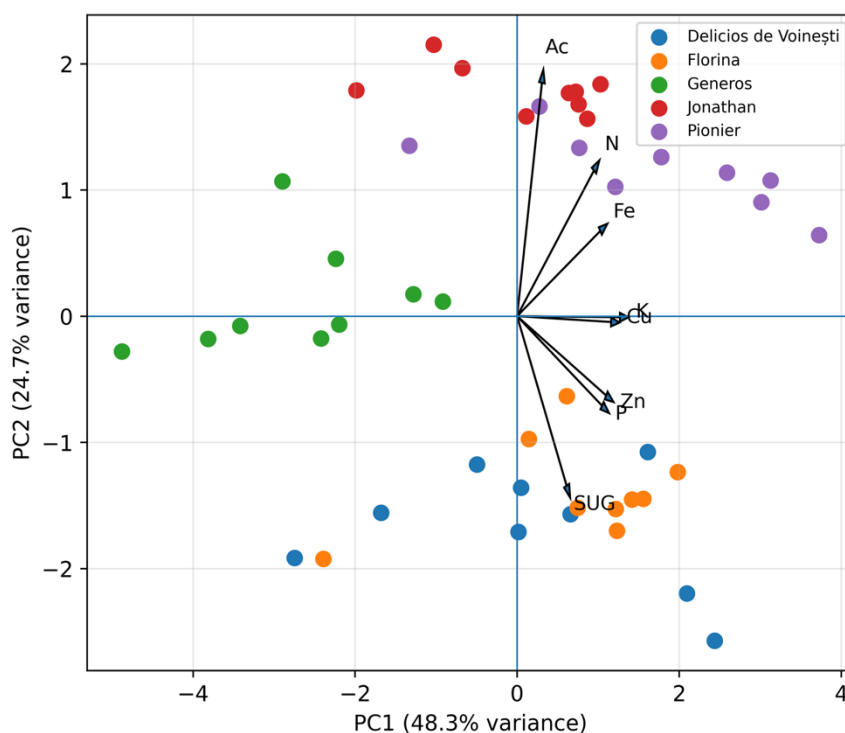


Figure 9. PCA biplot of nutritional and fruit quality variables

The positioning of the vectors indicated the dominant directions of variation, and the separation of the points by cultivar suggested an important genetic component in the way of capitalizing on foliar fertilization. The PCA loadings for the first two principal components are presented in Table 6.

Table 6. PCA loadings for the first two principal components

Index	PC1	PC2
N	0.338	0.412
P	0.378	-0.256
K	0.458	-0.003
Fe	0.371	0.244
Cu	0.422	-0.017
Zn	0.397	-0.227
Ac	0.108	0.651
SUG	0.218	-0.48

A conceptual model was generated as an integrative scheme for integrating the results: the leaf represents the nutritional diagnostic compartment, and the apple represents the qualitative expression compartment, Figure 10. In a final advanced version, this figure can be transformed into an interactive model or a 3D surface in which the fruit color is calculated from the FQI, and the leaf texture from the NSI. The 3D model illustrates the working hypothesis that the leaf, through its N-P-K-Fe-Cu-Zn status, constitutes the physiological basis for the expression of fruit quality indices.

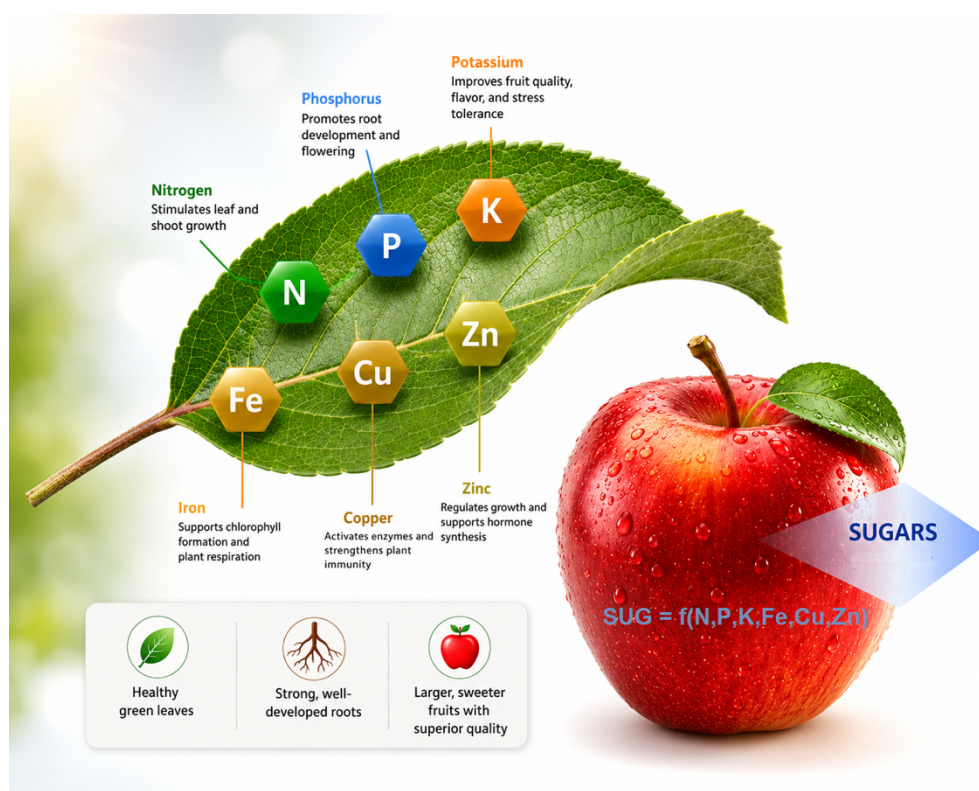


Figure 10. Conceptual model: leaf nutrition drives fruit quality

Cele cinci soiuri de mar considerate in cadrul studiului au fost caracterizate si diferite pe baza parametrilor foliari, in conditii de siguranta statistica, atat sub aspectul leaf area, cat si sub aspectul parametrilor geometriei fractale a frunzelor (Sala et al., 2015, 2017).

The results support the hypothesis that foliar fertilization modifies the nutritional status of trees, but the

amplitude of the response depends on the variety. This observation is in agreement with studies showing that fertilization management in apple orchards must be adapted to the cultivar and local pedoclimatic conditions (Neilsen et al., 2010; Milosevic and Milosevic, 2015; Ljavić et al., 2023). Calcium supplementation associated with other foliar products generated positive effects on plant nutrition and fruit quality indices. The positive effect of calcium has also been reported in other studies on different apple varieties (Kadir, 2004; Fallahi, 2013; Yu et al., 2018).

The apple varieties 'Pionier' and 'Florina' showed a higher potential for input utilization in terms of NSI, while 'Generos' had lower average values. This does not automatically mean that the variety has inferior agronomic performance, but indicates a less favorable nutritional profile in the fertilization system and conditions analyzed. The interpretation should be completed with data on production, fruit size, firmness and mineral content of the fruit, if these become available.

The relationship between NSI and FQI is not perfectly linear, confirming that leaf mineral status is an important but not sufficient condition for quality. Acidity and sugars are controlled by complex physiological processes, influenced by ripening, light exposure, fruit load, leaf/fruit ratio and genetic peculiarities. For this reason, the simultaneous use of NSI and FQI is more robust than the isolated interpretation of a single nutrient.

PCA highlighted the utility of multivariate analysis in identifying variety $\times$ fertilization combinations with a superior integrated profile. In the context of horticultural practice, a fertilization variant should be considered favorable only if it supports both nutritional balance and fruit quality, without generating imbalances between macro- and microelements.

An original contribution of the paper is the proposal of the synthetic indices NSI, FQI and FEI. These indices allow the transformation of multiple analytical data into a comparable system, useful for technological screening. In addition, the fertilization $\times$ nutrition $\times$ quality matrix, and the conceptual model provide a modern way of visual communication of the results, with potential for interdisciplinary articles combining horticulture, data analysis and visual modeling.

CONCLUSIONS

The apple varieties studied made differential use of the applied foliar fertilization, in terms of plant nutrition and fruit quality indices.

Foliar fertilization influenced the nutritional status of the trees, but the response was dependent on the variety.

The apple varieties 'Pionier' and 'Florina' had higher average NSI values, indicating a higher potential for the use of nutritional inputs under the analyzed experimental conditions.

Fruit quality, expressed by FQI, had a different dynamic than NSI, which shows that foliar nutrition must be correlated with variety-specific metabolism.

Multivariate analysis (PCA) and heatmaps allowed the identification of interaction patterns between fertilization, nutrition and fruit quality.

NSI, FQI and FEI indices can be used as synthetic tools for the interpretation of foliar fertilization experiments in apple.

STUDY LIMITATIONS

The interpretation of the results must be done in the context of some limitations specific to the analyzed data set. The analysis was based on average values for the five apple varieties, with eight foliar fertilization variants. The experiment was conducted in a single location, on chernozem and under non-irrigated conditions, which may restrict the degree of extrapolation of the results to other pedoclimatic conditions. In addition, the synthetic indices NSI, FQI and FEI represent analytical tools proposed in this study and require further validation on independent data sets and under different experimental conditions.

FUTURE RESEARCH DIRECTIONS

Future research should aim to validate the proposed synthetic indices (NSI, FQI and FEI) in multi-year and multi-location experiments, including different soil types, water regimes and cropping systems, or apple varieties. The integration of production indicators, fruit physical characteristics and post-harvest storage parameters would allow a more complete assessment of the efficiency of foliar fertilization. A promising direction is the development of decision support systems that integrate nutritional, climatic and technological data to optimize fertilization management in apple orchards.

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