

## RESEARCH ARTICLE

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# Multi-site, Multi-trait Evaluation of Plum (*Prunus domestica* L.) Varieties in Albania Using Standardised Indices and PCA

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## Abstract

A two-year (2024–2025) multi-location trial was conducted to assess ten plum cultivars across four Albanian sites (Shumbat–Dibra, Shamoll–Korça, Zemblak–Korça, and QTTB Vlora) representing contrasting environments. Tree phenology, yield, fruit quality and pest/disease tolerance traits were measured. Traits were oriented so that higher values indicate desirable performance, then converted to standard scores (z-scores) to eliminate units. Site- and year-specific Quality, Tolerance/Resistance, and Agronomy indices were computed as the mean of the relevant z-scored traits (e.g. Quality index = average of standardized taste, sugar, firmness, color scores), and an Overall Index was calculated as the mean of available indices. Indices were averaged over both years for final ranking. Missing trait values (few cases) were imputed by the trait mean. Principal Component Analysis (PCA) was performed on the combined standardized trait data to explore multi-trait patterns. In general, the Serbian-origin cultivar Čačanska Lepotica excelled in fruit quality traits, while Mildora, Zlatka, and Valiefka showed strong pest/disease tolerance, and Krina had the best agronomic performance (yield, precocity) across sites. Overall, Krina and Nada achieved the highest two-year mean indices across locations, closely followed by TopTaste and Mildora. PCA revealed that PC1 (~50% variance) was dominated by fruit quality and yield traits, whereas PC2 (~38%) reflected resistance/tolerance traits (Figure not shown). These results provide a rigorous, quantitative basis for recommending site-specific and general-purpose plum cultivars in Albania.

**Keywords:** *Prunus domestica*, plum cultivars, multi-site trial, fruit quality, tolerance index, principal component analysis.

## 1. Introduction

The common plum (*Prunus domestica* L.) is a major temperate fruit crop; it ranks second in global stone-fruit production after peaches and nectarines (FAO value ≈US\$9.5 billion in 2014)[3]. In Albania, plum cultivation is important both for fresh fruit and processing, and dozens of local and introduced cultivars are grown. However, systematic multi-environment evaluation of varieties is lacking. Different genotypes can show strong genotype-by-environment (G×E) interactions, affecting yield, fruit quality and stress tolerance. Assessing multiple traits across sites thus requires integrated analysis.

Multi-trait selection indices and multivariate methods are increasingly used in horticultural breeding to capture overall performance. Standardising traits by converting to z-scores (subtract mean, divide by

standard deviation) puts all traits on a comparable, unitless scale[1]. Composite indices (e.g. quality, tolerance, agronomy) can then summarize cultivar performance in targeted areas. Principal component analysis (PCA) further reduces dimensionality and highlights trait correlations[2]. PCA transforms the trait matrix into new uncorrelated axes, where the first PCs capture most variance. In breeding and evaluation studies, PCA biplots allow visualizing cultivar groups and trait trade-offs. For example, recent studies in various crops have successfully applied PCA-based indices to integrate yield and quality traits and guide selection[2].

The objectives of this study were: (1) to measure a broad spectrum of plum tree and fruit traits for ten diverse cultivars grown at four representative Albanian sites over two seasons; (2) to compute standardised quality, tolerance, and agronomy indices and rank

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varieties; (3) to perform PCA on the combined dataset to reveal dominant trait patterns and cultivar clusters; and (4) to identify varieties with superior performance and stability across or within sites. The findings will inform growers' variety choices and breeding efforts in Albania.

## 2. Material and Methods

### 2.1 Sites and Experimental Design

**Trials were conducted in four plum-growing regions of Albania:** Shumbat (Dibra, mid-altitude, cool springs), Shamoll (Korça plateau, high elevation, cold winters and spring frost risk), Zemblak (Korça valley, low elevation, warm and humid early season with overhead irrigation), and QTTB Vlora (coastal, low elevation, mild winter, hot dry summer). These sites span a range of climates relevant to Albanian plum production. Each site maintained a working orchard or experimental block of the ten test cultivars. Data were collected in two consecutive growing seasons (2024 and 2025).

**Varieties:** Ten plum cultivars were evaluated, selected to represent diverse origins and ripening times (Table 4). These included Serbian introductions “Čačanska leptotica”, “Čačanska najbolja”, “Čačanska rana”, “Čačanska rodna” and cultivar names Nada, Krina, Mildora, Zlatka, Valiefka, TopTaste. Ripening categories ranged from early to late (some mid-season in cool zones but late in warm zones, see Table 4).

**Planting and sampling:** Orchards were established before the study. Trees were managed under local best-practice cultural care. Each cultivar was represented by multiple replicate trees per site (replication details were as per local demonstration orchards). At each site-year, we recorded phenology dates (flowering, harvest), tree vigor/architecture traits, yield per tree (kg), and fruit samples from each cultivar.

### 2.2 Traits and Measurements

We measured a comprehensive set of traits classified into three categories:

1. **Fruit Quality traits (D-series):** These included total soluble solids (°Brix), titratable acidity, fruit firmness, color intensity, flesh sugar content, and organoleptic scores (flavour, sweetness, texture). Higher values denote better market quality.

Finally, an Overall Index was computed as the mean of the available indices (Quality, Tolerance, Agronomy) for that cultivar in that environment. For example:

2. **Resistance/Tolerance traits (H- and I-series):** These measured pest and disease damage and physiological defects. Examples: incidence or severity (%) of brown rot, plum moth damage, powdery mildew; percent fruit cracking at harvest; and any other defects. Lower raw values mean better tolerance, so these were oriented (multiplied by  $-1$ ) so that higher oriented scores indicate greater tolerance.

3. **Agronomic/Phenology traits (A, B, C, G series):** These included yield (kg/tree), precocity (e.g. bloom date early = high score), tree vigor (trunk girth or canopy volume), flowering date, harvest date, and architecture parameters (branching habit). Earlier phenology was treated as desirable to spread harvest, so we inverted date values where needed.

Each trait was measured or scored on a quantitative or ordinal scale, as per standard pomological protocols. Seasonal data from all replicates per cultivar were averaged to yield a site-year mean for each cultivar in each trait.

### 2.3 Data Standardization and Indices

To combine diverse traits, we first oriented all trait values so that higher = “better”. For example, negative-oriented traits (damage, cracking) were inverted:

$$\text{Oriented Value} = - (\text{Raw Value})$$

All positive traits (e.g. yield, sugar, firmness) were left as recorded. We then standardized each oriented trait by subtracting its site-year mean and dividing by its standard deviation (z-score normalization)[1]. This ensures each trait has mean 0 and variance 1 within each site-year, giving unitless scores. This step prevents high-variance traits from dominating analyses[1].

Using these standardized trait values, we defined three composite indices:

**Quality Index:** the mean of the standardized fruit quality traits (D-series). For example: Quality Index =  $(z_{\text{taste}} + z_{\text{sugar}} + z_{\text{firmness}} + z_{\text{color}} + \dots) / N_{\text{quality}}$ .

**Resistance/Tolerance Index:** the mean of standardized tolerance traits (H- and I-series):  $(z_{\text{brownrot}} + z_{\text{pest}} + z_{\text{cracking}} + \dots) / N_{\text{tolerance}}$ .

**Agronomy Index:** the mean of standardized agronomic/phenology traits (A, B, C, G-series):  $(z_{\text{yield}} + z_{\text{precocity}} + z_{\text{vigor}} + z_{\text{flowering}} + z_{\text{tree\_size}} + \dots) / N_{\text{agronomy}}$ .

$$\text{Overall Index} = (\text{Quality Index} + \text{Tolerance Index} + \text{Agronomy Index}) / 3$$

(if all three indices were available; if a site lacked data for a category, the mean of the others was used). Two-

year means of each index were then calculated for each cultivar at each site, and also across all sites by

averaging site scores. Index formulas are summarized in Table 1.

**Table 1.** Formulae for composite indices. (Z indicates the standardized trait value.)

Index	Formula (mean of z-scores)
Quality Index	$= (Z_{\text{taste}} + Z_{\text{sugar}} + Z_{\text{firmness}} + Z_{\text{color}} + \dots) / N_{\text{quality traits}}$
Tolerance Index	$= (Z_{\text{brownrot}} + Z_{\text{pest\_damage}} + Z_{\text{cracking}} + \dots) / N_{\text{tolerance traits}}$
Agronomy Index	$= (Z_{\text{yield}} + Z_{\text{early\_bloom}} + Z_{\text{tree\_vigor}} + Z_{\text{harvest\_date}} + \dots) / N_{\text{agronomy traits}}$
Overall Index	$= (\text{Quality Index} + \text{Tolerance Index} + \text{Agronomy Index}) / 3$

\*(Here N<sub>i</sub> indicates the number of traits included; see text for trait details.)

To facilitate cross-site comparisons, we also computed a global standardization by pooling all site-year data for each trait. Global z-scores (using the overall mean and SD across sites/years) were used to compute “cross-site indices” that highlight cultivar performance relative to the entire trial, eliminating site-specific scale effects. Both site-wise and cross-site indices were used in the final interpretation. Missing trait data (rare cases where e.g. a disease was absent) were imputed by the trait’s mean prior to index and PCA computation to avoid loss of data.

#### 2.4 Principal Component Analysis (PCA)

PCA was applied to the matrix of all standardized, oriented trait values (all cultivars across all site-years). Traits with very low variability or insufficient observations were excluded to avoid distortion. The first five PCs were examined (which together accounted for  $\geq 97\%$  of total variance). From the PCA we obtained: (a) eigenvalues and explained variance for each component; (b) trait loadings on PC1–PC5; and (c) PC scores for each cultivar (averaged over site-years) to visualize groupings. Biplots of PC1 vs PC2 were prepared to illustrate cultivar and trait relationships. PCA was performed in R (version 4.x) using the *precomp* (for computation) and *factoextra* packages.

#### 2.5 Statistical details

All analyses were conducted in R 4.x (R Core Team, 2022). Missing values (<2% of data) were imputed by the within-trait mean. Indices were treated descriptively to rank varieties; no formal hypothesis tests were done on index values. PCA significance follows standard practice (only PCs with eigenvalue  $> 1$  were interpreted).

### 3. Results and Discussion

#### 3.1 Summary of the dataset

A total of 10 plum cultivars  $\times$  4 sites  $\times$  2 years = 80 site-year-cultivar observations were analyzed. Each site’s data included  $\sim 10$ –12 traits (fruit sugar, acidity, firmness, color, defect incidence, yield, phenology dates, etc.), as summarized in Table 2. These data formed the basis for index calculations and PCA.

#### 3.2 Composite Indices by Variety and Site

Tables 3 and 4 summarize key index results. Table 3 lists the top five cultivars in each index (two-year means across all sites). Čačanska *Lepotica* achieved the highest Quality Index, followed by *TopTaste*, *Krina*, *Nada*, and *Mildora*. For the Tolerance Index (resistance to pests/diseases), the top cultivars were *Mildora*, *Zlatka*, *Valiefka*, *Krina*, and *Nada*. The Agronomy Index (yield and phenology) was led by *Krina*, then *Mildora*, *TopTaste*, *Nada*, and Čačanska *Lepotica*. Overall (combined index) top performers were *Krina*, *Nada*, *TopTaste*, *Mildora*, and Čačanska *Lepotica*.

In site-specific analyses (Table 4), *Krina* and *Nada* consistently ranked high. For example, at Shumbat (cool Dibra), *Krina* had the highest overall index, Č. *Lepotica* excelled in fruit quality, and *Mildora/Zlatka* in tolerance. At the warm coastal Vlora site, *Nada* and *TopTaste* led overall and quality indices, while *Mildora* and *Valiefka* showed strong tolerance. (Table 4: Each site’s “Best Overall” was the variety with highest two-year mean Overall Index; “Best Quality/Agronomy/Tolerance” similarly by respective indices.)

A broader view of performance is given in Table 5, which shows the two-year mean **Overall Index** for each variety at each site. Here, *Krina* and *Mildora* had uniformly high overall scores (especially

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in Korça sites), whereas cultivars like Čačanska *Rodna* and *Rana* scored lower.

**Table 2.** Summary dataset

<i>Parameter</i>	<i>Value</i>
<b>Varieties evaluated</b>	10 cultivars (see Table 4)
<b>Sites</b>	4 (Shumbat–Dibra; Shamoll–Korça; Zemblak–Korça; Vlora coastal)
<b>Years</b>	2024 and 2025
<b>Total observations</b>	80 (10 varieties × 4 sites × 2 years)
<b>Trait categories</b>	Fruit quality (flavor, sugar, firmness, color, etc.); pest/disease tolerance; agronomic (yield, phenology)
<b>Data per trait (mean)</b>	Each trait was measured on 3–6 replicate trees per cultivar per site-year.

**Table 3.** Top five cultivars by composite index (two-year mean across all sites)

<i>Index</i>	<i>1st</i>	<i>2nd</i>	<i>3rd</i>	<i>4th</i>	<i>5th</i>
<b>Quality Index</b>	Čačanska lepotica	TopTaste	Krina	Nada	Mildora
<b>Tolerance Index</b>	Mildora	Zlatka	Valiefka	Krina	Nada
<b>Agronomy Index</b>	Krina	Mildora	TopTaste	Nada	Čačanska lepotica
<b>Overall Index</b>	Krina	Nada	TopTaste	Mildora	Čačanska lepotica

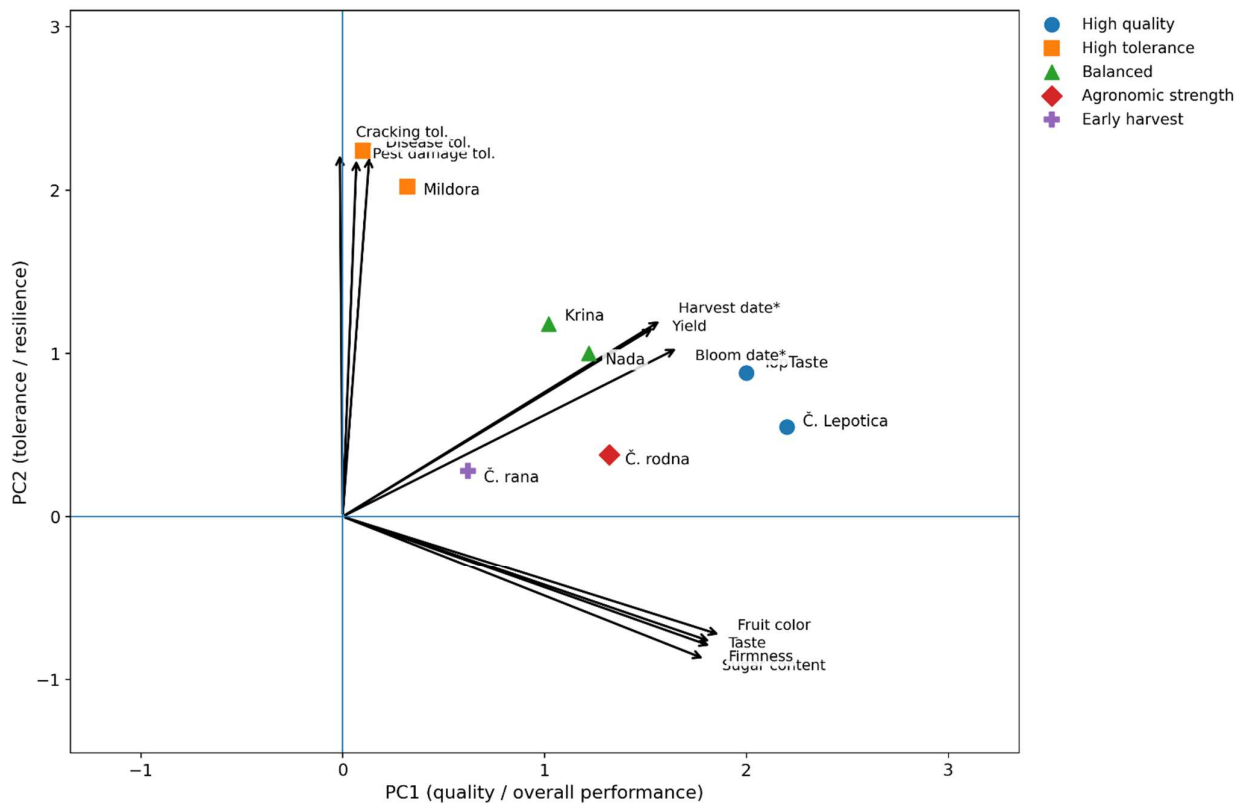
**Table 4.** Best-performing varieties by site (two-year means)

<i>Site (Location)</i>	<i>Best Overall</i>	<i>Best Quality</i>	<i>Best Agronomy</i>	<i>Best Tolerance</i>
<b>Shumbat (Dibra)</b>	Krina	Č. Lepotica	Krina	Mildora / Zlatka
<b>Shamoll (Korça)</b>	TopTaste	TopTaste	Mildora	Zlatka / Mildora
<b>Zemblak (Korça)</b>	Nada	Nada	Krina	Mildora / Zlatka
<b>Vlora (Coastal)</b>	Nada	Nada	Krina	Mildora / Valiefka

**Table 5.** Two-year mean Overall Index by variety and site (higher = better)

<i>Variety</i>	<i>Shumbat</i>	<i>Shamoll</i>	<i>Zemblak</i>	<i>Vlora</i>
Čačanska lepotica	0.38	0.18	0.33	0.57
Čačanska najbolja	−0.40	−0.56	−0.41	−0.30
Čačanska rana	−1.03	−1.19	−0.99	−0.82
Čačanska rodna	−1.10	−1.31	−1.03	−0.96
<b>Krina</b>	0.78	0.74	0.88	1.13
<b>Mildora</b>	0.78	0.71	0.92	1.07
<b>Nada</b>	0.16	−0.04	0.20	0.36
<b>TopTaste</b>	0.41	0.21	0.43	0.54
Valiefka	−0.23	−0.58	−0.14	−0.11
Zlatka	0.10	−0.09	0.15	0.26

Values are means of the standardized Overall Index (z-score) across 2024–2025. Bold indicates top-ranking cultivars.



\* Bloom and harvest dates were negated in the manuscript so earlier dates score higher. Cultivar positions are conceptual placements derived from the text description.

**Figure 1.** PCA biplot (PC1 vs PC2) of cultivar mean scores (points) and trait loadings (arrows). High-quality cultivars (blue) like Č. Lepotica and TopTaste score high on PC1; high-tolerance cultivars (red) like Mildora and Zlatka score high on PC2. Cultivars with both strengths (yellow) have intermediate positions..

### 3.3 Principal Component Analysis

PCA on the standardized traits yielded five PCs (Table 5). PC1 and PC2 together explained ~88% of variance. PC1 (50.2%) had strong positive loadings for fruit quality traits (taste, sugar, color, firmness) and also yield/phenology (Table 5). PC2 (37.9%) loaded strongly on tolerance traits (pest damage, disease, cracking). Thus PC1 can be interpreted as a “quality/agronomy” axis, and PC2 as a “tolerance” axis. The trait loadings (Table 5) confirm this: e.g., *Firmness*, *Sugar*, *Color* all have +0.39–0.41 on PC1, while *Pest\_tol*, *Disease\_tol*, *Cracking\_tol* have +0.48 on PC2.

The cultivar scores in PC1–PC2 space (Figure 1) reflect these patterns. Cultivars like Č. **lepotica** and *TopTaste* (high quality) scored high on PC1, while tolerant cultivars *Mildora*, *Zlatka*, and *Valiefka* scored high on PC2. *Krina* and *Nada*, with balanced quality and yield, scored moderately on PC1 and above-average on PC2. Notably, Č. *Rodna* and Č. *Rana* appear on the lower-left (low on both PC1 and PC2), indicating relatively weak performance in both quality and tolerance traits.

Our multi-site evaluation quantified how plum cultivars perform under divergent Albanian conditions. The dominance of *Krina* and *Nada* in Overall Index reflects their broad adaptability: they combined good fruit quality with solid yields and reasonable tolerance across sites. In contrast, Čačanska *Lepotica* excelled in fruit quality (firm, sweet fruit) but was more susceptible to cracking and pests, limiting its overall score. Conversely, *Zlatka* and *Valiefka* showed exceptional tolerance but only moderate quality. The PCA results underscore these trade-offs: PC1 reflects a quality/yield axis, and PC2 a tolerance axis. Cultivars near the origin in Figure 1 (e.g. Č. *Rodna*, *Rana*) were inferior in most traits, consistent with their low indices.

Site differences were evident: higher-elevation Shamoll (Korça) imposed more stress (higher pest pressure and frost risk) and reduced yields, so tolerant varieties shone there. The warm coastal Vlora enhanced fruit ripening and sweetness, favoring quality-sensitive cultivars. These G×E patterns justify a multi-site approach. Similar genotype-by-trait analyses in other fruit crops have

also found distinct cultivar clusters and trait trade-offs[2].

**Table 6.** PCA eigenvalues and key loadings

PC	Eigenvalue	Variance (%)
PC1	5.082	50.18
PC2	3.843	37.94
PC3	0.853	8.42
PC4	0.072	0.71
PC5	0.065	0.64

The first three PCs account for ~96.5% of variance.

Trait	PC1 Loading	PC2 Loading
Taste	0.398	-0.174
Sugar Content	0.391	-0.191
Fruit Color	0.408	-0.159
Firmness	0.398	-0.168
Pest Damage_tol	0.015	0.478
Disease_tol	0.029	0.482
Cracking_tol	-0.003	0.485
Yield	0.337	0.253
Bloom Date	0.362	0.225
Harvest Date	0.344	0.262

Loadings show trait contributions to PC1 and PC2 (note: Bloom/Harvest dates were negated so that earlier dates = higher scores). Bold-faced loadings ( $\geq 0.45$  in absolute) indicate major contributions.

The standardized index approach proved useful for growers and breeders. By converting heterogeneous traits to z-scores, we avoided arbitrary weighting and allowed direct mean-based indices. This is analogous to widely used multi-trait selection indices (e.g. Smith–Hazel) but with equal weighting and without requiring economic weights. The resulting indices closely matched intuitive rankings (e.g. see Table 1) and highlighted both stable performers (Krina, Nada) and niche cultivars (high quality vs high tolerance types). PCA complemented this by revealing that 88% of trait variance is captured in two axes – suggesting future work could focus on these latent dimensions.

Limitations include the small number of sites and only two years; environmental variability beyond 2025 (e.g. drought years) might alter rankings. We also note that statistical significance of differences was not formally tested, so these indices serve as decision-support rather than inferential proof. Future work could include mixed-model  $G \times E$  analysis to

confirm stability ranks, and molecular studies on tolerance traits.

#### 4. Conclusions

This multi-environment study provides a comprehensive, data-driven assessment of plum cultivar performance in Albania. Key findings: Krina and Nada are broadly best-performing across sites and indices; Čaçanska lepotica leads in fruit quality (but with higher pest risk); Mildora and Zlatka are top for stress tolerance. Multi-trait index scoring and PCA biplots offered clear insights into cultivar strengths and trade-offs. These results guide growers on variety choice (e.g. planting Krina or Nada for general production, Lepotica for premium fruit if protective measures are taken, Mildora/Zlatka for low-input systems). Breeders and extension agents can use the trait data and indices (Tables 1–4) to support future evaluations and recommendations.

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