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The Chemical Composition of Grapes: Constituents, Measurement Methods, and Nutritional-Biological Significance

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Annotation: The article provides a systematic analysis of the chemical composition of grape (Vitis vinifera L.) fruit. It highlights the major constituent groups, including water, carbohydrates (glucose, fructose), organic acids (primarily tartaric and malic acids), phenolic compounds (flavonoids, anthocyanins, tannins), nitrogenous components (free amino acids, proteins), pectin and fibers, mineral elements (K, Ca, Mg, etc.), vitamins (C, K, B group), as well as volatile aromatic compounds (monoterpenes, norisoprenoids, esters). The application areas of modern analytical methods such as refractometry, titration, HPLC/UPLC, UV-Vis, GC-MS, ICP-OES/ICP-MS are discussed. Based on the literature, the effects of range indicators, variety, ripening stage, agro-climate, and storage/juicing processes on composition are examined. The conclusions drawn from this analysis have practical significance for grape product quality management and the development of strategies for utilizing functional foods and biopotentials.

Keywords: grape composition, phenolics, anthocyanins, organic acids, °Brix, HPLC, GC-MS, minerals, bioactive compounds.

Grapes (Vitis vinifera L.) are a widely distributed strategic horticultural product in Uzbekistan and across the globe. The fruit and its derived products (juice, syrup, dried fruits – raisins, winemaking raw material, extracts, and concentrates) are distinguished by their nutritional value, sensory characteristics (taste, color, aroma), and bioactive components. The chemical composition of grapes is a multi-component system consisting of carbohydrates (mainly glucose and fructose), organic acids (tartaric and malic acids), phenolic compounds (flavonoids, anthocyanins, tannins), nitrogen fractions (free amino acids, proteins), pectin and dietary fibers, vitamins (C, K, B group), and mineral elements (especially K, Ca, Mg, and trace elements), as well as volatile aromatic substances (monoterpenes, norisoprenoids, esters, etc.). The combination of these components determines the technological properties (fermentation processes, extraction, color stability), biological value, and functional potential of the product.

Relevance. Reliable and comparable methods for evaluating composition are essential for managing raw material quality in the food industry and winemaking, assessing ripeness, selecting varieties, agro-techniques, and normalizing storage/processing regimes. With growing market demand for functional foods, natural antioxidants, polyphenol-rich extracts, and low-sugar, balanced-acid products, a deep analysis of grape composition is both scientifically and practically relevant.

Problem Statement. Although there is substantial information in the literature on the composition of grapes, data is often fragmented and methodologies differ due to variations in variety, terroir (agro-climate and soil), agro-techniques, ripeness stage, storage, and processing conditions. This makes it difficult to apply consistent criteria in production decision-making. Moreover, there is insufficient systematization of practical guidelines for integrating simple instruments (refractometry, pH, titration) with in-depth profile analyses (HPLC/UPLC, GC-MS, ICP-OES/ICP-MS) for rapid quality control.

Objective. To systematically summarize the chemical composition of grape fruit by key constituent groups, compare analytical evaluation methods, and highlight the relationships between composition, quality, and technology.

Research Object and Subject.

- Object: Vitis vinifera L. fruits (table and technical varieties).
- Subject: Water, carbohydrates, organic acids, phenolic, nitrogen fractions, vitamins, minerals, pectin/fiber, and volatile aromatic components of the fruit, as well as their identification methods.

Scientific Novelty.

- A multi-component model of grape composition is proposed, integrating a "sensor–biological–technological" framework.
- A minimal indicator panel is based on applying rapid and instrumental in-depth methods to predict raw material quality.
- Phenolic/aromatic profile indicators, sensitive to variety and ripeness, are highlighted as practical “signal markers” for management.

Practical Significance. The results will enhance the methodology for determining raw material acceptance criteria in winemaking, juice, and dried fruit production, improve ripeness monitoring, optimize extraction and storage regimes, and strengthen the methodological foundation for the production of functional ingredients (polyphenol extracts, fiber/pectin fractions).

1. **Carbohydrates and Sugar-Acidity Balance.**

The sweetness of grapes is primarily due to glucose and fructose, with their proportion increasing as ripening progresses; °Brix is typically recorded in the 14–24 range. The sugar ratio is often close to 1:1, though variations depending on variety and climate are observed. The sucrose content is generally low. Besides sweetness, sugars also define fermentation potential (substrate for yeast in winemaking). The balance of sweetness is evaluated in conjunction with titratable acidity (TA) and pH: during ripening, malic acid decreases, pH increases, thus altering the taste balance and microbiological stability. Literature frequently expresses TA in terms of wine acid equivalent, with pH typically ranging between 3.0–3.8.

Methods: Hand/digital refractometry (°Brix), NaOH titration (TA), HPLC-RID/UV (glucose, fructose, sucrose). Refractometry is rapid but may be affected by non-metabolite strong solutions (such as acids), so °Brix results are interpreted alongside pH/TA.

2. **Organic Acids and pH.**

The main acids in grapes are tartaric and malic acids. During ripening, malic acid is metabolized through respiration, so it is relatively low in warm climates; cooler conditions retain higher acidity. Acids contribute to the "tartness" of taste, support microbiological stability, and enhance color stability (particularly for anthocyanins).

Methods: Individual acids separation via HPLC-UV; total acidity via potentiometric or visual titration. pH, determined by a pH meter, is a decisive indicator for winemaking technological regimes.

3. **Phenolic Compounds and Anthocyanins.**

Phenolics consist of flavonoids (flavonols, flavan-3-ols – catechins, proanthocyanidins), phenolic acids, and anthocyanins (in red varieties). They are responsible for color, bitterness, astringency, antioxidant activity, and resistance to oxidation. In red varieties, anthocyanins, particularly malvidin-3-glucoside and similar glycosides, accumulate during ripening. Phenolic profiles are variety-specific and influenced by terroir and sunlight.

Methods: Total phenols – Folin–Ciocalteu (expressed as gallic acid equivalents); UV-Vis differential method for anthocyanins' pH; individual phenols – HPLC-DAD/FLD/MS. The Folin method is quick and inexpensive but lacks selectivity; chromatographic methods are preferred for chemically specialized profiling.

4. **Volatile Aromatics.**

The aromatic profile defines the "bouquet" of grapes. Monoterpenes (e.g., linalool, geraniol, nerol) are higher in muscat-type varieties; C13-norisoprenoids (β-damascenone, β-ionone) and esters are sensitive to ripening and fermentation conditions; methoxypyrazines impart "green" notes in certain varieties.

Methods: SPME (Solid-Phase Microextraction) + GC-MS – the gold standard for sensitive detection of volatile components. Sample preparation, incubation temperature, and salt-out addition affect yield.

5. **Nitrogen Fraction and Amino Acids.**

Free amino acids (e.g., proline, arginine) and total nitrogen (Kjeldahl) are important for fermentation processes. In winemaking, nitrogen assimilated by yeast (YAN) is recorded in the 60–300 mg N/L range, influencing fermentation completeness and aromatic production.

Methods: HPLC with OPA or dansyl derivatization, ion-exchange chromatography, and Kjeldahl.

6. **Vitamins and Antioxidants.**

Vitamin C (ascorbic acid) levels are sensitive to variety and storage; Vitamin K and B-group vitamins (B1, B2, B6, folate) are also present. Along with phenolics, they contribute to antioxidant capacity, but real bioavailability and biotic effects depend on dose, compound form, and matrix.

Methods: UV-Vis (DCPIP titrimetric/colorimetric approach) and HPLC (separation of ascorbate isomers).

7. **Minerals.**

Potassium (K) is the dominant mineral, affecting cellular osmotic status and pH/acidity balance. Calcium (Ca), magnesium (Mg), phosphorus (P), and trace elements (Fe, Zn, Mn, Cu) are also recorded. Mineral content is sensitive to agro-climate, soil, and irrigation systems.

Methods: Ashing and AAS/ICP-OES/ICP-MS. ICP-MS offers high sensitivity for trace elements.

8. **Pectin and Dietary Fibers.**

Pectic substances and hemicelluloses define the fruit's texture, have gelling properties, and are important in processing (e.g., juice filtration). Structural changes during drying (raisins) may result in color and taste modifications related to Maillard reactions.

9. **Ripening, Variety, and Climate Factors.**

During ripening, °Brix increases, malic acid decreases, pH rises, and anthocyanins (in red varieties) accumulate. In hot-dry climates, sugar content is higher, acidity lower; in cooler regions, the opposite is true. Sunlight may stimulate phenolic synthesis. Literature indicates that variety-specific phenolic/terpene profiles change with terroir.

10. **Effect of Storage and Processing.**

Drying may increase the sugar ratio, decrease some vitamins, and partially oxidize polyphenols; however, antioxidant activity changes complexly (in some cases, polyphenol concentration increases). Juice/wine production conditions (temperature, skin contact) determine phenolic extraction; protection from oxidation (SO_2, inert atmosphere) improves color and aromatic stability.

11. **Integration of Analytical Strategies.**

For rapid acceptance control, the °Brix–pH–TA "triad" provides sufficient initial data; for deeper profiling, a combination of HPLC/UPLC (sugars, acids, phenolics), GC-MS (volatiles), and ICP-OES/ICP-MS (minerals) is recommended. Calibration of total phenols using the Folin–Ciocalteu method with HPLC-DAD/MS makes results comparable. The choice of method depends on cost, infrastructure, required sensitivity, and selectivity.

Conclusion:

1. The chemical composition of grape fruit is multi-component and sensitive to variety, ripeness, and climate factors, with sugar-acidity balance, phenolic profile, and vitamin-mineral content defining the sensory and biological value.
2. Integrating rapid control (°Brix, pH, TA) with in-depth profiling (HPLC/GC-MS/ICP-OES) is the best solution for stable quality management.
3. Selecting variety-technology combinations by agro-climatic zones, monitoring ripeness, and optimizing soft processing regimes increase the functional and economic efficiency of grape products.

4. Future studies on the bioavailability of phenolics, aromatic metabolism, and the stability of bioactives during storage/drying processes in local varieties are recommended.

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