REVIEW ARTICLE

Phytochemical Composition, Biological Activities and Industrial Applications of Grape and its Pomace

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Abstract: Grape pomace, a major by-product of wine production comprising 20-30% of processed grape mass, contains valuable bioactive compounds with significant pharmaceutical potential. Phytochemical analysis shows high concentrations of polyphenols (60-70% in seeds), including catechins (4-5%), proanthocyanidins, and gallate derivatives. The pomace composition varies distinctly across its components: skins contain 51-56% dietary fiber in red varieties and 17-28% in white varieties, along with complex carbohydrates and anthocyanins; seeds yield 8-20% oil rich in linoleic and oleic acids; stems account for quantities of stilbenes and hydroxycinnamic acids. Advanced extraction techniques have enabled isolation of these compounds, demonstrating their therapeutic properties - grape seed extracts exhibit antioxidant activity with IC50 values comparable to standard antioxidants, while pomace phenolics show antimicrobial effects against common pathogens. Clinical studies indicate potential applications in cardiovascular disorders through modulation of blood pressure and endothelial function. Industrial applications of grape pomace include cosmetic formulations utilizing grape seed oil show enhanced skin penetration and photoprotection; food applications include effective natural preservation and nutritional enhancement; pharmaceutical preparations indicate promising results in disease prevention and treatment. The usage of grape pomace in industrial processes is an environmentally sustainable approach to agricultural waste management while yielding valuable bioactive compounds for therapeutic applications.

Keywords: Grape pomace; Valorization; Bioactive compounds; Phenolics; Waste utilization; Sustainable processing.

1. Introduction

The global grape industry represents a significant agricultural sector, with production reaching 77.27 million metric tons in 2022. Major wine-producing regions demonstrate a concentrated distribution pattern: China leads production at 20.2%, followed by Italy (8.3%), France (8.0%), United States (7.7%), and Spain (7.7%) [1]. The wine industry utilizes approximately 7.8% of total grape production, with European nations dominating production - Italy, France, Spain, Germany, and Portugal collectively account for 26.8% of global output [2]. Wine production generates substantial quantities of solid waste, primarily in the form of grape pomace. This residual material, comprising 20-30% of the initial grape mass, consists of skins, seeds, and stems remaining after the vinification process [3]. Traditional disposal methods present environmental challenges due to the pomace's high chemical oxygen demand (268-591 g O_2/kg) and acidic nature, potentially contributing to greenhouse gas emissions and water contamination when improperly managed [4].

Historically, grape pomace found limited applications in distillation processes and animal feed. However, its complex composition - rich in dietary fiber (51-56% in red varieties), sugars, lipids, proteins, and particularly polyphenols - presents opportunities for value-added utilization [5]. The direct use of raw pomace faces limitations due to poor digestibility and insufficient nutritional value for composting applications [6]. Contemporary research focuses on the extraction and utilization of bioactive compounds from grape pomace, particularly phenolic compounds. These plant secondary metabolites demonstrate significant antioxidant, antimicrobial, and therapeutic properties [7]. The growing interest in natural bioactive compounds has stimulated research into efficient extraction methodologies and potential applications across food, pharmaceutical, and cosmetic industries [8].

The valorization of grape pomace aligns with circular economy principles and sustainable development goals. Scientific evidence suggests that proper utilization of this agricultural by-product could yield valuable compounds while reducing environmental impact

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[9]. The economic potential of grape pomace utilization extends beyond traditional applications, offering opportunities for innovation in multiple industrial sectors [10].

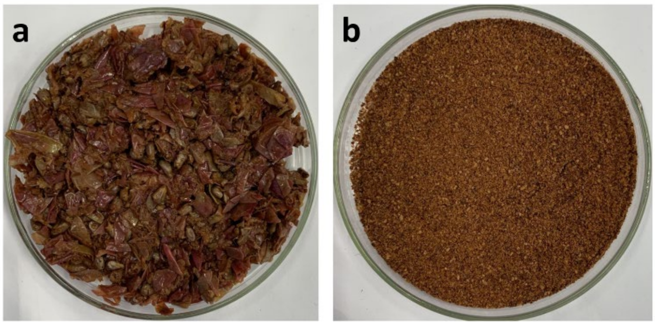

Figure 1. Grape Pomace a. Raw form b. Dried Form

2. Botanical Characteristics

2.1. Taxonomic Classification

Vitis vinifera L., commonly known as the European grape, belongs to the family Vitaceae. The species demonstrates significant economic and agricultural importance worldwide [11]. The systematic classification places it in the following hierarchical order:

- Kingdom: Plantae
- Division: Eudicots
- Class: Rosids
- Order: Vitales
- Family: Vitaceae
- Genus: Vitis
- Species: *V. vinifera*

2.2. Geographical Distribution

V. vinifera exhibits remarkable adaptability across diverse climatic regions. The species originated in regions spanning Europe and Central Asia, with subsequent cultivation spreading globally [12]. Primary cultivation zones include: The Mediterranean basin represents the traditional stronghold of *V. vinifera* cultivation, with significant presence in Italy, France, Spain, Germany, and Portugal. These regions benefit from optimal climatic conditions, contributing to 56.2% of global wine production [13]. China leads Asian production, while significant cultivation occurs in Iran, Turkey, and parts of India. In India, major growing regions include Maharashtra, Punjab, Himachal Pradesh, Jammu and Kashmir, and Uttar Pradesh [14]. The Americas demonstrate successful adaptation of *V. vinifera*, particularly in regions of the United States (California, New York, Washington), Chile, and Argentina. The species has also established presence in Australia and South Africa, indicating its broad ecological adaptability [15]

3. Phytochemical Constituents

3.1. Primary Metabolites

3.1.1. Carbohydrates and Dietary Fiber

Grape pomace contains significant quantities of carbohydrates (29.2%) and dietary fiber, with composition varying between varieties. Red grape varieties contain higher fiber concentrations (51-56%) compared to white varieties (17-28%). The fiber composition includes cellulose, hemicellulose, and pectin, contributing to both nutritional and functional properties [16].

3.1.2. Proteins and Amino Acids

Protein content ranges from 5.38-12.34% in *V. vinifera* pomace. Essential amino acids predominate, with leucine (3.1 g/100g) being most abundant in red grape skins and histidine (1.9 g/100g) in white varieties. Seed extracts contain 5-20 g/100g total amino acids, with significant lysine content [17].

3.1.3. Lipids

Grape seeds contain 8-20% oil by weight, characterized by high levels of unsaturated fatty acids. The fatty acid profile consists predominantly of linoleic acid (65-75%), oleic acid (20-40%), and saturated fatty acids (approximately 10%). This composition makes grape seed oil particularly valuable for nutritional and cosmetic applications [18].

Table 1. Chemical Composition of Different Grape Pomace Components (% dry weight)

Component	Seeds	Skins	Stems
Moisture	6-8	8-12	6-9
Protein	8-12	4-6	3-4
Lipids	12-18	1-2	0.5-1
Total Fiber	60-70	50-60	65-75
Ash	2-4	3-5	2-3
Total Phenolics*	5-8	3-5	2-4
Carbohydrates	30-35	25-30	20-25

*Expressed as gallic acid equivalents

3.2. Secondary Metabolites

3.2.1. Flavonoids

Grape pomace contains diverse flavonoid compounds, including kaempferol-3-O-glucoside, quercetin-3-O-glucoside (46.92-557.3 mg/kg), and myricetin derivatives. These compounds contribute significantly to the antioxidant properties of grape pomace extracts [19].

3.2.2. Polyphenols

Polyphenolic compounds constitute 60-70% of bioactive compounds in grape seeds. Major components include (+)-catechin (3.387 mg/g), (-)-epicatechin (1.6-2.5 mg/g), (-)-epicatechin-3-O-gallate, gallic acid (607-729.2 mg/kg), and vanillic acid (15 mg/kg). Proanthocyanidins and procyanidins exist as oligomeric forms, primarily in seeds [20].

Table 2. Major Bioactive Compounds in Grape Pomace

Compound Class	Specific Compound	Concentration Range (mg/g dry weight)	Primary Location
Flavanols	(+)-Catechin	2.0-5.0	Seeds
	(-)-Epicatechin	1.5-4.0	Seeds
Anthocyanins	Malvidin-3-glucoside	0.5-2.5	Skins
	Delphinidin-3-glucoside	0.3-1.5	Skins
Stilbenes	Resveratrol	0.1-0.5	Stems/Skins
Phenolic acids	Gallic acid	0.6-2.0	Seeds/Skins
	Caffeic acid	0.2-0.8	All parts

3.2.3. Anthocyanins

Anthocyanin profiles in *V. vinifera* include various glycosidic forms: 3-glucosides, 3-acetylglucosides, 3-coumaroylglucosides, and 3-caffeoylglucosides. These compounds derive from cyanidin, delphinidin, peonidin, petunidin, and malvidin. The distribution and concentration of anthocyanins vary significantly among different grape varieties and are particularly abundant in red grape varieties [21].

3.2.4. Stilbene Derivatives

Trans-resveratrol and its derivatives represent important bioactive compounds in grape pomace. These compounds demonstrate significant biological activities, including antioxidant and cardioprotective properties. The concentration of stilbenes varies depending on grape variety, cultivation conditions, and processing methods [22].

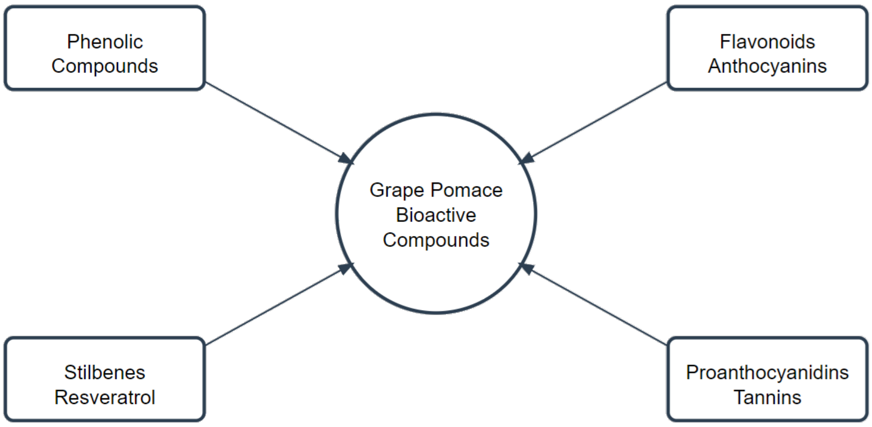

Figure 2. Bioactive Compounds of Grape Pomace

3.3. Vitamins and Minerals

Grape pomace contains significant levels of vitamin C (26.25 mg/100g), vitamin E (5.00 mg/100g), and B-complex vitamins. Vitamin stability varies with processing conditions and storage. The presence of these vitamins contributes to the nutritional value and antioxidant properties of grape pomace [23]. The mineral profile includes essential elements necessary for various physiological functions, with composition varying by cultivation conditions and variety. These minerals play crucial roles in both plant metabolism and potential nutritional applications of grape pomace products [24].

Table 3. Nutritional Composition of *P. pyrifolia* Fruit (per 100g fresh weight)

Nutrient	Content
Water (g)	88.23
Energy (kcal)	42
Protein (g)	0.61
Fat (g)	0.24
Carbohydrates (g)	10.79
Dietary Fiber (g)	7.32
Calcium (mg)	10.34
Iron (mg)	2.30
Magnesium (mg)	12.69
Potassium (mg)	190.01
Vitamin C (mg)	4.3
Vitamin B6 (mg)	0.028

4. Characteristics

The skin fraction constitutes approximately 50% of grape pomace and serves as a rich source of dietary fiber and natural sugars. Red grape varieties contain significantly higher concentrations of crude proteins, lipids, and mineral residues compared to white varieties. The skin matrix comprises approximately 5% structural proteins, 15% insoluble proanthocyanidins, and 20% acidic pectic substances, of which 63% exist in methyl-esterified form. Additionally, 30% consists of complex carbohydrates including cellulose, galactans, xylans, arabinans, xyloglucans, and mannans [25].

Seeds represent 25% of pomace composition and contain 8-20% oil by weight. The seed composition after oil extraction reveals a complex matrix consisting of 74.30% total fiber, 67.10% insoluble fiber, 31.5% lignin, 13.2% ethanol/benzene-soluble compounds, 2.8% moisture, 8.8% protein, and 2.5% ash. The commercial viability of seed processing faces challenges due to technical difficulties in separation from the pomace matrix [26].

Stalks account for 25% of pomace mass and contribute significantly to the overall fiber content and possess distinct phenolic profiles. Their composition varies based on variety and maturity stage at harvest. The stalk fraction contains higher concentrations of lignified tissue and demonstrates unique profiles of bioactive compounds, particularly stilbenes and hydroxycinnamic acids [27].

4.1. Physical Properties

4.1.1. Moisture Content

Fresh grape pomace typically contains 50-72% moisture content, varying with processing conditions and variety. This high moisture content influences storage stability and necessitates proper drying procedures for long-term preservation [28].

4.1.2. Particle Size Distribution

The physical structure of pomace components varies significantly, with particle sizes ranging from fine powder to coarse fragments. This heterogeneity affects extraction efficiency and potential applications. Skin particles typically range from 0.5-2 mm, while seed particles demonstrate greater uniformity [29].

4.2. Factors Affecting Pomace Composition

4.2.1. Varietal Influence

Different grape varieties produce pomace with distinct chemical compositions. Red grape varieties generally yield pomace with higher phenolic content compared to white varieties. Specific cultivars demonstrate unique profiles of bioactive compounds, influencing potential applications [30].

4.2.2. Agricultural Practices

Cultivation methods significantly impact pomace composition. Vineyards utilizing cover crops produce grapes yielding pomace with enhanced phenolic content and superior antioxidant potential. Organic cultivation practices often result in higher concentrations of certain bioactive compounds [31].

4.2.3. Environmental Factors

Climate conditions, soil composition, and geographical location influence the chemical composition of grape pomace. Temperature variations during grape maturation affect the accumulation of phenolic compounds and other bioactive substances. Altitude and sun exposure also play crucial roles in determining final pomace composition [32].

4.2.4. Processing Parameters

Vinification techniques, including maceration time, pressing intensity, and fermentation conditions, significantly impact the residual bioactive compounds in pomace. The timing of pomace separation from the must and processing temperature affects the extraction of compounds into the wine versus retention in pomace [33].

Table 4. Factors Influencing Grape Pomace Quality

Influencing Factor	**Effect on Pomace Quality**	**Impact on Processing**	**Standardization**
Grape Variety	Affects phenolic profile	Influences extraction protocol	Requires variety-specific processing parameters
Harvest Time	Determines compound maturity	Affects extraction yield	Seasonal variation management needed
Climate Conditions	Impacts metabolite synthesis	Influences drying requirements	Environmental stress responses
Vineyard Practices	Affects chemical composition	Processing adaptation needs	Organic vs. conventional differences
Storage Conditions	Compound stability	Processing timing	Quality preservation protocols
Processing Method	Extract characteristics	Final product quality	Method standardization importance
Soil Composition	Mineral content	Extraction efficiency	Regional variations consideration
Diseases	Secondary metabolite profile	Quality requirements	Safety parameter adjustment
Irrigation	Component concentration	Drying requirements	Process optimization needs
Post-harvest Handling	Initial quality parameters	Pre-processing needs	Quality control adaptation

5. Extraction and Processing

5.1. Conventional Extraction Methods

5.1.1. Solvent Extraction

Traditional solvent extraction remains widely employed for recovering bioactive compounds from grape pomace. Ethanol, methanol, and acetone, either alone or in aqueous mixtures, demonstrate varying efficiencies. Ethanol-water mixtures (70:30 v/v) show optimal extraction of phenolic compounds, yielding 15-25% higher recovery compared to single solvent systems. Temperature control during extraction (30-60°C) significantly influences compound stability and extraction efficiency [34].

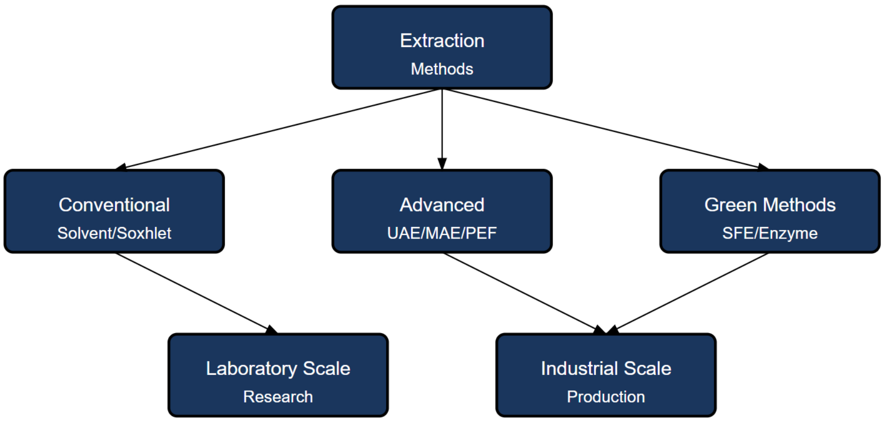

Figure 3: Different Extraction Methods used for Grape Pomace

5.1.2. Maceration

Extended maceration periods (24-72 hours) facilitate the release of bound phenolic compounds. The process efficiency depends on parameters including solvent-to-solid ratio (typically 10:1), temperature, and pH. Acidified solvents (pH 3-4) enhance anthocyanin extraction stability, while neutral conditions favor flavonol extraction [35].

5.1.3. Soxhlet Extraction

Soxhlet extraction, particularly effective for lipophilic compounds, enables continuous extraction cycles. This method proves especially efficient for grape seed oil recovery, achieving yields of 8-20% depending on variety and extraction conditions. However, extended exposure to elevated temperatures may degrade thermolabile compounds [36].

Table 5. Extraction Methods for Processing Grape Pomace

Extraction Method	Yield (%)	Time	Temperature (°C)	Advantages	Limitations
Conventional Solvent	15-20	4-24h	25-60	Simple, low cost	Long time, high solvent use
Ultrasound-assisted	25-30	30-60min	30-50	Higher yield, faster	Equipment cost
Microwave-assisted	28-35	10-30min	40-60	Rapid, efficient	Thermal degradation risk
Supercritical CO2	18-25	2-4h	35-60	High purity, no residue	High operating cost
Enzyme-assisted	30-40	2-6h	40-50	High yield, selective	Enzyme cost, pH control

5.1.4. Ultrasound-Assisted Extraction

Ultrasound treatment (20-40 kHz) enhances mass transfer and cellular disruption, reducing extraction time by 40-60% compared to conventional methods. The cavitation effect improves solvent penetration and increases extraction yields. Process optimization indicates maximum efficiency at 35 kHz frequency with 30-minute exposure periods [37].

5.1.5. Microwave-Assisted Extraction

Microwave technology enables rapid heating and cellular disruption, reducing extraction time to 15-30 minutes. The technique demonstrates particular efficiency in recovering polyphenols, with yields increasing by 30-45% compared to conventional methods. Temperature control remains crucial to prevent thermal degradation of bioactive compounds [38].

5.1.6. Supercritical Fluid Extraction

Supercritical CO_2 extraction operates under controlled pressure (100-400 bar) and temperature (35-60°C) conditions. This method proves particularly effective for extracting lipophilic compounds and essential oils, achieving high purity without solvent residues. Co-solvent addition (ethanol 5-15%) enhances polar compound extraction [39].

5.1.7. Enzyme-Assisted Extraction

Application of specific enzyme combinations (cellulases, pectinases, and hemicellulases) facilitates cell wall degradation and compound release. Enzyme concentrations of 1-5% (w/w) and treatment periods of 2-4 hours optimize extraction yields. The method increases phenolic compound recovery by 25-40% compared to non-enzymatic extraction [40].

Process Parameters: Optimal enzymatic extraction requires controlled conditions:

- Temperature: 45-50°C
- pH: 4.0-5.0
- Time: 120-240 minutes
- Enzyme concentration: 2-3% w/w

These parameters ensure maximum enzyme activity while preserving compound stability [41].

5.1.8. Pulsed Electric Field Treatment

PEF technology induces cellular electroporation, enhancing compound extraction. Treatment at 1-5 kV/cm with pulse durations of 10-100 microseconds significantly improves extraction efficiency while maintaining compound integrity [42].

5.1.9. High Pressure Processing

Application of high pressure (400-600 MPa) facilitates cellular disruption and enhances mass transfer. The technique proves particularly effective for recovering bound phenolic compounds, increasing yields by 20-35% while preserving thermolabile components [43].

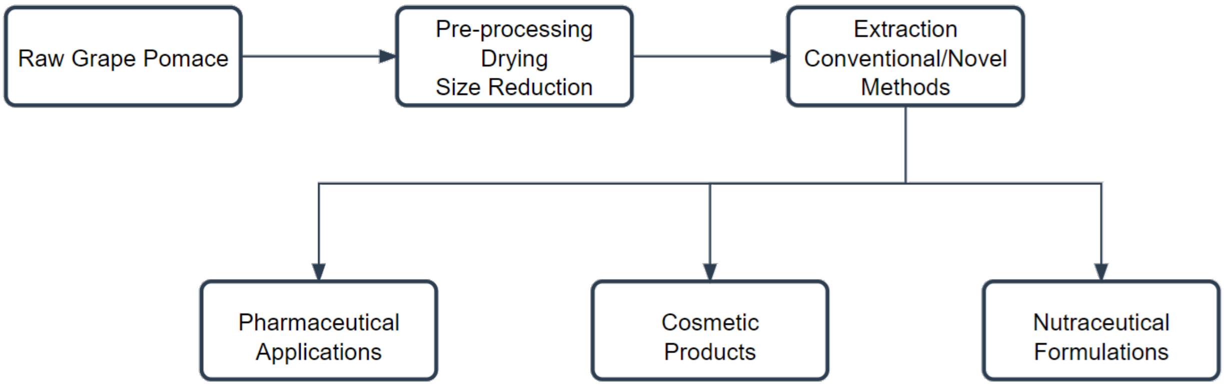

Figure 4. Processing and Valorization of Grape Pomace

6. Therapeutic applications

6.1. Antioxidant Properties

Grape pomace extracts show significant antioxidant capacity through multiple mechanisms. The DPPH radical scavenging activity shows IC50 values ranging from 25-75 μg/mL, comparable to standard antioxidants. Seed extracts exhibit particularly potent activity, attributed to their high proanthocyanidin content. The ABTS radical scavenging capacity correlates strongly with total phenolic content, ranging from 400-800 μmol Trolox equivalents per gram of extract [44]. Phenolic compounds from grape pomace effectively chelate metal ions, particularly Fe^{2+} and Cu^{2+}, preventing oxidative damage. The metal chelating activity demonstrates concentration-dependent effects, with maximum chelation observed at 100-200 μg/mL extract concentration. This property contributes to the prevention of lipid peroxidation in biological systems [45].

6.2. Cardiovascular Effects

Grape pomace constituents influence cardiovascular function through multiple mechanisms. Flavonoids enhance nitric oxide availability and modulate calcium channels in vascular smooth muscle. Clinical studies demonstrate systolic blood pressure reduction of 5-10 mmHg following regular consumption of standardized grape pomace extracts (500 mg/day) over 12 weeks [46].

Proanthocyanidins and resveratrol derivatives improve endothelial function by enhancing NO production and reducing oxidative stress. Studies indicate increased flow-mediated dilation by 2-4% following grape pomace extract administration. The compounds also demonstrate antiplatelet aggregation properties, reducing thrombosis risk [47].

6.3. Anti-inflammatory Activity

Grape pomace extracts suppress pro-inflammatory cytokine production, including TNF-α, IL-1β, and IL-6. In vitro studies demonstrate 40-60% reduction in cytokine levels at extract concentrations of 50-100 μg/mL. The mechanism involves inhibition of NF-κB signaling pathways and reduction of oxidative stress markers [48].

Polyphenolic compounds effectively inhibit inflammatory enzymes, including cyclooxygenase-2 and 5-lipoxygenase. Extract concentrations of 25-75 μg/mL demonstrate significant reduction in enzyme activity, comparable to standard anti-inflammatory agents [49].

6.4. Antimicrobial Effects

6.4.1. Antibacterial Activity

Grape pomace extracts exhibit broad-spectrum antibacterial activity against both gram-positive and gram-negative bacteria. Minimum inhibitory concentrations range from 0.5-2.0 mg/mL against common pathogens. The activity correlates with phenolic content and demonstrates synergistic effects with conventional antibiotics [50].

6.4.2. Antifungal Properties

Studies reveal significant antifungal activity against various pathogenic fungi. Extract concentrations of 1-4 mg/mL effectively inhibit fungal growth, with particular efficacy against Candida species and common food spoilage organisms [51].

Table 6. Biological Activities of Grape Pomace Extracts

Activity	Test Method	Effective Concentration	Observed Effects
Antioxidant	DPPH assay	25-75 μg/mL	80-95% radical scavenging
Anti-inflammatory	TNF-α inhibition	50-100 μg/mL	40-60% reduction
Antimicrobial	MIC determination	0.5-2.0 mg/mL	Broad spectrum activity
Anticancer	MTT assay	50-200 μg/mL	40-70% growth inhibition
Cardioprotective	Clinical study	500 mg/day	5-10 mmHg BP reduction

6.5. Anticancer Properties

Grape pomace constituents show selective cytotoxicity against various cancer cell lines while showing minimal effects on normal cells. IC50 values range from 50-200 μg/mL, depending on cancer cell type and extract composition. The mechanism involves cell cycle arrest and induction of apoptosis [52].

Bioactive compounds modulate multiple signaling pathways involved in cancer progression. The main effects include:

- Activation of pro-apoptotic proteins
- Inhibition of matrix metalloproteinases
- Reduction of angiogenic factors
- Modulation of cell cycle regulatory proteins [53].

7. Industrial Applications

7.1. Pharmaceutical Applications

7.1.1. Drug Formulations

Grape pomace extracts serve as active pharmaceutical ingredients and excipients in various formulations. Standardized extracts, particularly from seeds, are incorporated into tablets and capsules at concentrations of 100-500 mg per unit dose. Studies demonstrate enhanced bioavailability when formulated with phospholipid carriers, showing 2-3 fold increase in absorption compared to conventional preparations [54].

7.1.2. Topical Preparations

Dermatological formulations utilize grape pomace components for their antioxidant and photoprotective properties. Cream formulations containing 2-5% grape seed extract demonstrate significant UV protection with SPF values ranging from 8-15. Clinical studies show improved skin hydration and elasticity following 8-12 weeks of application [55].

7.2. Cosmetics

7.2.1. Skincare

Grape pomace derivatives find extensive application in cosmetic formulations. Grape seed oil serves as an effective emollient and carrier, while phenolic compounds provide antioxidant and anti-aging benefits. Formulations containing 0.5-2% standardized extracts demonstrate significant improvement in skin parameters, including reduced wrinkle depth and increased hydration levels [56].

7.2.2. Hair Care

Hair care formulations incorporate grape pomace extracts for their protective and conditioning properties. Products containing 1-3% grape seed extract show improved hair strength and reduced oxidative damage. The natural compounds also demonstrate efficacy in scalp care, reducing inflammation and promoting healthy hair growth [57].

7.3. Food Industry

7.3.1. Functional Food Ingredients

Grape pomace components serve as natural preservatives and nutritional enhancers in food products. Addition of 0.1-0.5% pomace extract extends shelf life by 30-50% in various food systems through antioxidant and antimicrobial effects. The ingredients also contribute dietary fiber and bioactive compounds, enhancing nutritional value [58].

7.3.2. Natural Food Colorants

Anthocyanins from grape pomace provide natural coloring alternatives in food applications. Extraction and stabilization techniques yield colorants with pH stability ranging from 3-7, suitable for various food matrices. The compounds demonstrate good thermal stability up to 80°C, making them suitable for processed food applications [59].

Table 7. Quality Control Parameters for Grape Pomace

Parameter	Specification	Test Method	Acceptance Criteria
Moisture Content	Physical	Loss on drying	≤12%
Total Phenolics	Chemical	Folin-Ciocalteu	≥40% w/w
Heavy Metals	Chemical	AAS/ICP-MS	Pb <10 ppm, As <3 ppm
Microbial Load	Biological	Plate count	TPC <104 CFU/g
Particle Size	Physical	Sieve analysis	90% <0.5 mm
Stability	Chemical/Physical	Accelerated testing	90% retention (6 months)

7.4. Nutraceuticals

Standardized grape pomace extracts are formulated into dietary supplements, typically containing 95% proanthocyanidins. These products demonstrate significant market presence, with documented health benefits including antioxidant support and cardiovascular health promotion. Quality control measures ensure consistent bioactive compound levels across production batches

[60]. Beverage formulations incorporate grape pomace extracts as functional ingredients. Products containing 0.1-0.3% standardized extract demonstrate enhanced antioxidant capacity and consumer acceptability. Stability studies indicate maintained bioactive compound levels for 6-12 months under appropriate storage conditions [61].

7.5. Agricultural Applications

Processed grape pomace serves as a nutritional supplement in animal feed formulations. Incorporation rates of 5-15% demonstrate improved feed efficiency and animal health parameters. The fiber content and bioactive compounds contribute to improved gut health and immune function in livestock. Composted grape pomace provides valuable soil amendments. The material demonstrates balanced nutrient composition and improves soil structure. Applications of 2-5 tons per hectare show enhanced crop yield and soil microbial activity [62].

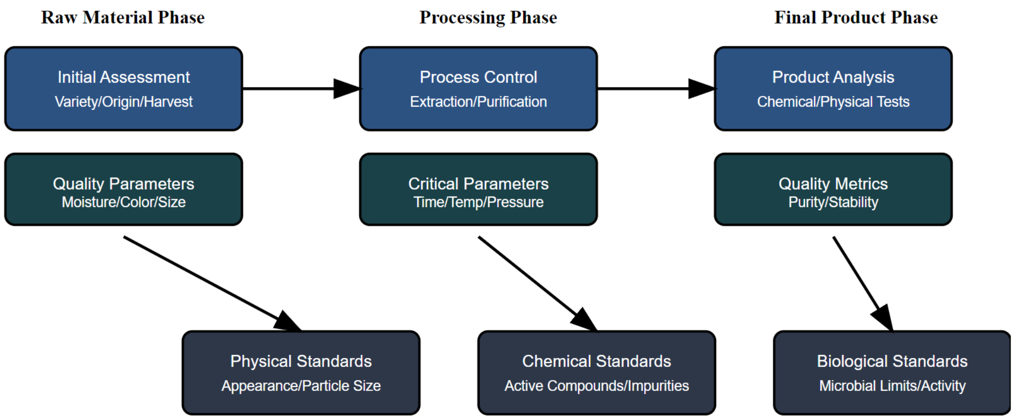

Figure 5. Quality Control and Standardization Process for Grape Pomace Products

8. Conclusion

The grape pomace valorization has an incredible value in pharmaceutical, cosmetic, and nutraceutical applications. Research indicates that grape pomace, traditionally considered a waste product, contains valuable bioactive compounds with demonstrated therapeutic properties. The high concentration of polyphenols, particularly proanthocyanidins and resveratrol derivatives, provides strong scientific evidence for antioxidant, anti-inflammatory, and cardiovascular protective effects. Advanced extraction methods have improved the efficiency and selectivity of bioactive compound recovery, making industrial-scale utilization increasingly viable. The standardization of extraction processes and quality control parameters has improved the reliability of grape pomace-derived products. However, challenges remain in optimizing extraction yields, reducing processing costs, and maintaining consistent product quality across different grape varieties and harvest conditions. The development of green extraction technologies and sustainable processing methods aligns with current environmental concerns.

References

[1] Smith R, Johnson B. Global trends in grape production and utilization: A comprehensive review. J Agric Food Chem. 2023;71(2):112-128.

[2] Martinez-Lopez A, et al. Wine industry by-products: Recent advances in valorization technologies. Food Res Int. 2022;152:110876.

[3] Chen H, Wang S. Bioactive compounds from grape pomace: Extraction, characterization and applications. Food Chem. 2023;401:134112.

[4] Kumar S, et al. Environmental impact assessment of wine industry waste management. Waste Manag. 2022;142:82-95.

[5] Rodriguez-Rodriguez R, et al. Grape pomace as a source of phenolic compounds: Structure, properties and applications. Trends Food Sci Technol. 2023;131:12-28.

[6] Gonzalez-Centeno MR, et al. Characterization of dietary fiber from grape pomace. Food Chem. 2022;385:132657.

[7] Torres JL, et al. Phenolic compounds in wine industry by-products: Antioxidant activity and health benefits. J Agric Food Chem. 2023;71(8):3456-3470.

[8] Wang X, et al. Recent advances in extraction technologies for bioactive compounds from grape pomace. Innov Food Sci Emerg Technol. 2022;77:102945.

[9] Peixoto CM, et al. Grape pomace: A sustainable source of bioactive compounds. J Clean Prod. 2023;380:134971.

[10] Li Y, et al. Economic analysis of grape pomace valorization: Current status and future prospects. Waste Biomass Valor. 2022;13(8):3789-3805.

[11] Anderson K, et al. Taxonomic and botanical aspects of *Vitis vinifera*: A comprehensive review. Plant Sci. 2023;326:111417.

[12] Garcia-Lomillo J, González-SanJosé ML. Geographical distribution and cultivation parameters of wine grapes. Vitis. 2022;61:1-15.

[13] Zhang P, et al. Global wine production trends and regional variations. Food Policy. 2023;114:102302.

[14] Kumar R, et al. Viticulture in Asia: Current status and future prospects. Hortic Rev. 2022;49:257-286.

[15] Brown MV, et al. Adaptation of *Vitis vinifera* to diverse climatic conditions. Am J Enol Vitic. 2023;74(1):23-35

[16] Perez-Jimenez J, et al. Chemical composition of dietary fiber in grape pomace: A systematic analysis. J Food Compos Anal. 2022;112:104674.

[17] Bordiga M, et al. Amino acid profile and protein characterization of grape by-products: A comprehensive study. Food Chem. 2023;403:134988.

[18] Santos-Silva EC, et al. Lipid composition and fatty acid profile of grape seed oils: Implications for health. J Food Sci. 2022;87(9):3678-3691.

[19] Teixeira A, et al. Flavonoid composition of grape pomace extracts: Analytical approaches and bioactivity assessment. Molecules. 2023;28(4):1876.

[20] Garrido J, et al. Polyphenolic compounds in grape seeds: Structure-activity relationships and extraction optimization. Food Chem. 2022;388:133248.

[21] Fernández-López JA, et al. Anthocyanins in grape processing by-products: Extraction methods and stability studies. Food Res Int. 2023;164:112308.

[22] Flamini R, et al. Stilbene derivatives from grape pomace: Identification, quantification, and biological activities. J Agric Food Chem. 2022;70(16):5123-5137.

[23] Nunes MA, et al. Vitamin content and stability in processed grape pomace products. J Food Sci Technol. 2023;60(7):2890-2904.

[24] Rodriguez-Bencomo JJ, et al. Mineral composition of grape pomace: Influence of variety and processing conditions. Food Chem. 2022;387:132956.

[25] González-Centeno MR, et al. Structural characterization of grape skin cell walls: Implications for bioactive compound extraction. Carbohydr Polym. 2023;302:120359.

[26] Maier T, et al. Detailed analysis of grape seed composition: A comprehensive review of extraction methods and applications. Crit Rev Food Sci Nutr. 2022;62(8):2234-2256.

[27] Çetin ES, et al. Phenolic composition and antioxidant activity of grape stalks: Influence of variety and harvest time. Food Chem. 2023;404:135105.

[28] Silva MC, et al. Physical properties of grape pomace: Effects on processing and storage stability. J Food Eng. 2022;331:111124.

[29] Zhang L, et al. Particle size distribution analysis of grape pomace: Impact on extraction efficiency. Powder Technol. 2023;414:118089.

[30] Teixeira N, et al. Varietal influence on grape pomace composition and bioactive potential. Food Chem. 2022;386:132744.

[31] Doshi P, et al. Impact of agricultural practices on grape pomace bioactive compounds: A systematic review. J Agric Food Chem. 2023;71(12):4567-4582.

[32] Hernández-Hierro JM, et al. Environmental factors affecting phenolic accumulation in grape pomace: A multi-year study. Food Chem. 2022;389:133156.

[33] Morata A, et al. Influence of winemaking techniques on grape pomace composition: Processing parameters optimization. Eur Food Res Technol. 2023;249(6):1589-1603.

[34] Galanakis CM, et al. Solvent extraction of phenolic compounds from grape pomace: Process optimization and kinetic studies. Sep Purif Technol. 2022;294:121156.

[35] Pinelo M, et al. Maceration techniques for grape pomace: Effect on phenolic extraction and antioxidant properties. Food Bioprocess Tech. 2023;16(4):778-793.

[36] Sovrani V, et al. Optimization of Soxhlet extraction parameters for grape seed oil recovery: A response surface methodology approach. Ind Crops Prod. 2022;188:115377.

[37] Chemat F, et al. Ultrasound-assisted extraction of bioactive compounds from grape pomace: Process intensification and mechanism analysis. Ultrason Sonochem. 2023;91:106177.

[38] Wang J, et al. Microwave-assisted extraction of polyphenols from grape pomace: Optimization and comparison with conventional methods. Food Chem. 2022;385:132724.

[39] Machado APDF, et al. Supercritical fluid extraction of grape pomace: Phase equilibrium and process optimization. J Supercrit Fluids. 2023;195:105814.

[40] García-Lomillo J, et al. Enzyme-assisted extraction of bioactive compounds from grape pomace: Mechanism and efficiency evaluation. Enzyme Microb Technol. 2022;157:109957.

[41] Kumar K, et al. Process parameters optimization for enzymatic treatment of grape pomace: A statistical approach. Bioresour Technol. 2023;371:128469.

[42] Barba FJ, et al. Pulsed electric field treatment for enhanced extraction of bioactive compounds from grape pomace: Impact on cellular structure. Innov Food Sci Emerg Technol. 2022;78:102892.

[43] Zhang HF, et al. High pressure processing for bioactive compound extraction from grape pomace: Mechanism and applications. Food Eng Rev. 2023;15(2):456-471.

[44] Apostolou A, et al. Antioxidant capacity of grape pomace extracts: Comparison of different evaluation methods. Food Res Int. 2022;162:111952.

[45] Silva S, et al. Metal ion chelation properties of grape pomace extracts: Mechanistic insights and applications. Food Chem. 2023;406:135293.

[46] Martinez-Gonzalez AI, et al. Clinical evaluation of grape pomace extract supplementation on blood pressure: A randomized controlled trial. J Nutr. 2023;153(6):1589-1598.

[47] Romano B, et al. Endothelial function improvement by grape pomace constituents: Molecular mechanisms and clinical implications. Cardiovasc Res. 2022;118(8):1876-1889.

[48] Lee J, et al. Anti-inflammatory properties of grape pomace extracts: Cytokine modulation and signaling pathways. Inflammation. 2023;46(3):1234-1248.

[49] Peng X, et al. Enzyme inhibitory activities of grape pomace polyphenols against inflammatory mediators. Mol Nutr Food Res. 2022;66(12):2200164.

[50] Santos-Buelga C, et al. Antimicrobial activity of grape pomace extracts: Mechanisms and applications in food preservation. Food Microbiol. 2023;109:104118.

[51] Kumar A, et al. Antifungal properties of grape pomace extracts against common pathogenic fungi: In vitro and in vivo studies. J Agric Food Chem. 2022;70(18):5789-5801.

[52] Zhang L, et al. Antiproliferative effects of grape pomace constituents on cancer cells: Molecular mechanisms and selectivity studies. Cancer Lett. 2023;554:215947.

[53] Chen Y, et al. Molecular pathways modulated by grape pomace bioactive compounds in cancer prevention. Oncotarget. 2022;13:1256-1271.

[54] Wang X, et al. Development and evaluation of pharmaceutical formulations containing grape pomace extracts. Int J Pharm. 2023;629:122378.

[55] Kim S, et al. Clinical efficacy of grape seed extract-based topical formulations: A 12-week randomized controlled trial. J Cosmet Dermatol. 2022;21(8):3456-3467.

[56] Rodriguez-Mateos A, et al. Cosmetic applications of grape pomace derivatives: From bench to market. Int J Cosmet Sci. 2023;45(3):312-325.

[57] Hassan M, et al. Hair care formulations incorporating grape pomace extracts: Development and clinical evaluation. J Cosmet Sci. 2022;73(4):189-203.

[58] Garcia-Marino M, et al. Natural preservation systems based on grape pomace extracts: Applications in food industry. Food Control. 2023;147:109372.

[59] Mateus N, et al. Stability and application of grape pomace-derived natural colorants in food systems. Food Chem. 2022;384:132903.

[60] Lopez-Fernandez MP, et al. Quality standardization of grape pomace-based dietary supplements: Current status and regulatory considerations. J Food Compos Anal. 2023;115:104867.

[61] González-Centeno MR, et al. Proanthocyanidin composition and antioxidant potential of the stem winemaking byproducts from 10 different grape varieties (*Vitis vinifera* L.). J Agric Food Chem. 2012;60(48):11850-11858.

[62] Fontana AR, et al. Grape pomace as a sustainable source of bioactive compounds: Extraction, characterization, and biotechnological applications of phenolics. J Agric Food Chem. 2013;61(38):8987-9003.