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Grape Seeds Processing: An Engineering Review of Processing Parameters, Yield Determinants, and Predictive Models

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Grape seeds, generated in large quantities as by-products of the Viti vinicultural industry, represent a valuable raw material for the cascading recovery of high-quality edible oil and polyphenolic compounds within an integrated biorefinery. This paper critically examines conventional and emerging extraction technologies for grape seeds, including mechanical pressing, solid–liquid extraction, subcritical water extraction, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and supercritical fluid extraction (SCO2). Focus is placed on the influence of key engineering parameters such as operating pressure, temperature, solvent flow dynamics, solid-to-solvent ratio, and particle size on mass transfer rates, oil yield, and bioactive stability. A quantitative techno-economic and sustainability comparison is established across green extraction routes to assess energy demands, scalability, and operational feasibility. Furthermore, process modelling approaches including solid–liquid mass transfer kinetics and the Broken and Intact Cell (BIC) model, are rigorously detailed, clarifying fundamental assumptions and boundary limits for scale-up and optimization.

1. Introduction

Grape seeds are increasingly gaining recognition as a valuable by-product of vinification due to their high lipid content and bioactive compounds concentration. In 2012, global wine production exceeded 252 million hectolitres, with the European Union contributing the majority, particularly France, Spain and Italy. Italy alone accounted for approximately 40 million hectolitres, serving as a focal point for numerous studies on grape seed extraction (Duba and Fiori, 2015). Vinification generates substantial solid residues, averaging over 0.3 kg per kilogram of processed grapes. Grape marc constitutes approximately two-thirds of these solids, with the remainder consisting of wine lees, that is composed of about 50 % skins, 25 % stems and 25 % seeds (Bacic, 2003). Recent research has highlighted the potential for valorising these by-products through the recovery of lipids, phenolic compounds and dietary fibres, making grape seeds a promising substrate for extraction processes aimed at producing high-value functional and industrial products (Lopes et al., 2025). In response to the growing interest, various extraction methodologies have been developed and optimised to improve the recovery of lipids and the related bioactive compounds from grape seeds. Extraction efficiency is strongly dependent on thermodynamic conditions, solvent properties, mass transfer dynamics, material pretreatment and equipment configuration (Bacic, 2003). This paper provides a detailed analysis of extraction technologies, process parameters influencing the yield and modelling approaches used to describe, correlate and forecast extraction performance.

2. Review Methodology

Literature was systematically sourced from Scopus, Web of Science, and ScienceDirect covering peer-reviewed studies published between 2000 and 2026. Search strings combined terms: ("grape seed" OR "grape pomace") AND ("supercritical CO2" OR "ultrasound" OR "microwave" OR "leaching") AND ("mass transfer" OR "kinetic model" OR "broken and intact cell"). Selection criteria prioritized studies presenting quantitative operating data,

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mass balances, kinetic rate constants, or techno-economic metrics. Descriptive agronomic and purely non-extractive characterization studies were excluded.

3. Unit Operations and Extraction Technologies

The primary extraction technologies for grape seed valorization differ significantly in selectivity, solvent requirements, and operational complexity (Lucarini et al., 2018; An et al., 2023). The generalized technical flowsheets are illustrated in figure 1 below (An et al., 2023).

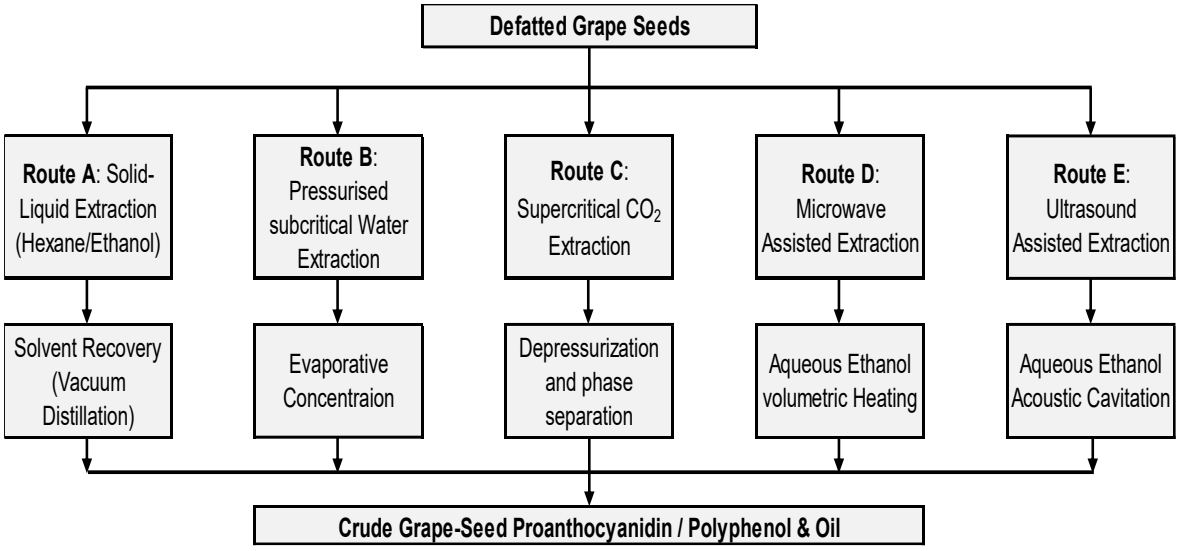


Figure 1: Schematic flow chart of extraction technologies for grape seed processing: a) Solid–liquid extraction; b) Water/subcritical water extraction; c) Supercritical Carbon Dioxide (CO_2) extraction; d) Microwave-assisted extraction; e) Ultrasound-assisted extraction (adapted from An et al., 2023).

3.1 Mechanical Pressing

Mechanical screw or hydraulic pressing applies compressive force to rupture seed structures and release oil (Rodríguez-Blázquez et al., 2025). Although chemical-free and operationally straightforward, incomplete cell disruption typically restricts oil recovery to 50–60%, leaving significant residual lipids in the press cake (Rodríguez-Blázquez et al., 2025; Lopes et al., 2025).

3.2 Solid–Liquid Extraction (Leaching)

Solid–liquid extraction involves solute leaching from the solid seed matrix into a liquid solvent phase (Wilson et al., 2013; Li et al., 2016). Non-polar organic solvents such as n-hexane are conventionally employed for lipid recovery, whereas polar solvents (aqueous ethanol or acetone) target proanthocyanidins (Bucić-Kojić et al., 2013; An et al., 2023). Extraction rates depend on solvent diffusion through the boundary layer and internal porous seed network (Li et al., 2016). Major industrial drawbacks include solvent flammability, environmental emissions, and the energy required for solvent distillation (Li et al., 2016; Lucarini et al., 2018).

3.3 Water and Subcritical Water Extraction (SWE)

Aqueous extraction uses water or pressurized hot water as the primary solvent (Breniaux et al., 2025). In Subcritical Water Extraction (SWE), liquid water is maintained under pressure (1-5MPa) at temperatures between 100°C and 200°C (Breniaux et al., 2025). Elevated temperatures lower the dielectric constant of water, matching the polarity of organic solvents and facilitating high proanthocyanidin recovery without toxic residues (Breniaux et al., 2025; An et al., 2023).

3.4 Supercritical CO_2 Extraction (SCO2)

Supercritical CO_2 operated above its critical point ($T_c = 31.1$°C, $P_c = 7.38$ MPa) combines gas-like diffusivity with liquid-like density (Duba and Fiori, 2015). This enables deep matrix penetration and high selectivity for grape seed lipids (Duba and Fiori, 2015; Sovová, 2017). Modifying density via pressure (20–50 MPa) and temperature

(40–60°C) allows precise fraction separation, while adding polar modifiers (e.g., 5–10% ethanol) enables the simultaneous extraction of phenolic compounds (Fiori et al., 2014; Duba and Fiori, 2015).

3.5 Ultrasound-Assisted (UAE) and Microwave-Assisted (MAE) Extraction

UAE utilizes ultrasonic cavitation to induce mechanical shear and acoustic microjets, disrupting seed cell walls and enhancing interfacial mass transfer (Mehta et al., 2022; An et al., 2023). MAE uses non-ionizing electromagnetic radiation to generate localized dielectric heating that rapidly vaporizes internal moisture, building internal pressure until the seed matrix fractures (Chan et al., 2011; An et al., 2023). Both methods accelerate extraction kinetics and reduce overall solvent consumption (Chan et al., 2011; Mehta et al., 2022).

4. Engineering Parameter Influences and Sustainability Comparison

The recovery yield and transport efficiency of grape seed extraction depend on key engineering variables:
Operating Pressure: In SCO_2, higher pressures increase fluid density, strengthening solvating power and increasing oil solubility (Duba and Fiori, 2015; An et al., 2023). In liquid systems, moderate overpressures maintain subcritical phases and enhance matrix wetting (Breniaux et al., 2025).
Operating Temperature: Temperature exerts competing effects: elevated temperatures increase solute vapour pressure and molecular diffusivity while decreasing supercritical solvent density (Bucić-Kojić et al., 2013; An et al., 2023). For thermal-sensitive proanthocyanidins, excessive temperatures accelerate thermal degradation (Bucić-Kojić et al., 2013).
Solvent Flow Rate and Solid-to-Solvent Ratio: Increased flow rates reduce the external boundary-layer resistance and maintain a steep concentration gradient (Wilson et al., 2013). However, excessive solvent flow shortens contact residence time and increases downstream separation costs (An et al., 2023).
Particle Size and Pretreatment: Size reduction increases specific surface area and shortens internal diffusion paths (An et al., 2023). Pretreatment steps (milling, drying, enzymatic deconstruction) rupture outer cell walls, facilitating mass transfer (An et al., 2023; Sovová, 2017).
Table 1 below summarizes the operating envelopes, dominant transport mechanisms, energy requirements, and techno-economic metrics of these technologies.

Table 1: Comparative engineering and sustainability evaluation of grape seed extraction technologies.

Technology	Target solute	Dominant Transport Mechanism	Typical Operating Range	Environmental Safety Profile	References
Solid–Liquid Leaching	Lipids/ Phenolics	Molecular diffusion & liquid film resistance	50–70°C, 1 atm, 2–6 h, Liquid/Solid: 10–20 mL/g	High VOC emissions; flammability hazard; solvent residue removal required	An et al. (2023); Li et al. (2016)
SCO2	Lipids (non-polar bioactives)	Convective solubility & internal porous diffusion	25–45 MPa, 40–60°C, 1–3 h, CO_2 flow: 2–5 kg/h	Green solvent; zero toxic residue; continuous CO_2 recycle	Duba and Fiori (2015)
Subcritical Water (SWE)	Proanthocyanidins / Phenolics	Polar solubility tuning & thermal matrix degradation	100–180°C, 2–5 MPa, 15–60 min	Non-toxic solvent; thermal degradation risk for heat-sensitive bioactives	Breniaux et al. (2025)
UAE	Polyphenols / Proanthocyanidins	Acoustic cavitation & surface erosion	100–400 Watts, 25–50°C, 10–30 min	Low energy footprint; compatible with green aqueous solvents	Mehta et al. (2022); An et al. (2023)
MAE	Polyphenols / Bioactives	Dielectric volumetric heating & internal matrix rupture	200–800 Watts, 60–110°C, 5–60 min	Rapid kinetics reduce processing footprint; dielectric hotspot risk	Chan et al. (2011); An et al. (2023); Casazza et al. (2015)

5. Mathematical modelling of extraction kinetics

5.1 Single -phase mass transfer model

Mathematical models are widely used to describe the kinetics of solute release from plant matrices during extraction. These models rely on mass balance equations linking the solute concentration in the solid phase to that in the surrounding solvent (Bucić-Kojić et al., 2013). Internal mass-transfer resistance, governed by effective diffusivity and particle radius, and external film resistance are combined into an overall mass-transfer coefficient, Eq (5). The driving force is the difference between the liquid-phase concentration in equilibrium with the bulk solid and the actual bulk liquid concentration, Eq (4). Integrating the solid-phase balance, Eq (1), with the rate expression of Eq (4) and c eliminated using Eq (2), gives an exponential approach to equilibrium, from which the extraction yield follows as Eq (6). The lumped parameter B in Eq (6) collects the equilibrium and solvent-loading effects into a single group, giving a compact form for parameter fitting.

$$ms\frac{dw}{dt} = -J, w(t=0) = wu \tag{1}$$

where m_s is the mass of dry seed (kg), w is the mass fraction of solute in the solid phase (kg/kg), t is the extraction time (s) and J is the mass transfer rate (kg/s). The concentration in the bulk liquid phase is linked to w by the overall solute mass balance (Bucić-Kojić et al., 2013):

$$w + Lc = wu \tag{2}$$

where L is the volumetric solvent loading (m³ of solvent per kg of dry seed), c is the solute concentration in the liquid phase (kg/m³) and w_u is the initial mass fraction of solute in the dry seed (kg/kg). The model assumes linear equilibrium of the extracted constituent between the liquid and solid phases, characterised by the partition constant K (kg/m³). With this convention Lc is a mass ratio, so Eq (2) is dimensionally consistent, and the group KL is dimensionless.

$$C^* = Kw^* \tag{3}$$

The mass transfer rate J is approximated using the linear driving force

$$J = k_0 A(Kw - c) \tag{4}$$

where A is the overall particle surface area (m²) and k_0 is the overall mass transfer coefficient (m/s), which combines the external liquid-phase coefficient k_L (m/s) and the internal solid-phase coefficient k_s(m/s) as resistances in series:

$$\frac{1}{k_0} = \frac{1}{k_L} + \frac{K}{\rho s}\frac{1}{ks} \tag{5}$$

where ρs is the solid density (kg/m³). Both terms of Eq (5) have units of s/m, so Eq (4) yields kg/s, consistent with Eq (1). By integrating Eq (1), substituting J from Eq (4), and eliminating c using Eq (2), the extraction yield C (kg of solute in the liquid phase per kg of dry seed) can be expressed in a simplified form as:

$$C = \frac{w_u}{B}\left\{1 - \exp\left[-\frac{k_o ABK}{m_s}t\right]\right\} \tag{6}$$

where B = (1 + KL)/KL is a dimensionless lumped parameter combining the partition constant and the solvent loading. The exponent group k_oABK/m_s reduces to s^{-1}, and the equilibrium yield as $t \to \infty$ is w_u/B, equivalently $KLw_u/(1 + KL)$.

5.2 Broken and Intact Cell (BIC) model

Plant material extraction generally begins with a quick release of solutes, followed by a slower, diffusion-limited phase. This occurs because size reduction results in a mix of ruptured and intact cells within the bed. Solutes from broken cells dissolve almost instantly upon contact with the solvent, while those inside intact cells must diffuse through the cell walls (Bucić-Kojić et al., 2013). The BIC model reflects this by dividing the solid matrix into easily accessible and confined portions, and it has been extensively used in supercritical and solvent extraction of plant materials (Sovová, 2017).

The fraction of broken cells is denoted f_b(dimensionless). The mass balance for the intact particle core is:

$$m_s(1 - f_b)\frac{dw_i}{\mathrm{dt}} = -J, \quad w_i(t=0) = w_u \tag{7}$$

Where w_i is the mass fraction of solute in the particle core with intact cells. The overall mass balance becomes:

$$(1 - f_b)w_i + f_b\frac{c}{K} + Lc = w_u \quad (8)$$

where the first term relates to the intact cells, the second term of mass fraction c/K, to the broken cells and the third term to the liquid phase. The mass transfer rate through the overall surface of the particle cores Ai is:

$$J = k_s A_i \rho_s \left(w_i - \frac{c}{K}\right) \quad (9)$$

Integrating Eq (7) with J substituted from Eq (9) and c eliminated using Eq (8) gives:

$$w_i = \frac{w_u}{(1+KL)}\left\{1 + KL\exp\left[-\frac{k_s A_i \rho_s}{m_s(1-f_b)}\frac{(1+KL)}{(KL+f_b)}t\right]\right\} \quad (10)$$

Combining Eq (10) with Eq (8) gives the extraction yield:

$$C = \frac{KLw_u}{(1+KL)}\left\{1 - KL\frac{(1-f_b)}{(KL+f_b)}\exp\left[-\frac{k_s A_i \rho_s}{m_s(1-f_b)}\frac{(1+KL)}{(KL+f_b)}t\right]\right\} \quad (11)$$

For spherical particles of radius R (m), the group Aρs/ms equals 3/R and Eq (11) becomes:

$$C = \frac{w_u}{B}\left\{1 - \frac{(1-f_b)}{(1+f_b(B-1))}\exp\left[-\frac{3k_s B}{R(1-f_b)[1+f_b(B-1)]}\frac{A_i}{A}t\right]\right\} \quad (12)$$

Since fb is the fraction of broken cells, the intact core occupies the remaining volume fraction, so (Ri/R)3 = 1 − fb and the surface-area ratio is Ai/A = (1 − fb)2/3. Substituting this together with ks = 5De/R for a spherical particle under the linear driving force approximation gives:

$$C = \frac{w_u}{B}\left\{1 - \frac{(1-f_b)}{(1+f_b(B-1))}\exp\left[-\frac{15D_e Bt}{R^2(1-f_b)^{\frac{1}{3}}[1+f_b(B-1)]}\right]\right\} \quad (13)$$

Where D_e is the effective diffusivity (m²/s). The area ratio cancels part of the (1 − fb) term carried in the denominator of Eq (12), leaving (1 − fb)1/3. The corrected form has the physically sensible property that the time constant diverges as fb → 0, that is, extraction becomes indefinitely slow when no cells are ruptured.

5.3 Applicability and limitations

The formulation above rests on three assumptions that bound its use. Linear equilibrium, Eq (3), holds only in the dilute region and fails once the fluid phase approaches saturation, which is the normal condition during the constant-rate period of supercritical extraction. In that period the extraction is solubility-limited rather than mass-transfer-limited, and the model over-predicts the initial rate. The effective diffusivity De lumps intraparticle diffusion, matrix swelling and particle deformation into one fitted parameter, so it is a correlating constant rather than a transport property and should not be transferred between feedstocks, grinding conditions or particle size distributions. The broken-cell fraction fb is treated as uniform across the bed, whereas milling produces a distribution of particle sizes and therefore of fb, so fitted values represent a bed average that shifts with the size distribution. The model is accordingly best used as a design correlation for interpolation within a tested operating window, and not for extrapolation beyond it. As a consistency check, Eq (11) reduces to Eq (6) at fb = 0, both give the equilibrium yield KLwu/(1 + KL) as t → ∞, and both give zero yield at t = 0.

6. Conclusion

This review highlights that the effective recovery of high-value lipids and polyphenols from grape seeds depends greatly on tuning engineering parameters such as pressure, temperature, and particle size. Although traditional mechanical and solvent extraction methods are still widely used, modern green technologies offer better selectivity and product quality while avoiding the environmental issues linked to organic solvents. Mathematical models, especially the Broken and Intact Cell (BIC) model, provide a solid foundation for predicting biphasic extraction kinetics and optimizing industrial-scale processes. In conclusion, combining these innovative extraction methods with accurate process modeling is crucial to improving the sustainability and economic sustainability of grape seed valorization in the global grape industry.

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