Drying Kinetics and Stability of Fatty Acids in Grape Pomace Seeds Under Mild Thermal Conditions

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Grape pomace, a significant by-product of the wine industry, is rich in health-promoting compounds, including polyunsaturated fatty acids, dietary fiber, and polyphenols, and holds strong potential for use in functional foods and nutraceuticals. This study investigates the effects of low-temperature convective drying at 40°C on the drying behavior and fatty acid composition of grape seeds from ten Vitis vinifera L. cultivars. To model the drying process, six thin-layer drying models were applied. Among them, the Logarithmic model provided the best fit for most cultivars, showing excellent agreement between predicted and experimental drying curves. Effective moisture diffusivity values varied considerably among cultivars, reflecting differences in pomace structure and seed composition. Fatty acid analysis via gas chromatography revealed that polyunsaturated fatty acids—particularly linoleic acid—were the predominant lipid class in fresh grape seeds. After drying, a moderate reduction in polyunsaturated fatty acids was observed, accompanied by a corresponding increase in saturated fatty acids. Despite these changes, certain cultivars, such as Prokupac and Merlot, retained favorable nutritional profiles. The results support the application of mild drying protocols to preserve the functional quality of grape seeds while improving energy efficiency. This research contributes to the sustainable valorization of grape pomace and highlights its potential applications, such as functional oil ingredients, antioxidants in skincare, and encapsulated nutraceutical formulations.

Keywords: *Grape pomace, drying kinetics, fatty acid composition, seed oil stability, food by-product valorization, sustainable processing.*

1. INTRODUCTION

Grape pomace (GP), the leftover skins, seeds, and stems after grape pressing, is a major by-product of the global wine industry. For every 100 kg of grapes processed, approximately 20–30 kg of pomace is generated [1]. Historically considered waste, GP has recently gained attention due to its rich composition of bioactive compounds, including polyphenols, dietary fibres, organic acids, and lipids, which confer antioxidant, anti-inflammatory, antimicrobial, and even anticancer properties [1,2]. The valorization of GP fits within the framework of a circular economy, promoting waste minimization and the recovery of valuable bioresources [3]. Similar efforts involving low-energy drying technologies for biological materials have been previously explored, particularly in the context of solar-assisted drying and optimization of moisture removal processes [4]. By utilizing GP as a raw material for the extraction of functional ingredients, industries can contribute to sustainability while simultaneously creating economic opportunities across the food, pharmaceutical, and cosmetic sectors [5]. In this context, grape pomace is no longer viewed as waste but as a multifunctional raw material for developing high-value products.

The composition of GP is highly variable and depends on multiple factors, including grape variety, cultivation conditions, and winemaking techniques. Red grape pomace generally contains higher concentrations of anthocyanins and tannins, while white grape pomace features a lighter phenolic profile but can still contain significant amounts of flavonoids and phenolic acids [6, 7].For example, skins and seeds from red cultivars such as Cabernet Sauvignon and Merlot are particularly rich in flavan-3-ols and proanthocyanidins, which exhibit potent antioxidant activity [2,8]. Additionally, factors such as fermentation duration, temperature, and the presence of enzymes impact the retention and release of bioactive compounds during processing. Therefore, a detailed analysis of GP from different grape varieties is essential for understanding its full valorization potential [3,6].

This study investigates grape pomace derived from ten grape varieties, including both international and autochthonous types: Pinot Blanc (PB), Pinot Noir (PN), Cabernet Franc (CF), Cabernet Sauvignon (CS), Welschriesling (WR), Merlot (ME), Prokupac (PK),Riesling (RR), Chardonnay (CH) and Vranac (VR). The cultivars were selected to represent a range of phenolic and lipid profiles, geographic origin, and oenological significance in Central and Southern Europe.The selected grape

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varieties reflect a diverse range of pomace characte–ristics relevant for nutraceutical and functional appli–cations. Red cultivars such as CS and CF are known for producing pomace with a high content of procyanidins and anthocyanins, compounds recognized for their potent antioxidant activity and cardiovascular benefits [8]. ME and PN offer a balanced phenolic profile, combining moderate tannin content with aromatic complexity, making them suitable for a broad spectrum of bioactive applications (Maier et al., 2009). Among white varieties, CH and PB yield pomace with lower total phenolic content but still contribute valuable flavonoids and antioxidant potential [9]. WR and RR, typical of Central European vineyards, are noted for their light yet distinct phenolic profiles, often rich in flavonols and hydroxycinnamic acids. These compounds enhance their potential for use in mild antioxidant formulations. Indigenous varieties such as PK and VR, both traditional red grapes from the Balkan region, have recently gained attention due to their elevated levels of gallic acid, catechins, and other bioactive phenolics, positioning them as promising sources for natural antioxidant extraction [10].

Numerous extraction techniques are available to isolate valuable compounds from GP. Traditional methods such as solvent extraction (using ethanol, methanol, or water) remain widespread due to their simplicity and efficiency [2]. However, concerns about environmental impact and solvent residues have led to increased interest in green extraction methods, including ultrasound-assisted, microwave-assisted, and ohmic heating technologies[3]. Recent studies show that aqueous extraction under optimized pH conditions can yield high concentrations of polyphenols while avoiding the use of organic solvents [11]. Moreover, enzyme-assisted extraction can improve cell wall breakdown, enhancing the release of bound phenolic compounds [6]. The choice of method depends on the intended application of the extract, whether in food preservation, cosmetic formulation, or nutraceutical supplementation.

Although the drying behavior and oil recovery from grape by-products have been the subject of various studies, many of these investigations are based on high-temperature processes, which often lead to degradation of thermolabile bioactive components. Moreover, grape pomace is frequently considered a homogeneous material, without sufficient attention to differences in varietal composition that may significantly affect drying kinetics and product quality. Reports on effective diffusivity are typically presented in isolation, without establishing a connection to the microstructure of the pomace—particularly the ratio of skins to seeds or changes in fatty acid composition. Studies that simultaneously address the kinetics of moisture removal and the preservation of lipid quality under mild drying conditions remain limited.

Considering these limitations, this work focuses on the drying characteristics of grape pomace from ten distinct cultivars, employing a low-temperature regime of 40°C. The approach integrates modeling of thin layer drying with detailed analysis of fatty acid composition using gas chromatography. By examining the relationship between drying parameters and compositional traits, especially those related to seed content and lipid profilethe study contributes to a more nuanced understanding of how pomace structure influences both drying efficiency and the quality of the final product.

The main objective of this study is to conduct and evaluate the effect of controlled low-temperature drying (below 50°C) on the preservation of fatty acids in grape seeds. This specific temperature range was selected based on previous studies and the known thermal sensitivity of polyunsaturated fatty acids, particularly linoleic and linolenic acids, which are prone to oxidative degradation at higher temperatures [13]. Drying below 50°C has been reported as optimal for maintaining lipid quality and antioxidant potential in grape seed oil.Grape seeds, a by-product of winemaking, are rich in unsaturated fatty acids, particularly linoleic and oleic acids, which tend to undergo oxidative degradation under thermal stress. Efficient drying is crucial not only for microbial stabilization and extending shelf life but also for preserving the integrity of thermolabile bioactive compounds. The specific objectives are:

1.To identify optimal drying kinetic parameters that ensure effective moisture removal while minimizing oxidative losses of valuable fatty acids.

2.To systematically analyze the impact of low-temperature convective drying on the total lipid content and fatty acid profile of grape seeds. By integrating principles of process engineering, thermodynamics, and food chemistry, this study aims to establish a scientific basis for optimizing low-temperature drying protocols for the valorization of grape seeds.

2. MATERIALS AND METHODS

2.1 Pulp preparation

In this study, grape seeds from 10 different grapevine (*Vitis vinifera L.*) cultivars commonly grown in the Balkan region were used. These cultivars were selected based on their oenological significance, regional pre–valence, and diversity in phenolic content. The grape samples were obtained at full technological maturity from vineyards located in the same agroecological reg–ion to ensure comparability. The varieties included both red and white wine grapes, covering a wide spectrum of genotypic and phenotypic traits (Table 1).

After harvest, the grapes were mechanically pressed to obtain grape pulp. Red grape varietals were pressed following fermentation and maceration, whereas white grape varieties were pressed just after destemming. For every variety under consideration, a pneumatic press (Škrlj, PST 16, 400V 50Hz 3PH, capacity 16 hl) was employed.

2.2 Drying process

The purpose of drying the grape pulp is to facilitate the separation of seeds from the skins, which, in the long term, enables the mechanization and automation of this process. From an industrial perspective, seed-skin separation is a critical preprocessing step that allows for

the selective valorization of each pomace fraction. Grape seeds are primarily used for oil extraction due to their high content of polyunsaturated fatty acids, while skins serve as a source of polyphenols and dietary fibers. Efficient drying reduces the adhesion between these components, thereby supporting mechanical sepa–ration and specialized downstream processing, ultima–tely improving process efficiency and product stan–dardization [2].The resulting pulp (composed of skins, seeds, and residual juice) was spread in a thin layer (Figure 1) and dried in an oven at 40°C, a temperature selected to preserve the integrity of thermolabile com–pounds, such as polyunsaturated fatty acids and poly–phenols, while minimizing oxidative degradation during drying [12], [13].Laboratory drying oven (Sterimatic ST-11, Instrumentaria Zagreb) was used for drying samples using hot air, with the possibility of precise temperature control. This drying oven does not control or regulate relative humidity, as it operates solely with dry heated air. The estimated relative humidity inside the chamber typically ranges between 5% and 10%, depending on the set temperature and ventilation condi–tions. A digital thermometer with a K-type thermo–couple (accuracy ±1°C) was used to monitor the actual temperature inside the drying oven. Additionally, a mercury thermometer was placed inside the chamber as a reference to further ensure the accuracy of temperature control during the drying process.

Figure 1. Oven drying of grape pulp at 40ºC

Drying grape seeds at a low temperature of 40°C is beneficial because it helps preserve their valuable bioactive compounds, such as antioxidants, vitamins, and essential fatty acids. In this study, the drying process lasted approximately 20 to 30 hours, depending on the cultivar, until a stable final mass was reached. Mass measurements were taken at 60-minute intervals using a precision scale (±0.5 g) to monitor moisture loss and determine the drying kinetics. Drying at 40°C minimizes the risk of thermal damage and preserves the natural aroma and flavor of the seeds. The change in pulp mass during the drying process was monitored on a scale with an accuracy of ±0.5 g.A similar methodology was used in the research presented in [12-14].

After drying, the seeds were manually cleaned to remove skin residues and damaged seeds andmeasured (Figure 2) and then stored in plastic zippered bags.

Figure 2. Grape seeds mass measurement

2.3 Drying analysis

The moisture ratio (*MR*) was used to create the drying kinetic curvesas a function of the drying time (min), till reaching mass equilibrium (1).

$$MR = \frac{X - X_{\mathrm{e}}}{X_0 - X_{\mathrm{e}}} \tag{1}$$

where are:

X – mean moisture content at time τ (kgkg^{-1});

X_e – equilibrium moisture content of the product (kgkg^{-1});

X_0– moisture content at the initial time (kgkg^{-1});

Drying kinetics of various grape seeds have been previously modeled using simplified drying equations [21-23]. These models have shown applicability in predicting moisture behavior during low-temperature drying processes. Based on these experiences, we decided to apply the following drying models in this study (Table 2): semi-theoretical drying models whose equations are derived from Newton's law of cooling (Page, Logaritmic, Two-term model), empirical models derived from Second Fick's law of diffusion (Aghbashlo, Wang & Singh model), and empirical multiparameter model [24].

Table 1. Red and white cultivars used in the study[12,16-20]

No.	Serbian Name	English Name, (Abbrev.)	Latin Name (V. vinifera L. cv.)	Color	Wine Type	Geographic Origin	Harvest Time	Seed Mass (mg)
1	Burgundacbeli	Pinot Blanc, (PB)	*Pinot Blanc*	White	Dry, fresh	France (Burgundy)	September	~45–60
2	Burgundaccrni	Pinot Noir, (PN)	*Pinot Noir*	Red	Dry, elegant	France (Burgundy)	Late September	~50–65
3	Cabernet Frank	Cabernet Franc, (CF)	*Cabernet Franc*	Red	Dry, full-bodied	France (Bordeaux)	October	~60–75
4	Cabernet sovinjon	Cabernet Sauvignon, (CS)	*Cabernet Sauvignon*	Red	Dry, tannic	France (Bordeaux)	October	~60–80
5	Italijanski rizling	Welschriesling, (WR)	*Welschriesling*	White	Dry, light	Central Europe	Late September	~45–55
6	Merlo	Merlot, (ME)	*Merlot*	Red	Dry, soft	France	October	~60–75

						(Bordeaux)		
7	Prokupac	Prokupac, (PK)	*Prokupac*	Red	Dry, rustic	Serbia	October	~55–70
8	Rajnskirizling	Rhein Riesling, (RR)	*Riesling*	White	Dry, aromatic	Germany (Rhine)	September	~45–60
9	Šardone	Chardonnay, (CH)	*Chardonnay*	White	Dry, complex	France (Burgundy)	September	~50–65
10	Vranac	Vranac, (VR)	*Vranac*	Red	Full-bodied, dry	Montenegro, North Macedonia	October	~55–70

Table 2. Thin-layer drying models

Page	$MR = \exp(-k\tau^n)$
Logaritmic	$MR = a \cdot \exp(-k\tau^n) + c$
Two-term	$MR = a \cdot \exp(-K_1\tau) + b \cdot \exp(-K_2\tau)$
Aghbashlo	$MR = a \cdot \exp\left(\frac{K_1\tau}{1+K_2\tau}\right)$
Wang & Singh	$MR = 1 + a \cdot \tau + b \cdot \tau^2$
Zlatanovic	$MR = \exp(-k\tau),\ k = a + b \cdot T^m + c \cdot \varphi^n$

MR - Moisture ratio
τ - time (min)
T-temperature(°C)
φ - relative humidity
a,b,c,k,K,m,n - equation parameters

As the equilibrium condition was achieved, the moisture analysis was performed in an oven, through the static gravimetric method (105 °C for 24 h) following the methodology of the Association of Official Analytical Chemists [25].

The effective diffusivity (D_{eff}) was determined using the diffusion model of the Fick's Law of thin-layer drying, as presented in (2).

$$MR = \frac{8}{\pi^2} \cdot \exp\left(-\frac{\pi^2 D_{\text{eff}} \tau}{4z^2}\right) \tag{2}$$

where:
z – ½ thickness of the thin layer of the pulp on a tray (m)
τ - time (min)

Determination of the effective diffusion coefficient is further carried out using a graph-analytical method, which is preceded by taking the logarithm of (2). This procedure yields linear functions of the form (3).

$$\ln MR_n = C + K \cdot \tau_n \tag{3}$$

$$D_{\text{eff}} = \frac{4z^2}{\pi^2} K \tag{4}$$

where: C - constant of the linear function, and K - slope coefficient.

The effective diffusion coefficient can be determined depending on the geometric shape of the material and the previously determined slope coefficient (4).

The coefficient of determination (R^2) was used to evaluate the goodness of fit of the regression models applied in this study. R^2 quantifies the proportion of the variance in the dependent variable that can be explained by the independent variable(s) in the model (5).

$$R^2 = 1 - \frac{SS_{\text{res}}}{SS_{\text{tot}}} \tag{5}$$

where: SS_{res} – sum of squares of residuals (unexplained variation), SS_{tot} –total sum of squares (total variation). An R^2 value of 1 indicates a perfect fit, whereas a value of 0 suggests that the model does not explain any of the variability in the response data.

2.4 Fatty Acid Extraction and GC–FID Analysis from Small-Scale Grape Seed Samples

For the analysis of fatty acid composition, a small sample of grape seeds (up to ~1g) was used. The seeds were finely ground under cold conditions to prevent oxidation. Lipids were extracted following a Folch-based protocol using a chloroform–methanol solvent system. The fatty acid profile of grape seed oil samples was determined by gas chromatography-flame ionization detection (GC-FID) following methylation to fatty acid methyl esters (FAMEs). Briefly, extracted oils were subjected to transmethylation using 14% boron trifluoride (BF_3) in methanol at 100°C for 1 hour. The resulting FAMEs were extracted with hexane and dried over anhydrous sodium sulfate.

GC analysis was performed on an Agilent 7890B GC system equipped with a flame ionization detector and a SP-2560 capillary column (100 m × 0.25 mm i.d., 0.20 μm film thickness). The injection volume was 1 μL in split mode (split ratio 1:50). Injector and detector temperatures were maintained at 250°C and 280°C, respectively. High-purity helium served as the carrier gas at a constant flow rate of 1.0 mL/min.

The oven temperature program was set as follows: initial temperature of 140°C held for 5 minutes, increased at 4°C/min to 240°C, and held at 240°C for 15 minutes. Fatty acid methyl esters were identified by comparing their retention times with those of standard FAME mixtures (Supelco 37 Component FAME Mix, Sigma-Aldrich). Quantification was performed by area normalization, and results were expressed as relative percentages of total fatty acids.

Quality control measures included running blanks and standards after every ten samples to ensure analytical precision and reproducibility.

3. RESULTS AND DISCUSSION

Ten distinct types of grape pomace, including both red and white varieties, were tested for drying behavior. The experimental data were fitted using various mathematical models (Table 2) to determine the most accurate representation of drying kinetics. The results

showed variation in drying rates and moisture ratio profiles, depending on the type of pomace (Figure 3). The types that showed the fastest moisture decrease, with total drying durations under 20 hours, were CH, RR, and CF. However, with total drying times exce–eding 30 hours, PB and ME had slower moisture re–lease, indicating denser or more moisture-retentive structures.

Best-fit models varied across the cultivars (Table 3). The Logarithmic model proved to be the most suitable for most of the samples, providing excellent fits with R^2 values exceeding 0.99, indicating a strong correlation between experimental and modeled data. Specifically, ME and VR achieved the highest accu–racy with R^2 values of 0.999852 and 0.999894, res–pectively, confirming the model's effectiveness in capturing their drying behavior. Other varieties, such as PN, PK, and WR, also demonstrated high model conformity using the Logarithmic model, with minor variation in parameter values reflecting their unique drying dynamics.Interestingly, two cultivars required alternative models to best represent their drying curves. CS was best described by the Two-term model (R^2 = 0.999794), suggesting a more complex drying process involving multiple mechanisms. Similarly, RR was best fitted by the Aghbashlo model (R^2 = 0.993940), indicating distinct moisture transport characteristics compared to other varieties.

Model performance depended on specific grape variety characteristics, such as initial moisture content, dry matter content, pomace composition,i.e., amounts of seeds and skin in the pulp (Table 4). Initial moisture content ranged from 62.3% PN to 80.9% PK, indi–cating variability in grape juice yield and tissue struc–ture among varieties. Following drying, the equilibrium moisture content fell to low levels (2.5–9.5%), con–firming efficient moisture removal under the applied conditions.Dry matter content in the wet pomace was relatively consistent across most varieties (18.3–28.9%), with CH and RR exhibiting the highest values, likely due to their thicker skins or lower juice fractions. These structural attributes likely contributed to their slower initial moisture loss, but potentially better stability after drying. Compositionally, the dried po–mace displayed varying ratios of skin to seed content. PN had nearly equal parts skins and seeds (50.8% and 49.2%, respectively), while WR had the most seed-rich profile (38.9% seeds). The high seed content in vari–eties such as CF and CS may contribute to differences in internal moisture transport and thermal behavior.

Effective moisture diffusivity (D_{eff}) ranged widely, from 1.147×10^{-7} m/s^2 PB to 6.242×10^{-7} m/s^2 CH. This nearly fivefold difference underscores the role of pomace microstructure and composition in moisture migration.

These findings align with previous research, which has shown that drying behavior and moisture diffu–sivity are strongly influenced by the structural charac–teristics of the material, as demonstrated in studies on the shrinkage and drying kinetics of herbal roots and related biological materials [26].The highest D_{eff} values observed in CH and RR suggest a more porous or fractured matrix conducive to faster internal moisture transport. In contrast, PB and ME exhibited slower diffusion, potentially due to denser skin or compacted pulp-seed structures.It should be noted that D_{eff}values reported for each cultivar were obtained from single experimental runs and represent characteristic values derived from drying kinetics modeling. Due to the absence of replicate measurements, statistical compa–risons (e.g., ANOVA) could not be performed. This represents a limitation of the present study. Future work will aim to include multiple replicates per culti–var to allow for statistical validation of the observed differences.

The analysis of fatty acid composition in fresh grape seeds from ten *Vitis vinifera L.* cultivars revealed notable variability in the proportions of polyunsa–turated (PUFAs), monounsaturated (MUFAs), and sa–turated fatty acids (SFAs), as well as in the nutritional quality indicator PUFA/SFA ratio (Table 5). All culti–vars exhibited a predominance of PUFAs, parti–cularly linoleic acid (omega-6), with the highest levels ob–served in PK (77.04%) and CF (76.6%).

Table 3. Selected Curve Fit Models for Drying Kinetics of Grape Pomace Varieties

Grape Abbrev.	Best curve fit drying model			
	Model	Equation	Parameters	R^2
PB	Logaritmic	$MR = a \cdot \exp(-k\tau^n) + c$	a=-0.18128, k=1.188765, c=1450.560	0.997821
ME			a=-0.02286, k=1.022448, c=545.6685	0.999852
WR			a=-0.024893, k=1.017150, c=414.23515	0.998665
VR			a=-0.003337, k=0.956489, c=309.90605	0.999894
PN			a=-0.038599, k=1.037376, c=423.51742	0.999872
PK			a=-0.015917, k=1.017976, c=375.3992	0.999820
CF			a=-0.031345, k=1.018766, c=359.92484	0.999662
CH			a=1.072344, k=0.004282, c=-0.074504	0.992418
CS	Two-term	$MR = a \cdot \exp(-K_1\tau) + b \cdot \exp(-K_2\tau)$	a=-3.194719, K_1=0.002204, b=4.185928, K_2=0.002408	0.999794
RR	Aghbashlo	$MR = a \cdot \exp\left(\frac{K_1\tau}{1+K_2\tau}\right)$	a=1.0170, K_1=0.003476, K_2=-0.00068	0.993940

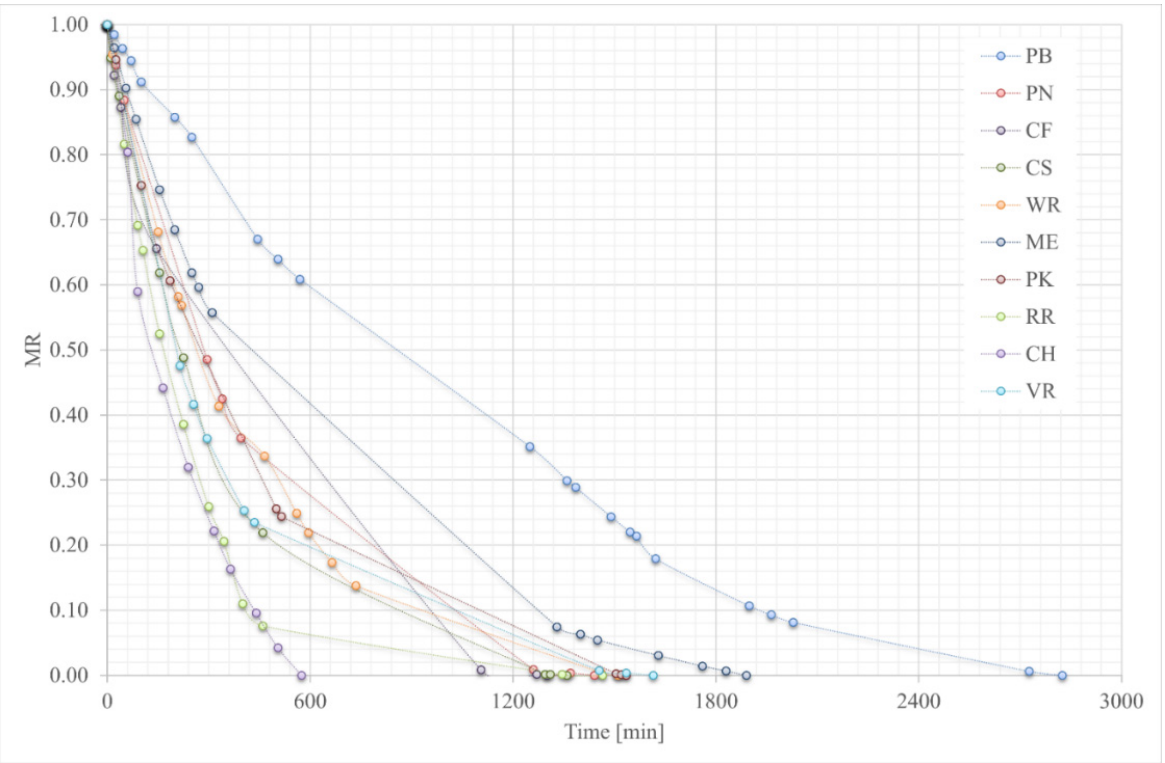

Figure 3 The change of MR vs. Time for the grape pulp of all cultivars used in the study, at 40ºC

MUFA content ranged from 12.0% in CFto 22.9% in RR, with oleic acid (omega-9) as the principal monounsaturated component. The SFA content was generally low, except in RR (17.9%) and VR (14.0%), where elevated levels of palmitic and stearic acids were observed. The PUFA/SFA ratio, used as an indicator of lipid nutritional quality, was highest in PK (7.84) and WR (7.80), suggesting superior health-promoting potential. Conversely, RR had the lowest PUFA/SFA ratio (3.31), primarily due to its elevated SFA and MUFA contents.The evaluation of changes in fatty acid composition of grape seeds from ten *Vitis vinifera L.* cultivars before and after processing revealed consistent trends across all analyzed varieties (Table 6). A reduction in polyunsaturated fatty acids (PUFAs) was observed in all samples, with decreases ranging from −3.5% in ME to −4.5% in CH. Despite this reduction, PUFAs remained the dominant lipid fraction. Monounsaturated fatty acids (MUFAs) exhibited a moderate increase in all cultivars, with the most significant change noted in CH (+2.8%) and PB (+2.5%). The content of saturated fatty acids (SFAs) increased substantially, most notably in CH (+6.0%), PB (+5.5%), and CF (+5.5%).

These changes led to a relative shift toward a less favorable lipid profile, as the reduction in PUFAs coupled with increased SFAs could potentially lower the nutritional quality of the grape seed oils. However, cultivars such as PK and ME still retained appreciable levels of unsaturated fatty acids post-treatment, indi–cating their continued potential for functional food applications. The importance of optimizing drying re–gimes for preserving active compounds has also been emphasized in previous dryer prototype studies aimed at enhancing thermal and nutritional efficiency during low-temperature processing [27].

Table 4. Observed values of wet and dry grape pomace properties, including the effective diffusivity (Deff) analyzed by Fick's Law model

Grape Abbrev.	Wet grape pulp			Dried grape pulp		
	Initial moisture content, [%]	Equilibrium moisture content, [%]	Dry matter, [%]	Skins, [%]	Seeds, [%]	Effective diffusivity $D_{eff} \times 10^7$ [m^2/s]
PB	69.5	8.5	28.2	72.8	27.2	1.147
ME	76.1	4.7	23.7	68.6	31.4	2.420
WR	72.2	8.0	27.0	61.1	38.9	3.694
VR	64.0	2.5	23.8	65.0	35.0	4.076
PN	62.3	2.5	26.1	50.8	49.2	4.204
PK	80.9	9.5	18.3	69.1	30.9	4.459
CF	75.8	4.2	24.0	57.1	42.9	5.223
CS	71.7	4.5	22.9	57.3	42.7	5.860
RR	70.9	7.8	28.2	64.2	35.8	5.987
CH	69.2	9.5	28.9	70.9	29.1	6.242

Table 5. Fatty Acid Composition of Fresh Grape Seeds from Different Vitis vinifera L. Cultivars

Grape Abbrev.	PUFAs, [%]	Linoleic Acid, omega-6, [%]	MUFAs, [%]	Oleic Acid, omega-9, [%]	SFAs, [%]	Major SFAs, [%]	Trans Fats, [%]	PUFA/SFA
PB	71.5	71.04	17.1	16.63	11.4	Palmitic (6.91), Stearic (3.72)	0.036	6.27
PN	73	72.47	16.5	16.04	10.5	Palmitic (6.42), Stearic (3.46)	0.03	6.95
CF	76.6	76.11	12	11.77	11.4	Palmitic (6.01), Stearic (4.67)	-	6.72
CS	76.2	75.73	12.2	11.86	11.6	Palmitic (6.60), Stearic (4.26)	-	6.57
WR	74.9	74.48	15.5	15.13	9.6	Palmitic (5.46), Stearic (3.41)	0.066	7.80
ME	73	72.48	17	16.2	10	Palmitic (5.71), Stearic (4.12)	0.013	7.30
PK	77.04	76.56	13.13	12.5	9.83	Palmitic (5.75), Stearic (3.48)	-	7.84
RR	59.2	58.79	22.9	21.53	17.9	Palmitic (9.45), Stearic (7.03)	1	3.31
CH	76.2	75.7	12.6	12.29	11.2	Palmitic (6.18), Stearic (4.24)	0.05	6.80
VR	68	66.8	21.2	19.9	14	Palmitic (9.80), Stearic (4.50)	-	4.86

Table 6. Changes in Fatty Acid Composition of Grape Seeds from Different Vitis vinifera L. Cultivars Before and After Processing

Grape Abbrev.	PUFA		MUFA		SFA	
	wet, [%]	dried, change in %	wet, [%]	dried, change in %	wet, [%]	dried, change in %
PB	71.5	-4.0	17.1	2.5	11.4	5.5
PN	73	-3.5	16.5	2.2	10.5	5.0
CF	76.6	-4.0	12	2.0	11.4	5.5
CS	76.2	-3.6	12.2	2.0	11.6	5.5
WR	73	-4.0	17	2.0	10	5.8
ME	77.04	-3.5	13.13	1.8	9.83	5.5
PK	59.2	-4.0	22.9	1.5	17.9	4.0
RR	76.2	-3.8	12.6	2.3	11.2	5.4
CH	74.9	-4.5	15.5	2.8	9.6	6.0
VR	68	-3.9	21.2	2.1	14	5.4

4. CONCLUSION

This study underscores the significance of cultivar-specific characterization in the drying and valorization of grape pomace. Variations in drying kinetics, effective diffusivity, and compositional attributes among grape varieties reveal that a universal drying approach is suboptimal. Instead, tailored drying strategies are necessary to enhance energy efficiency, product quality, and suitability for applications in the food, pharmaceutical, and bioenergy sectors.

The Logarithmic model demonstrated broad applicability for simulating drying behavior; however, certain cultivars may require more complex modeling to accurately capture drying dynamics due to differences in pomace composition, particularly the ratio of skins to seeds and inherent diffusivity. In addition, the analysis of fatty acid profiles in grape seeds revealed a predominance of polyunsaturated fatty acids (PUFAs), particularly linoleic acid (omega-6), across all cultivars.

The PUFA/SFA ratio, a marker of nutritional quality, was highest in PK and WR, indicating their potential for use in functional foods and nutraceuticals. However, post-processing reductions in PUFA content and increases in saturated fatty acids across all samples suggest that drying conditions must be optimized to preserve beneficial lipid components. Despite these changes, cultivars such as ME and PK retained favorable lipid profiles after processing, further supporting their suitability for high-value applications. Future research should focus on scaling these findings to industrial levels, incorporating real-time monitoring and control systems to optimize drying protocols and enhance the economic and nutritional value of grape pomace.

The findings of this study offer a foundation for practical implementation in the development of energy-efficient drying technologies aimed at the valorization of grape pomace. The observed variation in effective moisture diffusivity (Deff), ranging from $1.147\times10^{\square\square}$ m²/s in PB to $6.242\times10^{\square\square}$ m²/s in CH, underscores the influence of cultivar-specific pomace composition on drying behavior. Such differences allow for the tailoring of drying protocols to optimize processing efficiency and preserve the quality of valuable compounds. Notably, the retention of polyunsaturated fatty acids, with linoleic acid content remaining predominant after drying in all cultivars, confirms the suitability of low-temperature drying (40°C) for maintaining nutritional integrity. These outcomes are particularly relevant for small and medium-scale wineries seeking to extract grape seed oil or produce antioxidant-rich extracts, while also aligning with industrial trends in the functional food, cosmetic, and pharmaceutical sectors.

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NOMENCLATURE

a, b, c, K_1, K_2, m, n	Empirical model constants [–]
D_{eff}	Effective moisture diffusivity [m²/s]
τ	Drying time [min]
MR	Moisture ratio [–]
SS_{res}	Sum of squares of residuals [–]
SS_{tot}	Total sum of squares [–]
T	Temperature [°C]
X	Moisture content [kg/kg]
z	Half thickness of drying layer [m]
φ	Relative humidity [%]

Abbreviations

GP	Grape Pomace
PUFA	Polyunsaturated Fatty Acid
MUFA	Monounsaturated Fatty Acid
SFA	Saturated Fatty Acid
CH	Chardonay
RR	Riesling
CF	Carbernet Franc
CS	Cabernet Sauvignon
PB	Pinot Blanc
PN	Pinot Noir
ME	Merlot
PK	Prokupac
WR	Welschriesling
VR	Vranac
FAME	Fatty Acid Methyl Ester
GC-FID	Gas Chromatography – Flame Ionization Detection

КИНЕТИКА СУШЕЊА И СТАБИЛНОСТ МАСНИХ КИСЕЛИНА У СЕМЕНКАМА ГРОЖЂА ПОД УМЕРЕНИМ ТЕРМИЧКИМ УСЛОВИМА

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Винска пулпа, значајан нуспроизвод винске индустрије, богата је једињењима која позитивно утичу на здравље, укључујући полинезасићене масне киселине, дијетална влакна и полифеноле, и има велики потенцијал за примену у функционалној храни и нутрацеутичким производима. Ова студија истражује утицај конвективног сушења на ниској температури од 40°C на понашање током сушења и састав масних киселина у семенкама грожђа десет сорти *Vitisvinifera L.*. За моделовање процеса сушења примењено је шест модела сушења у танком слоју. Међу њима, логаритамски модел показао се као најприкладнији за већину сорти, показујући одличну сагласност између предвиђених и експерименталних кривих сушења. Вредности ефективне дифузивности влаге значајно су варирале између сорти, што одражава разлике у структури комине и саставу семенки.

Анализа масних киселина методом гасне хроматографије показала је да су полинезасићене масне киселинепосебно линолна киселина биле доминантна липидна класа у свежим семенкама грожђа. Након сушења, уочено је умерено смањење садржаја полинезасићених масних киселина, праћено одговарајућим порастом засићених масних киселина. Упркос овим променама, одређене сорте, као што су Прокупац и Мерло, задржале су повољан нутритивни профил. Резултати подржавају примену блажих режима сушења ради очувања функ–ционалног квалитета семенки грожђа, уз побољ–шање енергетске ефикасности. Ово истраживање доприноси одрживој валоризацији комине грожђа и истиче њене потенцијалне примене, као што су функционалне компоненте уља, антиоксиданси у козметици и инкапсулирани нутрацеутици.