วารสารวิจัยและพัฒนา
วไลยอลงกรณ์ ในพระบรมราชูปถัมภ์
สาขาวิทยาศาสตร์และเทคโนโลยี

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สำเนาถูกต้อง
(เกษมสี ออนเพียร)

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วัตถุประสงค์

1. เพื่อเป็นสื่อกลางในการเผยแพร่ผลงานบทความวิจัยทางด้านวิทยาศาสตร์และเทคโนโลยี ได้แก่ อาหาร วิทยาศาสตร์การแพทย์และสุขภาพ วิทยาศาสตร์ธรรมชาติ เกษตรศาสตร์ วิทยาศาสตร์ประยุกต์ วิทยาศาสตร์สิ่งแวดล้อม วิศวกรรมศาสตร์สาขาอื่นๆ และเทคโนโลยีสารสนเทศ สู่นักวิจัย นักวิชาการและผู้สนใจทั่วไป
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ข้อความและบทความในวารสารนี้
เป็นความคิดเห็นของผู้นิพนธ์โดยเฉพาะ
กองบรรณาธิการไม่มีส่วนรับผิดชอบในเนื้อหา
และข้อคิดเห็นนั้นๆ แต่อย่างใด

สำเนาถูกต้อง
(เกตุวดี ออนฟ้อง)

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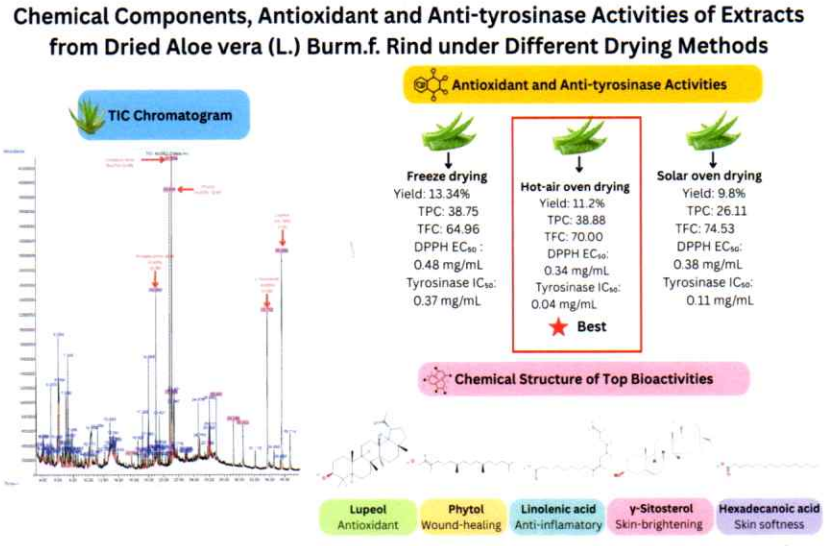
สำเนาถูกต้อง
(เกตุวลี ลอนเพียร)

Chemical Components, Antioxidant and Tyrosinase Inhibitory Activities of Dried *Aloe vera* Rind Extract under Different Drying Methods

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ABSTRACT



Aloe vera (L.) Burm.f. is a widely utilized medicinal plant, primarily valued for its gel in food, cosmetics, and pharmaceuticals, while the rind is usually discarded as waste. This study investigated the phytochemical composition and bioactivities of Aloe vera rind extracts prepared using different drying methods: freeze drying, hot air oven drying, and solar oven drying. The dried rind powders were extracted and analyzed their chemical components as total phenolic and flavonoid contents, including antioxidant and tyrosinase inhibition. Freeze drying method provided the highest extraction yield (13.34 ± 0.50%). Total phenolic contents were 38.75 ± 0.11, 38.88 ± 0.59, and 26.11 ± 0.49 mg gallic acid equivalents/g for freeze, hot air oven, and solar drying, respectively, while flavonoid contents were 64.96 ± 1.45, 70.00 ± 4.55, and 74.53 ± 2.49 mg rutin equivalents/g. Antioxidant activities, assessed by DPPH and FRAP assays, revealed EC values of 0.48 ± 0.09, 0.34 ± 0.01, and 0.38 ± 0.01 mg/mL (DPPH), and 45.27 ± 0.56, 44.40 ± 1.09, and 42.99 ± 0.03 mg FeSO equivalents/g (FRAP). Tyrosinase inhibition showed IC values of 0.37 ± 0.00, 0.04 ± 0.00, and 0.11 ± 0.00 mg/mL, highlighting the superior inhibitory activity from hot air oven drying. GC-MS analysis of this extract identified bioactive compounds including lupeol, linolenic acid, γ-sitosterol, phytol, tocopherols, squalene, and fatty acids, associated with antioxidant, anti-inflammatory, UV-protective, and tyrosinase-inhibitory properties. These findings suggest that Aloe vera rind, particularly when processed by hot air oven drying, is a promising resource for value-added applications in skincare and cosmetic development.

Keywords: *Aloe vera*, Drying method, Antioxidants capacity, Tyrosinase inhibition, GC-MS

1. Introduction

Aloe vera (scientific name: *Aloe vera* (L.) Burm.f.), commonly known in Thailand as a traditional herbal plant. Vonpian (2025) identified Aloe vera as belonging to the Asphodelaceae family based on the sample submitted. Among its species, *Aloe barbadensis* Miller is the most extensively studied worldwide due to its rich profile of bioactive compounds. These compounds offer diverse health and cosmetic benefits, including antioxidant activity, anti-inflammatory effects, skin hydration, and collagen stimulation (Sánchez et al., 2020; Moghaddasi & Verma, 2011). While the gel inside the leaf is widely used, the rind—often discarded as waste in the food and cosmetic industries—also contains valuable phytochemicals.

สำเนาถูกต้อง
(เกศสุดา ลอนพ้อย)

Aloe vera has an interesting mechanism of action, which is a medicinal and therapeutic property (Surjushe et al., 2008). It has been suggested that the polysaccharides in *Aloe vera* play a role in protecting the skin from damage caused by internal and external factors. The polysaccharides in *Aloe vera* prevent the increase in proteins that induce cell death. *Aloe vera* polysaccharides may act as scavengers of oxygen-free radicals, being such as DPPH, alkyl radicals, superoxide, and singlet oxygen, as well as hydroxyl radicals that may be generated from superoxide, hydrogen peroxide, which are weak initiators of lipid peroxidation, and may also be effectively eliminated (Moghaddasi & Verma, 2011). *Aloe vera* is a perennial, shoot-producing, stemless plant. The leaves are long and may have white spots. The number of white spots depends on the age of the tree. The edges are serrated, which may be hard to touch like thorns, but are not dangerous. In terms of use, the leaves are made up of two main parts: the rind, which is the part that is attached to the latex, and the clear gel inside (Moghaddasi & Verma, 2011; Benzidia et al., 2019). Most of the parts that are popularly used in various manufacturing industries are the gel and the pulp inside, which have lots of rich vitamins (Hamman, 2008). The outer covering has rarely been researched and utilized, as it is often discarded as waste, even though there is significant essential nutrition in the rind (Miladi & Damak, 2008). The research by Quispe et al. (2018) examined the chemical makeup and antioxidant properties of *Aloe vera* from Chile's Pica Oasis using UHPLC-Q/Orbitrap/MS/MS. It identified 25 phenolic compounds, such as cinnamic acids, chromones, anthracene derivatives, and C-flavonoids, in various parts of the plant (rind, flowers, gel, and roots). The findings revealed that the rind exhibited the strongest antioxidant activity.

Aloe vera rind, often considered a byproduct, contains a variety of bioactive compounds, including flavonoids, phenols, steroids, and alkaloids, which contribute to its antioxidant and anti-tyrosinase properties (Mahadi et al., 2019). Comparative analyses have shown that *Aloe vera* rind extract exhibits stronger tyrosinase inhibition and antioxidant activity than the inner gel, as evidenced by lower IC_{50} values in both DPPH scavenging and tyrosinase inhibition assays (Mahadi et al., 2019). Additional research has identified specific phenolic compounds in *Aloe vera*, such as aloesin and its derivatives, that act as competitive inhibitors of tyrosinase, further supporting the potential of *Aloe vera* rind as a source of natural tyrosinase inhibitors for cosmetic and pharmaceutical applications (Kim et al., 2017; Recent studies have highlighted the presence and significance of tyrosinase inhibitory activity in *Aloe vera* rind extracts. Tyrosinase is a key enzyme involved in melanin biosynthesis and is associated with hyperpigmentation and skin aging. *Aloe vera* extracts have also demonstrated inhibitory effects on collagenase and elastase, enzymes responsible for skin texture and elasticity, further supporting their anti-aging potential (Sacan, Akev, & Yanardağ, 2024; Chailap & Nuanyai, 2022). These findings suggest that *Aloe vera* rind, beyond its traditional uses, may serve as a valuable raw material for developing products aimed at managing hyperpigmentation and oxidative stress (Añibarro-Ortega et al., 2019; Sacan, Akev, & Yanardağ, 2024).

The important substances found in *Aloe vera* rind are mostly found as anthraquinones (laxative & antimicrobial), polyphenols & antioxidants, terpenoids, tannins, sterols, carbohydrates, plant fiber, vitamins, minerals, enzymes (Rodríguez, ER, et al., 2010; Nalimu et al., 2021; Kushwaha et al., 2023). The literature reveals a diverse array of drying techniques available for preparation of *Aloe vera*, each with distinct advantages and limitations. Traditional methods such as sun and hot-air drying remain popular due to their simplicity and cost-effectiveness, yet they often compromise the retention of key bioactive compounds and product quality (Vega et al., 2007; Mali & Swami, 2024). In contrast, advanced techniques like freeze drying and Refractance Window™ drying offer superior preservation of nutrients, colour, and gel structure, albeit at higher operational costs and with greater technical demands (Minjares-Fuentes et al., 2016; Ayala-Aponte et al., 2021). Spray drying, while efficient and scalable, may not fully protect sensitive polysaccharides and vitamins (Kaur et al., 2017; Kim et al., 2024). The choice of drying method is further influenced by the intended application, available resources, and desired product characteristics (Pawar et al., 2023). Additionally, pretreatment strategies—such as blanching, enzymatic treatment, and careful mechanical preparation—can enhance drying efficiency and final product quality (Pisalkar et al., 2014). In the context of *Aloe vera* processing, most existing literature emphasizes drying techniques applied to the inner gel or pulp, with limited attention given to the rind—despite its potential value in extraction and bioactive compound recovery (Thamkaew et al., 2020). This gap highlights the need for targeted research on *Aloe vera* rind, particularly in relation to drying preparation.

Drying is a critical step in the preparation of plant-based extracts, as it influences the stability and concentration of bioactive compounds. Cheekham et al. (2023) demonstrated that drying temperature

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significantly affects the antioxidant and antibacterial activities of sweet potato cultivars, with moderate heat preserving more bioactive compounds than higher temperatures. For this research, conventional drying methods were selected—namely freeze drying, hot-air oven drying, and solar oven drying—based on their accessibility and practicality within the in-house production. Freeze drying is widely recognized for its ability to preserve the yield and chemical composition of bioactive compounds, color, and structure in plant materials, although it is associated with higher operational costs and sometimes greater loss of certain antioxidants compared to other methods (Thamkaew et al., 2020; Minjares-Fuentes et al., 2016; Hossain et al., 2010). Hot-air oven drying, the most common laboratory-scale method, offers simplicity and scalability but may result in significant loss of volatile compounds, color degradation, and shrinkage, especially at higher temperatures (Thamkaew et al., 2020; Shaw et al., 2016). Solar drying, while the oldest and most accessible technique, is valued for its low cost and suitability for resource-limited environments, though it often leads to lower retention of essential oils and antioxidants due to prolonged exposure to sunlight and less control over drying conditions (Thamkaew et al., 2020; Orphanides et al., 2016). To address these limitations and avoid the impact of unpredictable weather during the rainy season, this study employed a solar oven instead of traditional solar drying. The solar oven provides a more controlled environment, while still maintaining the energy efficiency and accessibility of solar-based methods. The selection of these methods aligns with the practical constraints of this study and enables a comparative evaluation of drying efficiency and quality outcomes for *Aloe vera* rind, contributing to a more inclusive understanding of *Aloe vera* processing beyond the commonly studied pulp (Thamkaew et al., 2020).

Recent interest in sustainable practices and zero-waste extraction has led researchers to explore ways to recover beneficial compounds from *Aloe vera* rind, transforming waste into high-value ingredients. To achieve this, drying techniques such as freeze drying, hot air oven drying, and solar drying play a crucial role in preserving the rind's bioactive properties for further extraction (Chailap & Nuanyai, 2022). This approach not only supports environmental sustainability but also enhances the potential of *Aloe vera* rind as a natural ingredient in cosmetic formulations. Furthermore, Itsarasook et al. (2023) explored the antioxidant and wound-healing properties of *Aloe vera* infused in canola oil. Although their focus was on oil-based formulations, the study reinforces the multifunctional potential of *Aloe vera*-derived products in skin-related applications, particularly due to their antioxidant and anti-inflammatory properties. All these qualifications can promote skin rejuvenation, moisture retention, and anti-aging effects (Sitthikariya & Chokdeesamrit, 2019). Thus, this study aims to evaluate the impact of different conventional drying methods—freeze drying, hot-air oven drying, and solar oven drying—on the extraction efficiency and quality of bioactive compounds from *Aloe vera* rind. The rind, after being cleaned and separated from the inner gel, is subjected to each drying method before extraction. The research focuses on identifying phenolic and flavonoid compounds, assessing antioxidant and tyrosinase inhibitory activities, and analyzing the chemical composition using GC/MS. These drying techniques were selected not only for their scientific relevance but also for their practical applicability in small-scale production settings, such as SMEs and community enterprises, where access to high-end technology may be limited. By using cost-effective and accessible methods, this study aims to provide insights that can be adapted for local industries, promoting the sustainable use of agricultural by-products and supporting the development of innovative microemulsion serum which is the natural cosmetic ingredients from *Aloe vera* rind. The key innovation is the downstream microemulsion formulation, which transforms the dried crude rind extract into a high-performance small molecule for skin-absorbable serum. This supports sustainable valorization of agricultural waste (*Aloe vera* rind) into value-added natural cosmetics.

2. Research method

Plant material

Fresh *Aloe vera* leaves used in this study were obtained from *Khun Som's Aloe vera Farm*, Ban Nong Bua, Bor Nok Subdistrict, Mueang District, Prachuap Khiri Khan Province, which were harvested in November, during the dry season, and only mature leaves with rind widths were selected for this study. This botanical was identified from the Department of Botany, Faculty of Science, Chulalongkorn University, herbarium number A17914(BCU). The specimen was identified as Aloe vera (Vonpian, 2025). *Aloe vera* leaves were washed with tap water, the inner gel was removed and used elsewhere while, the rind (5,000 kg)

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was a by-product. *Aloe vera* rinds were stripped of thorns and washed with distilled water until almost no mucus remained. The rinds were chopped into pieces (approximately 1–2 cm), all of these (adjusted to grand total 4440 g) were collected and equally divided into three batches of 1480 g each. Each batch was subjected to one of the three drying methods. All rinds were stored in a refrigerator (2-8°C) before drying.

Drying method

Method I Freeze-drying (lyophilization):

1480 g of *Aloe vera* rind samples were pre-frozen at –20 °C for 24 h to solidify the tissue. Lyophilization was performed in a freeze dryer (Model LCC-1-7960032, LABCONCO Corporation, USA) under a condenser temperature of –50 °C and a chamber pressure of 0.1–0.2 mbar until a constant dry weight was achieved (approximately 48 h) (Labconco Corporation, n.d.; Guancha-Chalapud et al., 2022). The dried rind material was then ground into fine powder using a laboratory mill, sieved through a 40-mesh sieve, and stored in airtight containers at –20 °C until extraction.

Method II Hot air oven drying:

1480 grams of *Aloe vera* rinds were evenly distributed on stainless steel trays in a single layer and placed in a hot air oven (Model ULM400, MEMMERT, Germany) at 50 °C for 10 h until a constant weight was obtained (Pawar et al., 2023; Mali & Swami, 2024; Memmert GmbH + Co. KG, n.d.). The dried samples were ground into fine powder using a laboratory mill, sieved through a 40-mesh sieve, and stored in airtight containers at room temperature until extraction.

Method III Solar oven drying:

1480 grams of *Aloe vera* rinds were placed on mesh trays and dried in a solar oven built at Valaya Alongkorn Rajabhat University under direct sunlight with adequate air circulation for 7days. according method of Buntham, Yongphet, Boonwittaya, & Tongcom (2024). This oven primarily utilizes solar energy and is equipped with a fan system to enhance internal air and heat circulation. The structure is made with grade-A polycarbonate sheets, which effectively absorb and retain heat, allowing for more stable drying conditions. The drying process was continued until the samples reached a constant weight, which typically took around seven days, depending on sunlight intensity (Ariza et al., 2024). The dried samples were ground into fine powder using a laboratory mill, sieved through a 40-mesh sieve, and stored in airtight containers at room temperature until extraction.

Extraction

The powdered rind samples from each drying method were extracted by the maceration technique with 95% ethanol. For each method, 100 g of rind powder was placed in a 1-L beaker with 500 mL of ethanol, sealed, and soaked for 7 days. In a related study, Pukumpuang and Seansrimon (2023) evaluated the antioxidant and anti-tyrosinase activities of Thai colored rice extracts. Their results showed that ethanolic extracts exhibited strong radical scavenging and enzyme-inhibitory effects, supporting the use of ethanol as an effective solvent for extracting phenolic and flavonoid compounds—similar to the extraction method used in this study. The extracts were filtered to separate residues and concentrated using a rotary vacuum evaporator, followed by freeze-drying. The percentage yield of each extract was calculated in triplicate.

Determination of total phenolic compounds (TPC)

The total phenolic compounds of *Aloe vera* rind extracts were determined by the Folin-Ciocalteu colorimetric assay modified from the method of Soncharoen & Jongitt (2024) and Chaudhary (2023). Briefly, 20 mg of each dried *Aloe vera* rind extract was dissolved in 10 mL of 95% ethanol to obtain a 2 mg/mL solution. The total phenolic content was determined using the Folin-Ciocalteu method. A 2 mg/mL solution was prepared by dissolving 20 mg of each dried *Aloe vera* rind extract in 10 mL of 95% ethanol. Then, 100 μL of the sample was mixed with 8,400 μL of distilled water, followed by 500 μL of Folin-Ciocalteu reagent and 1,000 μL of 20% sodium carbonate. The mixture was incubated in the dark at room temperature for 1 hour, and absorbance was measured at 760 nm. Results were compared with a gallic acid standard curve and expressed as mg GAE/g dried

Determination of total flavonoids compounds (TFC)

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The total flavonoid content assay was examined by the Aluminum chloride colorimetric method, modified method from Pękal & Pyrzynska (2014) and Wattanuruk et al. (2020). 10 mg of each dried *Aloe vera* rind extract was dissolved in 10 mL of 80% ethanol to obtain a 1 mg/mL solution. A sample solution was prepared by weighing 10 mg of each of the three types of *Aloe vera* rind extracts and dissolving them in 80% ethanol, adjusting the volume to 10 mL. Then, 1 mL of the sample solution was pipetted into a 10 mL volumetric flask, followed by the addition of 4 mL of distilled water. At 0 minutes, 0.3 mL of 5% sodium nitrite was added; at 5 minutes, 0.3 mL of 10% aluminum chloride was added; and at 6 minutes, 2 mL of 1 M sodium hydroxide was added. The volume was adjusted to 10 mL with distilled water, shaken well, and the absorbance was measured at 510 nm. A blank was prepared by pipetting 5 mL of distilled water into a 10 mL volumetric flask, followed by the same sequence of reagent additions. The absorbance was measured at 510 nm and compared to a calibration curve constructed using rutin as the standard. Results were expressed as milligrams of rutin equivalent per gram of dried extract (mg RE/g dried extract). The experiment was performed in triplicate, and the average was calculated.

The initial dry weights and extraction solvents for phenolic and flavonoid assays were optimized based on the sensitivity and specificity of each colorimetric method to ensure accurate and reproducible results.

Determination of Radical Scavenging Activity by DPPH

The antioxidant activity of *Aloe vera* rind extract was conducted by DPPH (2 ,2 -diphenyl-1 -picrylhydrazyl radical scavenging assay according to a modified method from Sirivibulkovit et al. (2018), Senajuk et al. (2020) and Sharma (2024). Briefly, weigh 0.02 g of the selected *Aloe vera* rind extract and dissolve it with 40 mL of 95% ethanol. Shake with a shaker to help dissolve. The stock solution is 0.5 mg/mL. Dilute the sample with 95% ethanol to obtain concentrations of 500, 250, 125, 62.5, and 31.25 μg/mL Test the ability to capture DPPH radicals compared to the butylated hydroxytoluene (BHT) standard solution. Mix the solution into each mixture, test sample (extract + DPPH solution), blank (extract + ethanol, without DPPH), and control (DPPH solution + ethanol, without extract). After incubation in the dark at room temperature for 30 minutes, absorbance was measured at 517 nm. The percentage of DPPH radical scavenging activity was calculated using the following equation (1) and calculate and the EC_{50} value was calculated from the graph showing the relationship between % inhibition and concentration.

$$\% \text{ Scavenging} = A_C - A_A / A_C \times 100 \quad \ldots\ldots\ldots\

The tyrosinase inhibitory activity was evaluated using a modified dopachrome method adapted from Khaomek & Jantanu (2016) and Wattanarak (2021). *Aloe vera* rind extracts were dissolved in 95% ethanol and diluted to final concentrations of 62.5, 125, 250, and 500 µg/mL. The assay was performed in a 96-well microplate using L-DOPA as the substrate and kojic acid as the positive control. After incubation at 37°C for 30 minutes, absorbance was measured at 510 nm. The percentage of tyrosinase inhibition was calculated, and IC values were determined by plotting the log concentration of the sample against the inhibition percentage using linear regression. The absorbance values from these wells were used to calculate the percentage of tyrosinase inhibition as follows: equation 3.

$$\text{Tyrosinase inhibition (\%)} = [(A_C - A_D) - (A_A - A_B)] / A_C - A_D \times 100 \quad \text{.....(3)}$$

Where A_A = absorbance of sample reaction, A_B = absorbance of sample blank, A_C= absorbance of control reaction and A_D = absorbance of control blank.

Gas chromatography/mass spectrometry (GC-MS) analysis

GC–MS analysis was performed to identify and quantify the volatile components in the Aloe vera rind extract samples, following the method described by Yoruk and Paksoy (2024) with modifications for quality assurance and verification on the hot-air oven-dried extract (10 mg/mL in methanol) using an Agilent 7890 GC coupled to a 5973 MSD with a ZB-5MS Plus column (30 m × 0.25 mm × 0.25 μm). Helium flowed at 1 mL/min; injector at 280 °C (split 5:1); oven program: 70 °C (hold), ramp 10 °C/min to 150 °C, 5 °C/min to 190 °C, 10 °C/min to 290 °C (hold 12 min). Full scan m/z 40–550 at 70 eV. Compounds were identified via Agilent MassHunter (B.07.00) against the W10N14.L library; only matches with quality >80% were reported (triplicate analyses, RSD <5% for major peaks). Relative abundance was based on normalized peak area percentages from the total ion chromatogram.

Statistical analysis

All experiments were conducted in triplicate (n = 3), and data were presented as mean ± standard deviation (SD). Statistical analyses were performed using IBM SPSS Statistics.Ink (IBM SPSS Statistics30.0). One-way analysis of variance (ANOVA) followed by Tukey's post hoc test was used to determine statistical significance among groups. Differences were considered statistically significant at $p < 0.05$.

3. Results and discussion

Aloe vera rind extract yields

A comparative analysis of three conventional drying methods—freeze drying, hot air oven drying, and solar oven drying—used for processing *Aloe vera* rind before extraction. Each method began with an identical fresh weight of 1,480 grams. After drying, the freeze-drying method resulted in the lowest dry weight (85.87 g), indicating the most efficient moisture removal. In contrast, hot air oven drying and solar oven drying yielded higher dry weights of 99.55 g and 104.18 g, respectively, suggesting less moisture removal. Following extraction, the weight of extract obtained was highest for freeze drying (11.46 g), followed by hot air oven drying and solar oven drying (both 9.10 g). The percentage yield was also highest for freeze drying at 13.34% ± 0.50, demonstrating its superior efficiency in preserving extractable compounds. Hot air oven drying yielded 9.14% ± 0.40, while solar oven drying had the lowest yield at 8.73% ± 0.30. In terms of appearance, freeze-dried samples were solid and light green, indicating minimal thermal degradation. Hot air oven drying produced a solid, dark green sample, suggesting moderate thermal impact. Solar oven drying resulted in a solid, light brown sample, which may reflect greater exposure to sunlight and oxidation.

Overall, freeze drying proved to be the most effective method in terms of moisture removal, extract yield, and preservation of appearance, while solar oven drying was the least efficient among the three (Pawar et al., 2023).

Table 1. Percentage yield of *Aloe vera* rind extract from different drying method

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Drying method	Weight after drying (g)	Weight after extraction (g)	Percentage yield	Appearance
Freeze drying(I)	85.87	11.46	13.34 ±0.50[a]	solid, light green
Hot air oven drying(II)	99.55	9.10	9.14 ± 0.40[b]	solid, dark green
Solar oven drying(III)	104.18	9.10	8.73 ± 0.30[c]	solid, light brown

Means ± standard deviation with different letters in the same column were significantly different at the level ($p < 0.05$); n = 3

Total Phenolic compounds

The total phenolic compounds analysis of the average values of all 3 variables, it was found that extraction from the hot air oven drying method showed the highest total phenolic content value of 38.88±0.59, followed by extraction using the freeze-drying method of 38.75 ±0.11 and the extraction from the solar oven drying of 26.11±0.49 mg GAE/g dried extract, respectively. From the statistical results, the freeze drying and hot air oven methods are significantly different from the results of the solar oven drying method. These findings align with the observations of Añibarro-Ortega et al. (2019), who reported that *Aloe vera* rind and mucilage contained high phenolic concentrations, particularly anthrones and chromones, which are sensitive to thermal degradation. The lower phenolic content in solar-dried samples may be attributed to uncontrolled temperature fluctuations and prolonged exposure to sunlight, which can degrade heat-sensitive compounds. Eshun & He (2004) noted that certain *Aloe vera* compounds degrade above 60°C, a threshold likely exceeded during solar drying. This supports the hypothesis that solar drying, while accessible, may compromise the integrity of bioactive compounds.

Total Flavonoid

It was found that extraction from the solar oven drying method showed the highest total phenolic content value of 74.53±2.49, followed by extraction using the hot air oven drying method at 70.00±4.55, and the extraction of the obtained substances by freezing drying at 64.96±1.45mg RE/g dried extract, respectively (Table 2). The value of the statistical difference calculation is the same as the result obtained from the total phenolic value derived from different drying methods. Interestingly, the total flavonoid content was highest in solar-dried samples, suggesting that certain flavonoids may be more stable or even enhanced under solar drying conditions. This contrasts with the findings of Añibarro-Ortega et al. (2019), where flavonoid content was highest in the rind and flower extracts, with apigenin glycosides being predominant. The discrepancy may be due to differences in plant part analyzed (rind vs. whole leaf) and extraction solvents used. Our study used alcoholic solvents, which Añibarro-Ortega et al. (2019) also found to be more effective than water-based extractions for recovering antioxidants. Solar drying involves moderate to high temperatures and exposure to sunlight, which can induce stress responses in plant tissues. These stress conditions may stimulate the synthesis or release of certain flavonoids, especially those that are heat-stable or light-induced, such as apigenin glycosides. In contrast, phenolic compounds are generally more heat-sensitive, and prolonged exposure to heat and light can degrade them. A study by Gamage et al. (2021) found that solar drying significantly increased the total flavonoid content in certain medicinal plants like *Ocimum tenuiflorum* and *Hibiscus rosa-sinensis*, while the total phenolic content was either reduced or remained unchanged depending on the plant species. This suggests that flavonoids may be more resilient or even enhanced under solar drying conditions, possibly due to UV-induced biosynthesis or thermal release from bound forms.

Table 2. Total phenolic and flavonoid contents of *Aloe vera* rind extract from different drying methods

Drying method	Total Phenolic (mg GAE/g extract)	Total Flavonoid (mg RE/g extract)
Freeze drying(I)	38.75 ±0.11[a]	64.96 ±1.45[b]
Hot air oven drying(II)	38.88 ±0.59[a]	70.00 ±4.55[a,b]
Solar oven drying(III)	26.11 ±0.49[b]	74.53 ±2.49[a]

Means ± standard deviation with different letters in the same column were significantly different at the level ($p < 0.05$); n = 3

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The initial dry weights and extraction solvents used in the phenolic and flavonoid assays were selected based on the sensitivity and specificity of each colorimetric method. For the Folin–Ciocalteu assay, which is used to determine total phenolic content, a higher initial extract weight (20 mg) was used to ensure sufficient reaction with the Folin reagent and to produce a measurable absorbance at 760 nm. This method is generally less sensitive than the aluminum chloride method and may require a more concentrated sample to detect lower phenolic levels accurately (Pérez et al., 2023). In contrast, the aluminum chloride colorimetric method used for flavonoid determination is more sensitive and specific to flavonoid-aluminum complexes, which produce a strong absorbance at 510 nm (Pękal & Pyrzynska, 2014). Therefore, a lower initial extract weight (10 mg) was sufficient to generate reliable and reproducible results. Additionally, the choice of solvent differed to optimize solubility and reactivity: 95% ethanol was used for phenolic extraction due to its effectiveness in dissolving a broad range of phenolic compounds, while 80% ethanol was used for flavonoids to enhance the solubility of glycosylated flavonoids and reduce background interference. These methodological adjustments were made to ensure optimal assay performance, accurate quantification, and consistency across replicates. The Folin–Ciocalteu method is known to react with a broad range of reducing agents, which may lead to underestimation or interference in complex plant matrices. In contrast, the aluminum chloride method used for flavonoid determination is more selective for flavonoid structures, particularly flavones and flavonols, which may be more abundant or more extractable in *Aloe vera* rind. Additionally, the use of different standards (gallic acid vs. rutin) and their respective molar absorptivity may contribute to the observed differences in reported values (Apak et al., 2016; Prior et al., 2005).

The lowest total phenolic content in the solar oven-dried Aloe vera rind is in agreement with Añibarro-Ortega et al. (2019), who reported high levels of heat-sensitive phenolics in the rind, predominantly anthrones and chromones. The fluctuating and uncontrolled temperatures in solar oven drying—often exceeding 60 °C for prolonged periods under direct sunlight—promote thermal degradation and photo-oxidative losses of these compounds (Eshun & He, 2004). This explains the reduced total phenolic content compared to other methods, while flavonoids exhibited greater stability, yielding the highest total flavonoid content.

Moreover, our findings contribute to the growing body of evidence that accessible and cost-effective drying methods like hot air oven drying can rival or surpass freeze drying in certain contexts. This is particularly relevant for institutions or industries with limited access to freeze-drying equipment. While freeze drying is often considered the most accepted standard for preserving bioactive compounds, our result demonstrate that hot air oven drying can be a viable alternative, especially when targeting phenolic-rich extracts. (should be conclude from the result, have no information about cost-effective)

Antioxidant Activity

In this study, both antioxidant activity of 2,2-diphenyl-1-picrylhydrazyl radical scavenging assay (DPPH)and Ferric Reducing Antioxidant Power assay (FRAP) were employed to evaluate the antioxidant activity of *Aloe vera* rind extracts. Although both methods are based on electron transfer mechanisms, they differ in reaction conditions and compound sensitivity. Lipophilic antioxidants are more effective for DPPH because it operates in an organic solvent, but FRAP is better suited for hydrophilic compounds and functions in an acidic aqueous environment. The use of both assays provides a broader assessment of antioxidant capacity, especially in complex plant matrices like *Aloe vera* rind, which contains diverse phytochemicals. The differing trends observed between the two methods in this study may reflect the varied solubility and reactivity of the extracted compounds under each assay condition (Apak et al., 2016; Prior et al., 2005). Therefore, the inclusion of both assays enhances the reliability and depth of antioxidant profiling in this research. From Table 3, it was found that the extract preparation method by drying in a hot air oven at 55 °C obtained the highest EC_{50} result from the DPPH antioxidant test, which was significantly different from preparation by freezing, though not significantly different from the solar oven. As for the antioxidant test by FRAP, the highest antioxidant value was obtained from the extract preparation method by freezing, and it was not significantly different from the antioxidant activity from the hot air oven drying, but significantly different from the extract preparation by solar oven drying.

Table 3. Antioxidant activity of *Aloe vera* rind extract from different drying methods

Drying method	Antioxidant activity

	DPPH (EC_{50} (mg/mL))	FRAP (mg Eq.$FeSO_4$/g sample)
Freeze drying(I)	0.48 ±0.09 [a]	45.27±0.56 [b]
Hot air oven drying(II)	0.34±0.01 [b]	44.40 ±1.09 [a,b]
Solar oven drying(III)	0.38 ±0.01 [a,b]	42.99±0.03 [a]
BHT	0.00 ±0.00	107.62 ±0.81

Means ± standard deviation with different letters in the same column were significantly different at the level ($p < 0.05$); n = 3

From the analysis of the average variables, it was found that extraction from the hot air oven drying method had the best DPPH value with an EC_{50} value of 0.34±0.01, followed by extraction from the solar oven drying method at 0.38 ±0.01 and extraction of the obtained substances by freeze-drying at 0.48 ±0.09 mg/mL, respectively, compared to the control group (BHT). Different drying methods had a significant effect on the antioxidant content of DPPH-based products. Further, internal comparisons revealed that the freeze-drying and solar oven drying methods gave significantly different antioxidant content than the hot air oven drying method.

It also found that extraction by freeze drying showed the best FRAP value at 45.27±0.56, followed by the hot air oven drying method at 44.40±1.09 and extraction from solar oven drying at 42.99±0.03mg Eq.$FeSO_4$/ g sample, respectively, compared to the control group (BHT) with an average value of 107.62±0.81 mg Eq.$FeSO_4$ / g sample (Table 3). Different drying methods significantly affected the antioxidant content of FRAP, and internal comparisons revealed that the freeze-drying and hot air oven drying methods gave significantly different antioxidant content than the solar oven drying method.

In this study, the antioxidant activity of *Aloe vera* rind extracts was evaluated using different drying methods—freeze drying, hot air oven drying, and solar drying. The results showed that hot air oven drying yielded significantly higher antioxidant activity than freeze drying when measured using the DPPH method, while no significant difference was observed between the two methods using the FRAP assay. These findings suggest that hot air oven drying may enhance certain antioxidant properties more effectively than freeze drying, particularly in terms of radical scavenging activity. This finding tends to nearby by the findings of Hossen et al. (2022), who reported that hot air oven drying was superior to solar drying but did not compare it with freeze drying. Our study fills this gap by providing a direct comparison, showing that hot air oven drying can be as effective—or even superior—in some aspects to freeze drying, which is often considered the most accepted standard. Furthermore, consistent with Manye et al. (2023), our use of alcoholic solvents resulted in higher antioxidant yields compared to water-based extractions, reinforcing the importance of solvent selection in maximizing bioactive compound recovery. Overall, our findings contribute new insights by demonstrating that accessible and cost-effective drying methods like hot air oven drying can achieve comparable or better antioxidant extraction than more resource-intensive methods, depending on the assay used.

Tyrosinase activity

The comparative analysis of tyrosinase inhibition across the three drying methods. Drying by hot air oven gave the most potent inhibitory activity (IC_{50} = 0.04 mg/mL), followed by solar oven drying (IC_{50} = 0.11 mg/mL), and freeze drying (IC_{50} = 0.37 mg/mL, respectively. These results were statistically significant and indicate that the drying method has a direct impact on the bioactivity of the extracted compounds. These findings are consistent with Sacan et al. (2024), who reported that methanolic extracts of *Aloe vera* gel and rind exhibited dose-dependent tyrosinase inhibition, with the gel extract showing stronger activity (IC = 1.39 mg/mL) than the rind (IC = 2.15 mg/mL). Although their IC values were higher than those in this study, the trend supports the idea that *Aloe vera* gel and rind contain active compounds capable of inhibiting tyrosinase, especially when extracted with alcohol-based solvents (Sacan et al., 2024). Therefore, the hot air oven drying method was selected as the most effective for extracting bioactive compounds with strong tyrosinase inhibitory activity. This method offers the best composition and biological activity, as confirmed by statistical comparison. The selected extract can be considered a promising raw material for the development of cosmetic products aimed at skin brightening and anti-aging applications (Khaomek & Jantanu, 2016).

Mahadi et al. (2019) suggested that antioxidants are also related to anti-aging. Therefore, they conducted an experiment to test the effectiveness of antioxidants and the inhibition of the tyrosinase enzyme, which is useful in reducing dullness and delaying aging. They studied the rind of *Aloe vera* and compared its inner gel. It was found that the rind of *Aloe vera* is rich in free radicals and has a higher anti-aging effect than the inner gel by inhibiting the tyrosinase enzyme. The similarity in extraction temperature (not exceeding 55°C) and the use of ethanol-based solvents in our study and that of Mahadi et al. (2019) suggests that moderate heat combined with alcohol extraction may enhance the release of bioactive compounds responsible for tyrosinase inhibition. This supports the selection of hot air oven drying as an effective method for cosmetic applications.

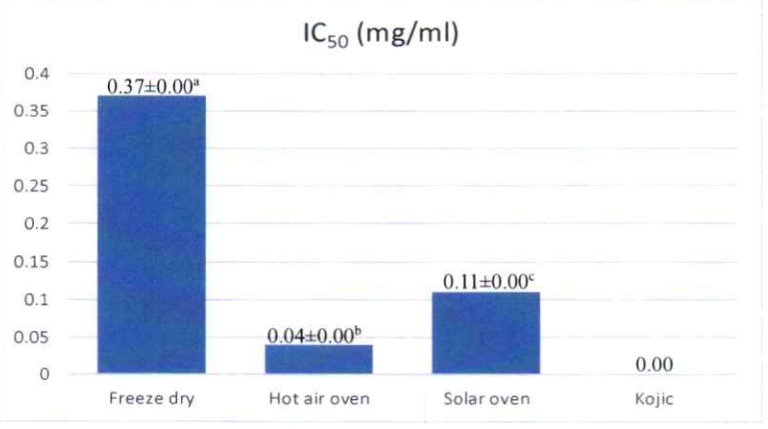


Figure 1. Anti-tyrosinase properties of *Aloe vera* rind extracts prepared by different drying methods

Additionally, Chailap and Nuanyai (2022) found that *Aloe vera* leaves harvested at 7–9 months exhibited the highest tyrosinase inhibition (18.68%) and antioxidant activity using the ABTS assay. This suggests that not only the drying method but also the maturity of the leaf influences the concentration of active compounds. While our study focused on drying methods, future work could explore the interaction between leaf age and drying technique.

From the preparation of *Aloe vera* rind extract, it was found that the results of the extraction from different preparation methods would produce all the desired results with different quantities but may not be seen as very different values. However, the statistical analysis suggests that it can be stated that the extracts from all three drying methods have significant effects on the total phenolic contents and the total flavonoid contents, including antioxidant activity, and tyrosinase enzyme inhibition.

Freeze drying is widely recognized for its ability to preserve sensitive bioactive compounds in plant materials. Studies by Femenia et al. (1999) and Antal (2015) have shown that freeze drying offers superior drying efficiency for *Aloe vera* gel, retaining high levels of Acemannan and minimizing thermal degradation. Chang et al. (2011) further demonstrated that freeze-dried *Aloe vera* gel retained over 90% of Acemannan, compared to only 30% retention in heat-dried samples. However, these studies primarily focus on the inner gel, whereas the present research investigates the rind, which has distinct chemical properties and thermal sensitivities. Although solar oven drying is often considered less efficient in terms of moisture removal and extract yield, its impact on certain bioactive compounds—particularly flavonoids—can be unexpectedly beneficial. In this study, solar-dried *Aloe vera* rind extracts exhibited the highest total flavonoid content, despite having the lowest total phenolic content and extract yield. This phenomenon may be attributed to the unique combination of moderate heat and UV exposure during solar drying, which can induce stress responses in plant tissues, leading to the biosynthesis or release of specific flavonoids. According to Belwal et al. (2022), solar drying, while less controlled than other methods, can enhance the concentration of certain heat- and light-stable compounds due to UV-induced metabolic activity and thermal softening of plant cell walls, which improves the extractability of flavonoids. However, the same conditions may also accelerate the degradation of more heat-sensitive phenolic compounds, explaining the lower total phenolic content observed. These findings highlight the complex interplay between drying conditions and phytochemical stability, suggesting that solar drying may be selectively advantageous for certain antioxidant compounds, even if it compromises others.

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In contrast to expectations based on gel-focused studies, our results show that hot air oven drying at 50°C yielded the highest biological activity in *Aloe vera* rind extracts. Specifically, this method produced the lowest IC_{50} value for tyrosinase inhibition (0.04 mg/mL), better than solar oven drying (0.11mg/mL) and freeze drying (0.37 mg/mL). These findings suggest that moderate heat may enhance the extractability of certain active compounds in the rind, possibly due to cell wall softening or improved solvent penetration. Eshun & He (2004) noted that thermostable compounds such as polysaccharides and minerals remain intact below 60°C, supporting the suitability of hot air drying at 50°C for preserving key components. Moreover, Mahadi et al. (2019) reported that *Aloe vera* rind contains higher levels of antioxidants and tyrosinase inhibitory activity than the inner gel, reinforcing the potential of rind-based extracts for anti-aging and skin-brightening applications. Our findings align with this, as the hot air oven method not only preserved antioxidant activity but also yielded a higher extract quantity and better economic efficiency. Compared to freeze drying, hot air drying was 5–10 times more cost-effective and required less preparation time, making it a practical choice for scalable cosmetic ingredient production.

In summary, while freeze drying is ideal for preserving delicate compounds in *Aloe vera* gel, hot air oven drying at 50°C proved to be the most effective method for preparing *Aloe vera* rind extracts with high biological activity and economic viability. This method supports the development of phytochemical-rich raw materials for cosmetic and healthcare formulations. Therefore, the experimental results found that the *Aloe vera* rind extract using the hot air oven method had the best total phenolic contents, as well as the preferred biological activity in terms of antioxidant and tyrosinase inhibitory activities.

Gas chromatography/mass spectrometry (GC-MS)

GC analysis of *Aloe vera* rind extract by the hot air oven drying method was performed to identify, quantify, and compare the phytochemical content, antioxidant capacity, and beneficial effects found in the samples using GC-MS (Nejatzadeh-Barandozi, 2013). Various volatile components, such as phenolic compounds, fatty acids, terpenoids, and esters, were found in the Aloe vera rind extract through GC-MS analysis (Table 4) and Group compounds and highlight % area for key bioactive classes (Table 5). A total of 34 compounds were identified with quality match scores >80% (except for the minor compound longifolenaldehyde at 70%, included for completeness as it represented 2.04% area). The main volatile compounds ranked included **alpha-amyrin (10.79% area), linoleic acid (8.07%), gamma-sitosterol (6.65%), phytol (4.01%), and hexadecanoic acid (3.83%)** respectively. These compounds are associated with antioxidant, anti-inflammatory, and antimicrobial properties, supporting the potential of *Aloe vera* rind as a value-added resource for cosmetic and pharmaceutical applications.

Table 4. Phytochemical compounds identified in Aloe vera rind extract by GC-MS.

No.	RT (min)	%Peak Area	Chemical Name	MW (g/mol)	Quality (%)*
1	3.396	0.25	2-Hydroxy-2-cyclopenten-1-one	98.10	80
2	3.988	0.45	2,4-Dihydroxy-2,5-dimethyl-3(2H)-furan-3-one	144.12	80
3	4.443	0.18	Benzyl chloride	126.58	91
4	6.971	0.50	2,3-Dihydrobenzofuran	120.15	91
5	9.578	0.18	Tetradecane	198.39	95
6	11.264	0.58	2,4-Di-tert-butylphenol	206.32	93
7	12.201	0.22	2-(Methoxymethyl)-3,5-dimethyl-4H-pyran-4-one	168.19	83
8	12.908	0.77	Hexadecane	226.44	93
9	15.764	0.18	Myristic acid	228.37	94
10	16.601	0.47	Octadecane	254.49	94
11	16.990	0.37	Isopropyl myristate	270.45	97
12	17.208	1.08	Neophytadiene	278.52	91
13	18.008	2.34	Lidocaine	234.34	95
14	18.532	0.29	Methyl palmitate	270.45	94
15	18.995	3.83	Hexadecanoic acid	256.42	99
16	19.437	0.80	Ethyl palmitate	284.48	98
17	19.538	0.35	Eicosane	282.55	91

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18	20.804	4.01	Phytol	296.53	97
19	21.030	1.71	9,12-Octadecadienoic acid	280.45	99
20	21.109	8.07	9,12,15-Octadecatrienoic acid (alpha-Linolenic acid)	278.43	99
21	21.347	1.25	Linoleic acid ethyl ester	308.50	95
22	21.421	1.03	9,12,15-Octadecatrienoic acid ethyl ester	306.48	98
23	22.922	0.18	2-Ethylhexyl trans-4-methoxycinnamate	290.40	86
24	25.986	0.37	1,8,11-Heptadecatriene	234.42	93
25	26.046	1.45	7,10,13-Hexadecatrienoic acid methyl ester	264.40	94
26	26.991	1.12	Squalene	410.72	91
27	29.248	1.27	beta-Tocopherol	416.68	94
28	30.522	1.63	dl-alpha-Tocopherol	430.71	97
29	32.116	0.64	Isocholesteryl methyl ether	398.66	83
30	33.733	6.65	gamma-Sitosterol	414.71	99
31	34.600	0.96	beta-Amyrin	426.72	98
32	35.455	0.46	9,19-Cyclolanost-24-en-3-ol (3.beta.)	426.72	95
33	35.654	10.79	alpha-Amyrin	426.72	93
34	36.714	2.04	Longifolenaldehyde	218.33	70

*The percent of quality is the percentage of compound identification was based on mass spectral comparison with the W10N14.L library, and only peaks with mostly Quality ≥80 % were considered reliable and reported (Stein, 2012).

GC–MS is well-suited for detecting volatile and semi-volatile, relatively non-polar compounds (e.g., fatty acids, triterpenoids, sterols, and diterpene alcohols) but has inherent limitations for highly polar, non-volatile, or thermally labile constituents such as glycosylated chromones (e.g., aloesin), anthraquinone glycosides, or high-molecular-weight polysaccharides. Previous research has commonly employed high-performance liquid chromatography (HPLC) for reliable quantification and detection of aloesin in Aloe vera extracts (Kim et al., 2017). The absence of aloesin in the present analysis is consistent with its low volatility and poor detectability under standard GC–MS conditions without prior derivatization or alternative methods such as HPLC-MS/MS. Thus the profile reported here complements rather than replaces targeted analyses of polar phenolics previously identified in Aloe vera rind by LC-based techniques.

These findings highlight the superior retention of bioactive compounds in the rind extract processed *via* hot air oven drying, as evidenced by higher abundances of fatty acids and terpenoids compared to other drying methods. Furthermore, the findings are consistent with previous GC-MS studies on *Aloe vera* leaf extracts, such as Lakshmi & Rajalakshmi (2011), who identified 26 bioactive compounds including n-hexadecanoic acid, squalene, and myristic acid. These compounds are known for their antioxidant, antimicrobial, and anti-inflammatory properties, supporting the therapeutic potential of *Aloe vera* extracts.

While these compounds are well-documented in Aloe vera literature, their relative abundances in the rind extract differ markedly from gel or whole-leaf profiles reported previously (e.g., Yoruk & Paksoy, 2024), where saturated fatty acids such as hexadecanoic acid often predominate (up to 28–30% in gel). In contrast, the rind showed substantial enrichment in pentacyclic triterpenoids (total ~18–20% for α-amyrin, β-amyrin, and γ-sitosterol combined) and omega-3/6 fatty acids, which are linked to stronger tyrosinase inhibition, UV protection, anti-inflammatory effects, and skin barrier support. As you can see the table summary of chemical class, group of key compounds, the percentage of peak area compared to evidence base with the relevant bioactivities in Relative abundances of key bioactive classes in hot-air oven-dried *Aloe vera* rind extract compared to gel/whole-leaf literature values (Table5) and retention times and peaks of whole Aloe vera rind extract by hot air oven drying method by GC-MS (Figure2).

Table 5. Relative abundances of key bioactive classes in hot-air oven-dried *Aloe vera* rind extract compared to gel/whole-leaf literature values

Chemical Class	Key Compounds (This Study – Rind, Hot-Air Dried)	% Peak Area (This study)	Comparison to Gel/Whole-Leaf Literature[1] (Yoruk & Paksoy, 2024)	Relevant Bioactivities (Supporting References)
Pentacyclic	α-Amyrin, γ-	~18–	Substantially higher than in gel	Tyrosinase inhibition,

Triterpenoids	Sitosterol, β-Amyrin	20% (total)	(typically trace to <2% in gel volatiles; triterpenoids/sterols often enriched in rind/outer tissues vs. inner gel)	collagen stimulation, UV-protective (Sirikhansaeng et al., 2017)
Unsaturated Fatty Acids	α-Linolenic acid (8.07%), Linoleic acid	~10–12% (total)	Similar to or moderately higher than gel (linoleic ~11–19%, linolenic ~16–22% in some gel/leaf studies; varies by extraction)	Anti-inflammatory, skin barrier repair (Simard et al., 2021)
Diterpene Alcohols	Phytol	4.01%	Higher than typical in gel (phytol ~1–4% or up to ~14% in some rind-inclusive or tannin extracts; lower in pure gel)	Antioxidant, wound healing (Islam et al., 2018)
Saturated Fatty Acids	Hexadecanoic acid (palmitic)	3.83%	Substantially lower than in gel (palmitic often ~11–32% in gel/leaf fatty acid profiles; dominant SFA in many gel studies)	Emollient properties, but less dominant in rind extract
Sterols / Tocopherols	γ-Sitosterol, α-/β-Tocopherol	~9–10% (total)	Higher than typical in gel (sterols like β-sitosterol/γ-sitosterol enriched in rind/outer fractions vs. lower in inner gel)	Anti-photoaging, radical scavenging (Nachbar & Korting, 1995)

[1] Note under table: Comparisons are based primarily on Yoruk & Paksoy (2024), which reports GC-MS volatile profiles of Aloe vera gel (e.g., major compounds include levoglucosan, various fatty acids/esters like octadecanoic acid methyl ester, tridecanoic acid, squalene) and extract forms, with limited direct % matches for rind-specific lipophilic. Supporting literature shows gel/whole-leaf often has higher saturated fatty acids (e.g., palmitic ~11–32%) and lower triterpenoids/sterols/phytol compared to rind-enriched samples (e.g., palmitic ~11–12% in some rind/tannin extracts; phytol up to ~14%). All values represent relative % peak areas from GC-MS (method-dependent; absolute concentrations vary by drying, extraction solvent, and plant part). Direct rind-gel comparisons are approximate due to study differences.

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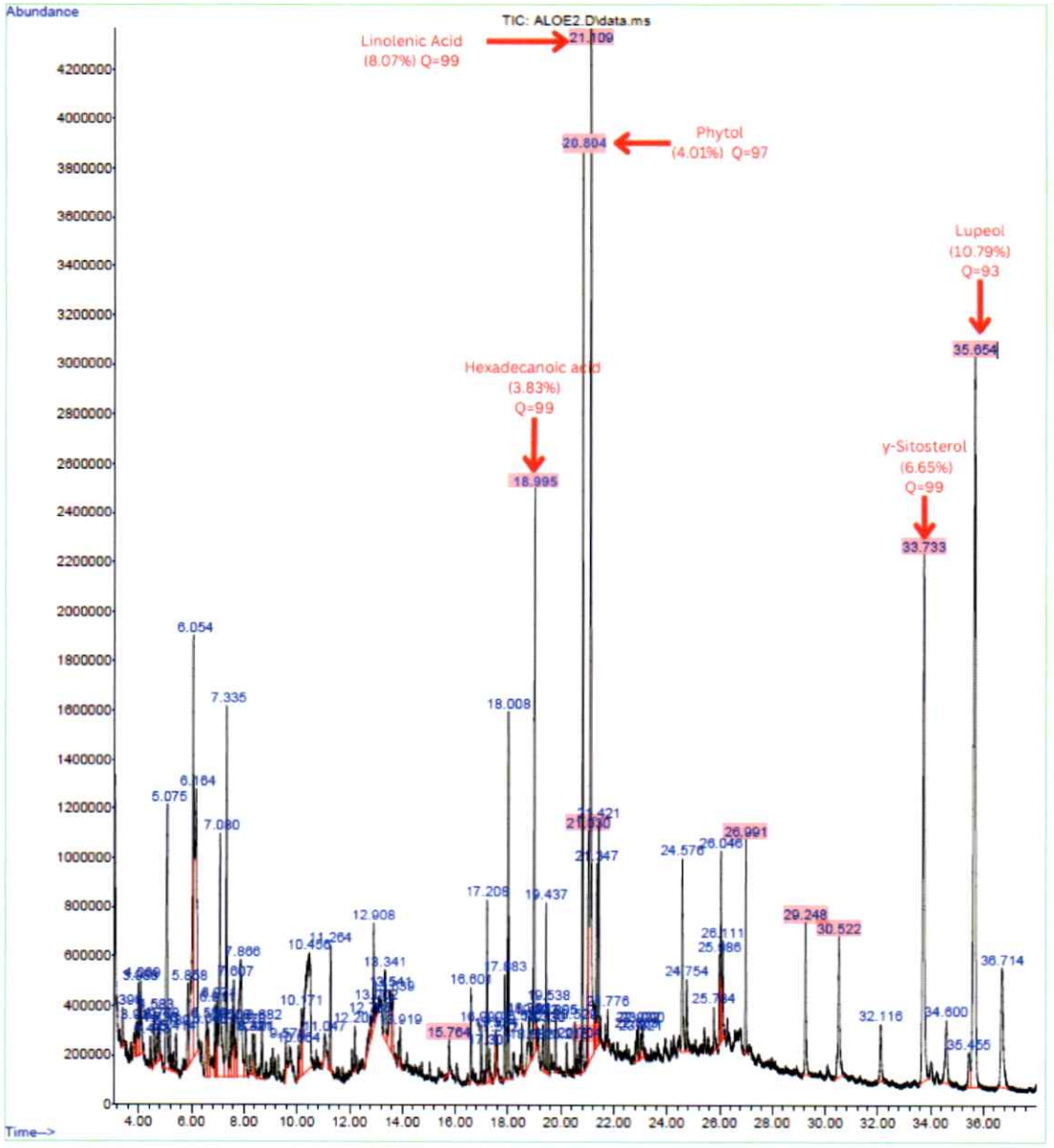


Figure 2. Retention times and peaks of compounds in whole *Aloe vera* rind extract by hot air oven drying method by GC-MS (Report highlighted by compound name, (%peak area), %Quality)

The GC–MS analysis of the *Aloe vera* rind extract prepared by hot-air oven drying revealed a rich profile of bioactive compounds with well-documented dermatological and cosmetic benefits (Table 4-5 and figure 2). Among the most abundant constituents, α-linolenic acid (8.07%) and linoleic acid (1.71% as free acid + 1.25% as ethyl ester) are essential omega-3 and omega-6 fatty acids known to strengthen the skin barrier, reduce trans epidermal water loss, and exhibit anti-inflammatory activity by down-regulating pro-inflammatory cytokines (Simard et al., 2021; Huang et al., 2023). Hexadecanoic acid (palmitic acid, 3.83%) and its ethyl ester contribute to skin softness and are frequently used as emollients in cosmetic formulations.

Phytol (4.01%), a diterpene alcohol derived from chlorophyll degradation, has been reported to possess antioxidant, anti-inflammatory, and wound-healing properties (Islam et al., 2018; Kim et al., 2023). γ-Sitosterol (6.65%) and α-amyrin (10.79%), both triterpenoids, are recognized for their ability to stimulate collagen synthesis, protect against UV-induced damage, and inhibit tyrosinase activity, thereby supporting anti-aging and skin-lightening effects (Sirikhansaeng et al., 2017; Fernández et al., 2001).

Tocopherol isomers (β-tocopherol 1.27%, dl-α-tocopherol 1.63%) are potent lipid-soluble antioxidants that prevent peroxidation of skin lipids and are widely incorporated in anti-photoaging products (Nachbar &

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Korting, 1995). Squalene (1.12%), a natural component of human sebum, acts as an excellent emollient and free-radical scavenger (Huang et al., 2009).

These findings show both similarities and important differences compared to the most recent comprehensive GC-MS study on Aloe vera published in the same journal. Yoruk and Paksoy (2024) analysed the gel and whole-leaf extracts of Aloe vera and reported hexadecanoic acid (palmitic acid) as the most abundant compound (up to 28–30 % in gel), followed by linoleic acid, phytol, and vitamin E derivatives. In contrast, the present study on Aloe vera rind revealed a markedly higher proportion of pentacyclic triterpenoids: α-amyrin reached 10.79 % and γ-sitosterol 6.65 %, whereas these compounds were either absent or present only in trace amounts (<0.5 %) in the gel-dominated samples of Yoruk and Paksoy (2024).

Conversely, the relative content of hexadecanoic acid was considerably lower in the rind (3.83 %) than in the gel (≈28 %). α-Linolenic acid (8.07 %) and phytol (4.01 %) were detected in comparable or slightly higher percentages in the rind compared to the gel values reported by the same authors (5–7 % and 2–4 %, respectively).

These compositional shifts clearly demonstrate that *Aloe vera* rind is a richer source of triterpenoids (α-amyrin, β-amyrin, γ-sitosterol) and omega-3 fatty acids, while the gel is dominated by saturated fatty acids such as palmitic acid. This complementary distribution explains why the rind extract exhibited superior tyrosinase-inhibitory activity (IC = 0.04 mg/mL) compared to literature values for gel extracts (typically 0.2–1.0 mg/mL), because α-amyrin and γ-sitosterol are recognised as potent tyrosinase and melanogenesis inhibitors (Sirikhansaeng et al., 2017).

Therefore, the present results reinforce and extend the conclusions of Yoruk and Paksoy (2024) by showing that *Aloe vera* rind, previously regarded as an agro-industrial waste, actually represents a sustainable and low-cost reservoir of high-value cosmetic actives that are either scarce or absent in the commercially exploited gel portion.

Plants from different regions exhibit variations in phytochemical profiles, with accessions from colder/northern zones (e.g., northern India) often showing higher antioxidant potential and phenolic content than those from hotter/southern or tropical zones (Kumar et al., 2017). Agro-climatic differences, including soil quality, altitude, and local climate, alter levels of phenolics, polysaccharides, and anthraquinones. Seasonal changes influence polysaccharide composition and other metabolites, with fluctuations linked to rainfall, dry vs. wet periods, or temperature cycles (Ahl et al., 2019). Some studies indicate seasonal effects on secondary metabolites in the latex/rind, though environmental conditions frequently outweigh pure seasonal variation in aloins (Ahl et al., 2019). Climate change-related shifts (e.g., altered precipitation and temperature) further affect phytochemical diversity and antioxidant activity (Kumar et al., 2017). These variations are particularly relevant for rind-derived bioactives. In this research would aim for sustainable microemulsion serums from agricultural by-products. Standardizing collection (e.g., same location/season) helps ensure consistency, as local humidity, heat, and monsoon patterns could influence rind composition.

The presence of these compounds was observed for the hot-air oven-dried rind extract compared to freeze- and solar oven-dried samples. Bioactive compounds such as aloin and phenolics are biosynthesized and accumulated in the living Aloe vera plant in response to environmental stresses during cultivation (González-Delgado et al., 2023). After harvest, no further synthesis occurs; the drying processes evaluated in this study serve only to preserve the pre-formed compounds by inactivating enzymes and reducing water activity. Collectively, these findings position *Aloe vera* rind, particularly when processed by hot-air oven drying, as a sustainable and valuable source of multifunctional actives for natural cosmetic and dermatological applications.

4. Conclusion

This study demonstrated that the drying method plays a critical role in determining the extraction efficiency and quality of bioactive compounds from *Aloe vera* rind. Among the three methods investigated, hot-air oven drying at 50 °C proved to be the most practical and effective approach, providing higher extract yields, preserving phenolic and flavonoid compounds, and exhibiting strong antioxidant and tyrosinase

inhibitory activities. Compared with freeze drying, hot-air oven drying was considerably more cost-effective, required less processing time, and maintained comparable extract quality, while solar drying showed limited consistency and efficiency. Overall, this study reinforces the importance of drying method selection in optimizing the antioxidant potential of *Aloe vera* rind extracts. It also highlights the need for further research into the thermal stability of specific compounds and the role of solvent systems in extraction efficiency.

GC–MS analysis confirmed that hot-air oven-dried extracts contained diverse bioactive compounds such as lupeol, phytol, linolenic acid, γ-sitosterol, and hexadecanoic acid with antioxidant, anti-inflammatory, and skin-brightening and softening potential, supporting their application in cosmetic formulations. These findings highlight hot-air oven drying as a viable technique for optimizing the value of *Aloe vera* rind, an underutilized agricultural by-product, and promoting its sustainable use in natural skincare product development. In addition to its scientific relevance, hot-air oven drying offers practical advantages for small- and medium-scale enterprises (SMEs) and community-based industries, where access to high-cost technologies is limited. Future studies should further investigate product formulation, stability, and cost management strategies to support the translation of these findings into commercial applications.

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