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Effect of different drying methods and conditions on volatile profile and sensory properties of avocado (*Persea americana* Mill.) seed flour as a food flavouring agent

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ABSTRACT

Avocado seeds, which account for up to 26% of fruit mass, remain largely underutilised despite their nutritional, functional, and bioactive potential. Their use as flavouring ingredients represents a novel valorisation strategy. This study investigated the effect of drying technology and process intensity on the volatile profile and sensory quality of avocado seed flour from the Pinkerton cultivar. A flavour-focused approach was applied, combining drying-process characterisation, HS-SPME-GC–MS volatilomics, trained-panel quantitative descriptive analysis, and consumer acceptability testing. Uniformly thin-sliced seeds were dried by hot-air (40, 50, and 60 °C) or microwave (400, 567, and 700 W), milled into flour, and analysed for colour, volatile composition, sensory attributes, and liking. Both drying technology and process intensity significantly influenced volatile composition and sensory properties, with aroma development mainly associated with lipid oxidation-related pathways and terpene modulation during drying. Microwave drying was faster and more energy-efficient than hot-air drying, substantially reducing processing time. Drying kinetics were satisfactorily described by an exponential-asymptotic model, regardless of the technology applied. Flours obtained under intermediate conditions (567 W and 50 °C) showed the highest acceptability and were characterised by sweet, fruity, and citrus notes, whereas more severe or milder conditions produced herbaceous or pungent odours associated with lower liking scores. Volatilomic and sensory data were strongly aligned, confirming a clear relationship between chemical markers and perceived aroma attributes. Overall, this work provides the first integrated evaluation of avocado seed flour as a potential flavouring ingredient and demonstrates that controlled drying can tailor its flavour profile for sustainable food applications.

1. Introduction

In recent years, avocado (*Persea americana* Mill.) cultivation has expanded considerably in countries of the Mediterranean area, driven by increasing global demand and favourable agroclimatic conditions (Cárceles Rodríguez et al., 2023). This rapid expansion has led to a substantial rise in avocado processing and thus its by-products (Tesfaye et al., 2022), which remain largely underutilised despite their promising nutritional, functional, and bioactive potential (Féliz-Jiménez & Sanchez-Rosario, 2024; Marra et al., 2024; Otero-Guzman & Andrade-Pizarro, 2025).

Among avocado by-products, seeds constitute approximately 20 - 26% of the fruit's total weight (Dabas et al., 2013), and they are particularly rich in starch (up to 60 - 70%) and dietary fibre; they also contain a wide range of bioactive molecules, including polyphenols, carotenoids, tocopherols, and phytosterols (Jimenez et al., 2021), which have been associated with different health-promoting benefits. Previous studies have incorporated nano-sized avocado seed powder into yogurt, reporting increases in ash, carbohydrate, and dietary fibre contents, together with higher polyphenol levels and antioxidant activity that supported the growth of selected probiotic strains (Elsayed & Elsayed, 2024). Moreover, avocado seed powder has been proposed as a partial substitute for wheat flour, markedly enhancing the fibre and polyphenolic content, as well as the antioxidant activity, of snacks, bread, and other cereal-based products (Nyakang'I et al., 2023; Siol & Sadowska, 2023). Furthermore, the potential of avocados in the discovery of new drugs for the prevention and treatment of cancer, microbial diseases, inflammatory diseases, diabetes, and cardiovascular diseases has

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been highlighted (Bhuyan et al., 2019).

Despite their wide range of potential food applications, owing to their high starch and dietary fibre content (Charles et al., 2022), and their promise for functional food development because of their richness in bioactive compounds (Fufa et al., 2025a), avocado seeds are still largely discarded or recycled for low-value uses such as animal feed or agricultural fertilisers. An innovative and still unexplored strategy for the valorisation of avocado seeds may lie in their potential use as flavouring agents. In fact, due to their distinctive volatile profile, tropical fruit seeds have the potential to be used as natural flavouring agents in processed foods (Zhang et al., 2025). Arango et al. (2025) reported the occurrence of terpenic and sesquiterpenic volatiles in fresh avocado seeds, suggesting a theoretical odour profile characterized by woody and balsamic notes. Spada et al. (2020) and Ravindran et al. (2020) demonstrated that jackfruit seed, following specific heat treatments, can be used to impart an intense chocolate aroma. Recently, Chen et al. (2025) characterised the phenolic profiles, chemical composition, and volatile compounds of the pulp, seed, and peel of unprocessed avocado fruits from different varieties cultivated in New Zealand. Earlier, Bayomy et al. (2023) investigated the volatile composition of Hass avocado kernels after roasting at 180 °C for 30 min. To the best of our knowledge, the volatile profile of dried avocado seeds has not yet been fully investigated. Indeed, previous studies have mainly focused on drying avocado seeds to preserve their bioactive compounds or to facilitate their grinding into flour for use as functional ingredients (Babiker et al., 2021; Figueroa et al., 2025; Fufa et al., 2025b). However, thermal processing modulates key chemical reactions, including Maillard reactions, lipid oxidation, caramelization, and the transformation of phenolic compounds (Wang et al., 2022), thereby significantly influencing the volatile profile and flavour perception.

In light of this, the present study investigates how different drying technologies and process intensities influence the volatile profile and sensory quality of avocado seeds from the Pinkerton cultivar, with the aim of producing an avocado seed flour with a desirable flavour profile suitable for use as a natural flavouring ingredient. To achieve this, we adopt a flavour-focused approach integrating drying-process characterisation, HS-SPME-GC-MS volatilomics, trained-panel quantitative descriptive analysis, and consumer acceptability testing.

The Pinkerton avocado is a widely cultivated and agronomically stable hybrid cultivar, characterized by an extended flowering period, which leads to a prolonged fruit-set window, typically ranging from November to February in Sicily. Its fruits exhibit physicochemical characteristics suitable for various processing applications, including oil extraction. However, unlike the extensively studied Hass cultivar, both the fruits and by-products of Pinkerton have received limited scientific attention, further supporting the relevance of investigating this variety. Within a circular-economy framework, this research is intended to support the valorisation of avocado seed as a by-product and to explore its potential as a sustainable, high-value natural flavouring ingredient for the food industry.

2. Materials and methods

2.1. Plant material

Avocado fruits of the Pinkerton variety, originating from an orchard located in northeastern Sicily (Italy), were purchased from a local greengrocer on three separate occasions between November and December 2024. The fruits exhibited a pear-shaped morphology and individual weights ranging from 200 to 230 g. They were characterized by a thin, deep-green exocarp enclosing yellow-green, creamy mesocarp and medium-sized seeds. Upon arrival at the laboratory, twenty fruits were selected from the batch, based on firmness, uniform deep-green skin coloration, and the absence of any external softening, all indicative of an early stage of ripeness. The seeds were carefully separated from the mesocarp, rinsed under a continuous tap water flow, and blotted with a paper towel. To standardize both slice thickness and exposed surface area, the seeds were rapidly sliced into discs of approximately 1 mm thickness using a stainless steel mandoline slicer (Fackelmann, 32 × 12.45 × 3.73 cm, model 45,331), ensuring a consistent heat-transfer area across treatments (Maskan, 2000). For the drying trials, the discs were randomly divided into six aliquots of approximately 60 g each and immediately processed to minimise enzymatic browning reactions.

2.2. Drying processes

Hot-air drying (HAD) and microwave drying (MWD) techniques were applied. For each procedure, about 20 slices (approximately 20 g) were placed, well-spaced among them, on each of the three uniform mesh dehydrator racks to expose both seed surfaces and have uniform water loss. HAD was performed at three different temperatures (40 °C, 50 °C, and 60 °C) at constant air velocity (1.5 m/s), using a tray dryer (UOP8, Armfield Ltd., Hampshire, England). For MWD, three different power levels were tested (400 W, 567 W, and 700 W) using a digital microwave oven (YC-PC322AE-S, Sharp, Milan, Italy). Microwave powers were selected based on preliminary trials to (i) encompass a meaningful range of treatment intensities, (ii) prevent visible scorching or localised overheating, and (iii) ensure attainment of the target moisture endpoint within practical processing times. During the drying processes, the samples were periodically removed from the dryer and weighed using an analytical balance (QUINTIX 65–1S, Sartorius, Göttingen, Germany) with an accuracy of 0.0001 g, to monitor the moisture ratio over time. Regarding the MWD process, the heating cycle durations have been carefully evaluated to prevent localised overheating of the sample.

A final moisture content of 11% was adopted as the target value for defining the end point of dehydration. Each process was repeated three times under the same conditions, and the average results were taken into consideration.

No enzymatic browning inhibitors (e.g., ascorbic acid, citric acid, or sulfites) were applied prior to drying in order to evaluate the direct effect of drying conditions on colour formation and volatile development.

2.3. Mathematical modelling of drying curves

Eq. (1) allows the calculation of the moisture ratio (MR) during drying experiments

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where M_t, M_0, M_e represent the moisture content at any time t (min), initial moisture content, and equilibrium moisture content, respectively.

In case of high-moisture biological materials (such as fruits, vegetables, starchy matrices), the equilibrium moisture content (M_e) is negligible compared to M_t and M_0 (Karaaslan & Ekinci, 2023). Moreover, during the falling-rate period, the material moisture remains far above equilibrium, and M_e can be reasonably treated as insignificant in the driving force for drying. Under these conditions, the moisture ratio was calculated using the simplified equation:

$$MR = \frac{M_t}{M_0} \quad (2)$$

For each treatment, the MR values were plotted against time (t) to obtain the experimental drying curves.

To describe the mathematical behaviour of these curves, the experimental data were fitted to three thin-layer drying models, namely those proposed by Henderson and Pabis (1961), Lewis (1921), and Yagcioglu et al. (1999), and the model providing the best fit was identified. Non-linear least-squares regression was applied to estimate the model parameters using the Levenberg–Marquardt optimization algorithm, whereas the coefficient of determination (R^2), the reduced chi-square

(χ^2), and the root mean square error (RMSE) were used as criteria to assess the goodness of fit.

2.4. Flour production

The dried seeds were finely ground using an electrical spice grinder (SG21BE, Cuisinart, Stamford, Connecticut, USA) for 5 min, and the particle size distribution of the resulting flours was measured by sieving. Because of the high moisture and starch content of the fresh seeds, grinding was performed only after drying. Wet milling would have produced a paste-like mass prone to agglomeration, uneven heating, and accelerated oxidative and enzymatic reactions.

The flours were promptly transferred into amber glass jars, sealed with metallic lids, and stored in a cool, dry, and dark place until use. Under these conditions, the flours remained stable (data not shown) for up to six months.

2.5. Moisture content

The final moisture content of the dried samples was assessed using the oven drying method, where the samples were kept at 110 ± 0.5 °C until a constant weight was reached (Condurso et al., 2019).

2.6. Colour analysis

The colour analysis was performed according to the method reported by Merlino et al. (2022). The measurements were conducted under SCE (specular component excluded) conditions. Twelve replications were conducted for each flour sample, and the results were expressed as average values. The mean values of $L*$, a*, and $b*$ were employed to calculate the total colour difference among samples processed with the same drying technology but under different conditions, according to the following equation.

$$\Delta E_{Lab} = \sqrt{\Delta L*^2 + \Delta a*^2 + \Delta b*^2} \quad (3)$$

If $0 \langle \Delta E_{Lab} < 1$, the observer does not notice a difference; $1 < \Delta E_{Lab} < 2$, only an experienced observer may notice the difference; $2 < \Delta E_{Lab} < 3.5$, an inexperienced observer also notices the difference; $3.5 < \Delta E_{Lab} < 5$, a clear colour difference is noticed, and $\Delta E_{Lab} \rangle\ 5$, the observer notices two different colours (Mokrzycki & Tatol, 2011).

2.7. QDA sensory analysis

Quantitative Descriptive Analysis (QDA) was carried out following the methodology described by Cincotta et al. (2025).

A panel of eight assessors (4 males and 4 females aged 25 - 50 years) was recruited from the Department of Veterinary Sciences, University of Messina, and trained in accordance with ISO 8586:2023 guidelines. Assessors were selected among healthy non-smokers who did not report allergies or temporary conditions (e.g., colds) that could interfere with sensory perception. To avoid sensory interference, they were instructed to refrain from consuming strong-flavoured foods, coffee, or mint products before the sessions. Only individuals demonstrating reliable and repeatable responses during training were included in the panel.

During training sessions, a common sensory vocabulary was established, and 15 odour descriptors - strength, sweet, herbaceous/green, fruity, woody, spicy, orange/citrus, waxy, pungent, fermented, paint, hay, fresh, honey, and floral - were selected based on frequency of citation.

Samples were analysed in triplicate in three different sessions and presented in randomised order. The assessors rated the intensity of each attribute on a 9 - point scale (1 = low, 9 = high). To minimise olfactory fatigue, sessions were interspersed with one-hour intervals. All judges signed an informed consent form in accordance with the ethical principles of the Declaration of Helsinki. Results were expressed as mean intensity values for each descriptor.

2.8. Consumers' acceptability test

The sensory acceptability of the seed flours was evaluated by a group of 86 untrained consumers (40 male and 46 female) aged between 22 and 60 years and recruited from the Department of Veterinary Science (University of Messina, Italy). Untrained assessors were selected among healthy non-smokers who did not report allergies or temporary conditions (e.g., colds) that could interfere with sensory perception. Participation in the survey was completely voluntary, and, prior to the tasting sessions, all participants signed an informed consent form in accordance with the ethical principles of the Declaration of Helsinki. To avoid sensory interference, consumers were instructed to refrain from consuming strong-flavoured foods, coffee, or mint products before the sessions. Each judge evaluated the 6 seed flours as-is in triplicate across three different sessions. In each session, the samples were assessed in randomised order and interspersed with 15-minute intervals to minimise olfactory fatigue. Participants were asked to rate odour and colour according to a nine-point hedonic scale (1=extremely unpleasant; 2=very unpleasant; 3=unpleasant; 4=slightly unpleasant; 5=neither pleasant nor unpleasant; 6=slightly pleasant; 7=pleasant; 8=very pleasant; 9=extremely pleasant). The overall acceptability was calculated from the average of all the ratings collected.

2.9. Volatile profile

The volatile aroma compounds of dried avocado seed flours were analysed using Headspace Solid-Phase Microextraction coupled with Gas Chromatography-Mass Spectrometry (HS-SPME-GC–MS), following the method described by Cincotta et al. (2024). One gram of seed flour was mixed with 18 mL of a saturated NaCl solution in a 40 mL glass vial, and the mixture was equilibrated at 40 °C under continuous stirring for 30 min. Volatiles were extracted using a DVB/CAR/PDMS fibre exposed to the headspace for 30 min, then thermally desorbed into the GC injection port (280 °C). Separation was performed on an SLB-5 ms capillary column, and detection was carried out using a triple quadrupole mass spectrometer in full scan mode (40–400 m/z). Compound identification was based on comparison with NIST '20 and FFNSC 3.0 libraries, retention indices, literature data, and reference standards.

2.10. Statistical analysis

The data were statistically elaborated by using XLStat software, version 2014.5.03 (Addinsoft, Damremont, Paris, France). Analysis of variance (ANOVA), followed by Duncan's multiple range test ($p < 0.05$), was carried out. Hierarchical clustering analysis was performed using the web tool ClustVis.

3. Results and discussion

3.1. Drying processes

It is well established that biological materials generally exhibit a negligible constant-rate drying period, with moisture removal occurring almost entirely during the falling-rate period (Madamba et al., 1996). This behaviour indicates that internal diffusion is the dominant mechanism governing moisture migration within the samples. Under such conditions, slicing avocado seeds into thin sections (1 mm) helps minimise internal moisture gradients, reduces thermal exposure, and ensures more uniform heat and mass transfer during dehydration. This preparation also enables the use of thin-layer drying models, which - although originally developed for diffusion-controlled systems - are widely applied to describe moisture ratio (MR) changes in a broad range of drying technologies, including microwave-assisted processes (Onwude et al., 2016). Fig. 1 shows the experimental and model-predicted

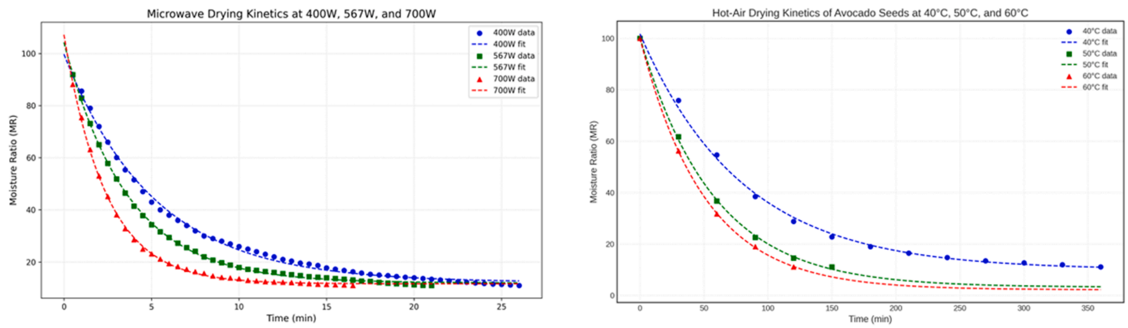

Fig. 1. Experimental and model-predicted moisture ratio of avocado seeds as a function of drying time under different drying technologies and conditions.

moisture ratio of avocado seeds as a function of drying time, under different drying technologies and conditions.

Among the models evaluated, the exponential-asymptotic equation proposed by Yagcioglu et al. (1999),

$$MR = a\,e^{-kt} + c \quad (4)$$

provided the best description of the thin-layer drying behaviour of avocado seeds across all drying methods and operating conditions. The suitability of exponential–asymptotic models for diffusion-controlled drying has also been demonstrated for other vegetable products (Doymaz, 2007).

Table 1 reports the fitted parameters a, k, and c, together with the corresponding R2, χ2, and RMSE values for each treatment. MWD samples showed significantly higher decay constants (k ranging from 0.1950 to 0.4211), indicating a rapid decrease in moisture ratio. This is consistent with the volumetric heating mechanism of microwaves, which generates internal vapor and enhances moisture migration from the core to the surface. As microwave power increases, the internal pressure gradients become more intense, reducing the effective diffusion path and shortening the falling rate period. Similar trends have been reported for other vegetable matrices dried under microwave conditions, where rapid internal heating accelerates moisture migration (Condurso et al., 2019; Maskan, 2000).

In contrast, HAD demonstrated significantly lower decay constants ($k = 0.00863$–0.02308), reflecting the slower kinetics typical of diffusion-controlled systems. In convective drying, heat is supplied externally through the product surface, while moisture movement within the material is primarily governed by internal diffusion. These results are consistent with previous studies reporting similarly low k values for HAD and confirming that convective drying is predominantly a diffusion-limited process (Joardder & Karim, 2023; Tauhiduzzaman et al., 2021).

Regardless of the drying method and conditions used, all flour samples had the same moisture end-point of approximately 11%. The reaching of this moisture level took between 16 and 26 min when using MWD, while it required between 120 and 360 min with HAD. These results are in line with previous studies that have described microwave drying as an energy-efficient technique that can dramatically increase mass transfer rates compared to conventional convective drying (Maskan, 2000). The consistently high R^2 values, along with low χ^2 and RMSE values, indicate a strong correlation between the model predictions and the experimental data. This confirms that, although the different heating mechanisms underlying MWD and HAD strongly influence the rate of moisture removal, under the studied conditions, the drying behaviour of avocado seeds can be effectively described using thin-layer drying models. In particular, the good performance of the exponential–asymptotic model is consistent with the presence of a residual moisture fraction, which is typical of dehydrated food materials.

Table 1
Estimated parameters (a, k, c), coefficient of determination (R^2), reduced chi-square (χ_r^2), and root mean square error (RMSE) of the exponential–asymptotic kinetic model $MR = ae^{-kt} + c$, fitted to the experimental datasets obtained under different drying technologies and conditions.

	a	k	c	R^2	χ^2	RMSE
HAD_40 °C	88.6760	0.00863	11.0400	0.9995	0.1323	0.3237
HAD_50 °C	92.0400	0.01538	10.9820	0.9998	0.0501	0.2238
HAD_60 °C	95.0200	0.02308	10.9500	0.9999	0.0309	0.1760
MWD_400W	87.5509	0.19500	12.1878	0.9973	0.0203	0.1425
MWD_567W	92.2652	0.27840	12.0608	0.9993	0.0757	0.3059
MWD_700W	95.5482	0.42110	11.6514	0.9993	0.0906	0.2967

3.2. Physical properties

After drying, the avocado seeds were processed into flour of comparable granulometry. The particle size distribution showed that approximately 34–35% of each flour sample consisted of coarse particles (> 400 μm), about 19% was retained between 250 and 400 μm, while the remaining 44 - 45% passed through the 250 μm sieve. These results indicate that the majority of the flours were composed of fine particles (< 250 μm). Regarding flour colour (Fig. 2), ΔE values highlighted that samples treated at 700 W appeared very different in colour than 400 W and 567 W samples, which, in contrast, exhibited the same colour. Among the HAD samples, observers can readily distinguish different colours between samples dried at 40 °C and those dried at 50 °C or 60 °C.

In detail, for the MWD samples, increasing microwave power from 400 W to 700 W led to a gradual increase in L* values, indicating a lighter appearance associated with shorter drying times. This trend may be associated with reduced exposure to oxidative browning and limited pigment degradation at shorter processing times, resulting from the higher microwave power. Conversely, *a** values decreased, suggesting a reduction in red-brown tones, while *b** values remained relatively stable, indicating minor changes in the yellow component. HAD samples exhibited the lowest *L** value at 40 °C, confirming darker colouration, likely due to the low processing temperature was unable to inhibit the enzymatic oxidation of phenolic compounds. The highest lightness occurred at 50 °C, whereas a decrease of *L** value at 60 °C may reflect enhanced non-enzymatic browning due to thermal acceleration of Maillard reactions. Both *a** and *b** increased with temperature in HAD, reflecting a shift toward more pronounced reddish-yellow hues, indicative of browning pigment formation. Since no antibrowning agents (e.g., ascorbic or citric acid) were applied, the colour development reflects the intrinsic response of avocado seed tissues to the different drying treatments. This is relevant because antibrowning compounds can modulate oxidative pathways and alter pigment formation during thermal processing (Chen et al., 2025).

These results agree with the findings of Süfer et al. (2025), who affirm that conventional techniques like sun and hot-air drying favoured enzymatic and non-enzymatic brownings, whereas drying technologies that cut down on processing temperature and drying time better preserve the colour.

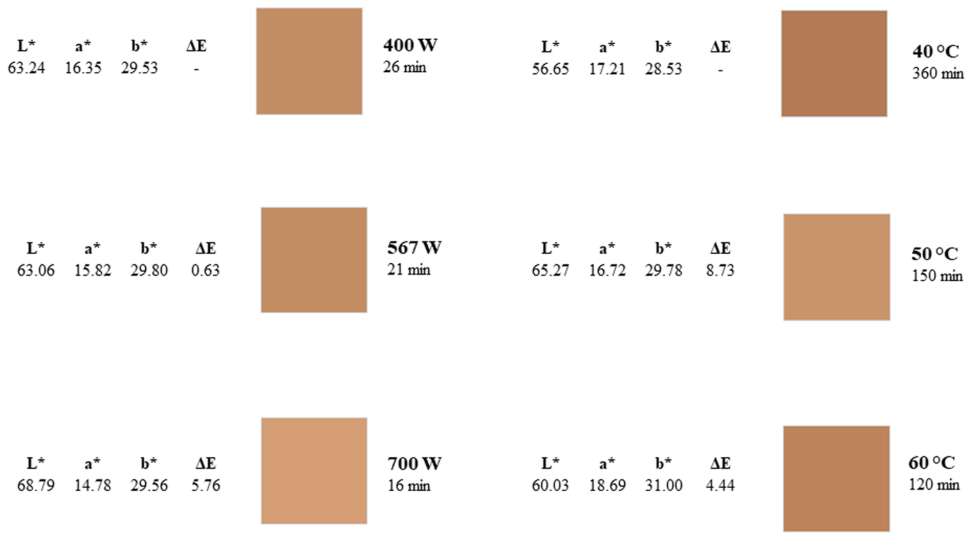

Fig. 2. Colour parameters (L*, a*, b*) of avocado seed flours obtained under different drying technologies and conditions.

3.3. Sensory analyses

Drying treatment significantly influenced the odour attributes, as evidenced by the QDA results (Fig. 3).

Within MWD treatments, clear differences emerged across microwave power levels. The samples dried at 400 W were characterised by more pronounced herbaceous, spicy, and honey-like notes, whereas the 567 W samples showed a reduction in herbaceous and spicy attributes and were instead described as fruitier and less waxy. In contrast, samples dried at 700 W had an odour profile dominated by pungent notes, accompanied by a reduction in fruity and hay-like attributes, suggesting that excessive microwave intensity negatively affected the sensory quality, likely due to the thermal degradation of key volatile compounds.

Regarding HAD samples, the flours dried at 40 °C and 60 °C exhibited similar sensory profiles, while the sample dried at 50 °C displayed a more pleasant odour profile, with higher sweet, fruity, and citrus notes and fewer herbaceous attributes. This indicates that a temperature of 50 °C favoured the development of volatile compounds associated with more pleasant odour notes.

3.4. Consumer acceptability

The combined outcomes of the hedonic ranking test and purchase intention survey are presented in Fig. 4. Clear and significant differences emerged among treatments, confirming that both drying technology and process conditions strongly influence consumer perception and potential market acceptance of avocado seed flours.

Samples treated at 567 W and 50 °C received the highest hedonic scores for colour, odour, and overall liking, which reflected the highest purchase intention among consumers. In contrast, treatments conducted at 400 W and 40 °C resulted in significantly lower sensory scores and a reduced willingness to purchase, associated with both less favourable odour and colour attributes. Increasing the temperature to 60 °C and the power to 700 W led to a slight decrease in hedonic ratings compared to 50 °C and 567 W, respectively, while consumer purchase intention remained relatively high.

Compared to QDA results, the samples rated most pleasant were those praised by the sensory panel for their distinct fruity, sweet, and citrus notes.

3.5. Volatile profile

Table 1S reports the composition of the flour samples obtained from MWD and HAD technologies at different powers (400 W, 567 W, and 700 W) and temperatures (40 °C, 50 °C, and 60 °C), respectively, as single components and classes of substances. All the seed flour samples exhibited a complex volatile aroma profile, with approximately 115 compounds identified. The most abundant chemical class, across all samples, was sesquiterpenes, especially hydrocarbon sesquiterpenes, followed by monoterpenes (mostly hydrocarbon), furanoic compounds, aldehydes, alcohols, esters, ketones, and phenylpropanoids, with differences in the percentage of each class among the different samples (Fig. 5). The compounds mostly represented were D-germacrene, α-*trans*-bergamotene, α- and β-cubebene, α- and β-pinene, (*E*)-caryophyllene, 2-tridecylfuran, (*E*)-β-santalol acetate, δ-cadinene, camphene, α-copaene, and limonene (Table 1S). Additionally, hexanol, (2*E*)-2-hexen-1-ol, (4*Z*)-4-decen-1-ol, (2*E*)-2-nonenal, benzaldehyde, nerol, and geraniol were found exclusively in flours from hot-air dried seeds.

Drying technologies qualitatively affected the volatile fraction composition of the flour samples, whereas, from a quantitative point of view, statistically significant differences emerged as a function of both drying methods and process conditions. To gain a clearer understanding of the differences in the volatile aroma profiles, a hierarchical clustering analysis was performed, and the results were presented as a heatmap in Fig. 6. The figure clearly shows the samples divided into two main groups. The first group consists of 700 W, 567 W, and 50 °C, while the second group includes 400 W, 40 °C, and 60 °C. This shows that drying conditions, rather than drying technologies, have a greater impact on the final volatile profile of avocado seed flour. This suggests that the drying process can be utilised to modify the volatile profile of avocado seed flour.

In the first group, samples dried at 567 W were closely grouped with the 50 °C samples, exhibiting a generally lower abundance of many volatiles compared to the other treatments. They were characterised by the highest content of 2-tridecylfuran, which imparts fruit notes, along with a good amount of sesquiterpenes like α-*cis*-bergamotene, α-*trans*-bergamotene, and β-bisabolene with citrus and woody notes. In contrast, the other sesquiterpenes were less represented, as well as hydrocarbon monoterpenes, the latter being key contributors to herbal, citrus, and resinous odour. Additionally, in the samples dried at 50 °C, oxygenated compounds (including monoterpenes, sesquiterpenes, and aliphatic compounds) such as eucalyptol, terpinen-4-ol, linalool, *trans*-linalool oxide, nerol, geraniol, α-santalol acetate, (*Z*)-β-santalol acetate, (*E*)-β-santalol acetate, octanol, and (4*Z*)-4-decen-1-ol, were also present. Some of these compounds are clearly oxidation products, whose formation was probably promoted by the longer heating time in the HAD treatment compared to the MWD. Another volatile that was particularly

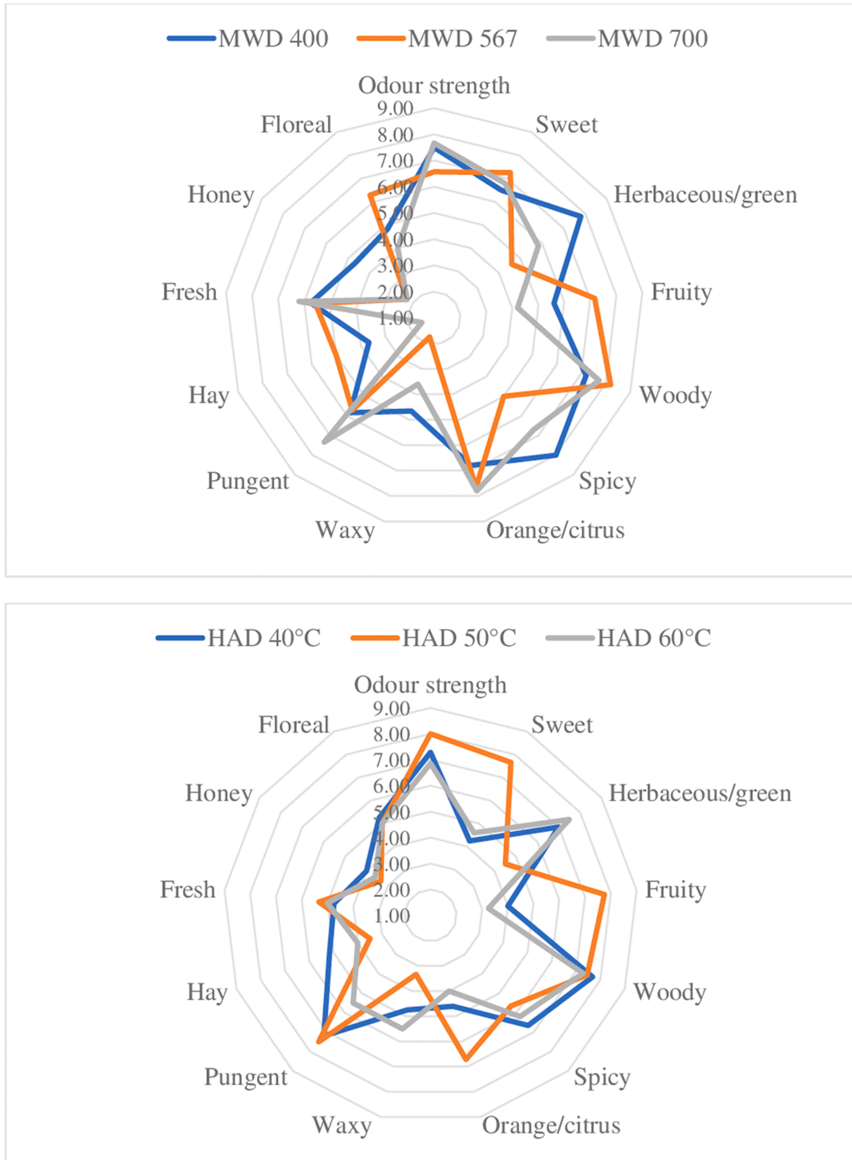

Fig. 3. Spider plot representation of QDA results for the odour attribute of avocado seed flours obtained under different drying technologies and conditions.

well represented in both 567 W and 50 °C samples was avocadynofuran, namely 2-(tridec-12-yn-1-il)furan; this compound, along with 2-tridecylfuran, arose from the degradation of persin, an acetogenin synthesised in the oil cells of avocado tissues (Rodriguez-Saona & Trumble, 2000). Avocadynofuran is also naturally present in leaves, seeds, and fruit of *Persea americana* Mill, as well as in other species within the genus Persea, regardless of the treatment received. More recent studies report avocadynofuran as a product of flavonoid degradation, the formation of which depends on the hardness conditions of extraction (Laurentcya et al., 2025). To date, this compound has only been identified within the genus Persea and exhibits both insecticidal and antimicrobial properties (Fahs et al., 2025; Rodriguez-Saona & Trumble, 2000).

Persin poses a safety concern due to its well-documented toxic effects on certain animal species (Hunashal et al., 2025). However, regarding avocado seeds and their derived ingredients, current evidence indicates limited data on human toxicity and no specific regulatory approvals for seed-derived ingredients (Paternina-Ricardo et al., 2025).

Nevertheless, avocado seed has already been explored in several food applications, including flour-based formulations, bread enrichment (Jaramillo-De la Garza et al., 2025), and ready-to-eat extruded snacks (Permal et al., 2023), with processed seed-derived products generally exhibiting safe levels for moderate consumption (Paternina-Ricardo et al., 2025). In the present study, seed flour was used only as a flavouring component, implying a low expected intake that substantially mitigates any safety concerns.

The composition of volatile profiles in samples dried at 567 W and 50 °C aligned with their sensory characteristics identified through QDA analysis. Indeed, sensory analysis highlighted the prevalence of fruity, sweet, and citrus attributes, along with fewer herbaceous, spicy, and waxy odours, which altogether contributed to higher consumer acceptability.

The samples dried at 567 W and 50 °C were further clustered with samples dried at 700 W. These last ones were primarily characterised by high levels of hydrocarbon monoterpenes, including β-pinene, α-pinene, camphene, limonene, α-terpinene, γ-terpinene, sabinene, myrcene, α-phellandrene, δ−3-carene, isoterpinolene, α-thujene, and terpinolene. They also contained sesquiterpenes such as β-selinene and (*E*)-caryophyllene, along with aldehydes like octanal, decanal, and (4*Z*)-4-decenal, as well as oct-3-en-2-one and esters including octyl, hexyl, and decyl acetate. This combination of terpenes and lipid-oxidation products

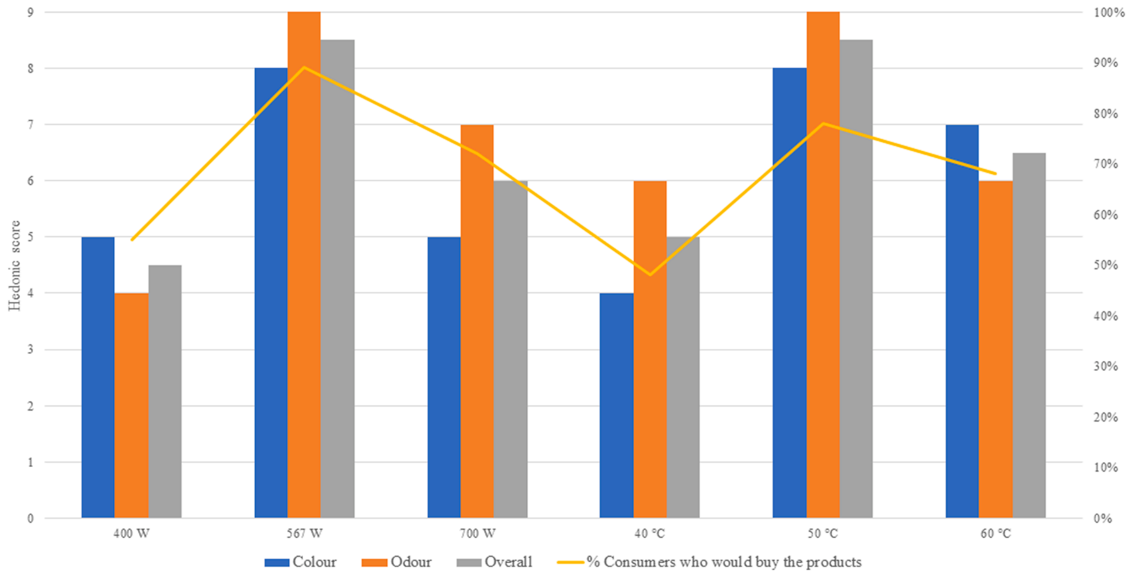

Fig. 4. Combined chart of hedonic scores and purchase intentions for avocado seed flours obtained under different drying technologies and conditions.

indicates that high microwave power facilitated the release of terpenes and the formation of lipid degradation products, thus generating fresh, pungent, citrus, and woody odour notes, as perceived by the sensory panelists.

The second cluster consists of samples dried at 40 °C and 60 °C, which are closely correlated and subsequently grouped with the 400 W samples. The 40 °C and 60 °C samples exhibited highly similar volatile profiles, primarily due to the presence of hydrocarbon sesquiterpenes, including β-cubebene, cadina-3,5-diene, D-germacrene, α-copaene, β-copaene, α-humulene, *trans*-cadina-1(6),4-diene, and γ-muurolene, which also contributed to the aroma with citrus, fruity, radish-like, spicy, herbal, and woody attributes. Furthermore, the presence of oxygenated sesquiterpenes such as cubebol, T-muurolol, and δ-cadinol provides spicy, minty, and herbaceous odours, enhancing the overall complexity of the volatile fraction. Additionally, samples dried at 40 °C exhibited a significant amount of aldehydes and alcohol with six carbon atoms, known as green-leaf volatiles. These compounds are responsible for herbaceous and vegetable notes and result from lipid oxidation. Although the drying temperature was low, the extended duration of the process likely promoted the oxidation.

From a mechanistic perspective, drying-induced volatile formation in avocado seed flour can be rationalised by considering the seed as a predominantly starch-rich matrix with a smaller but reactive unsaturated lipid fraction. Under mild and prolonged drying, incomplete enzyme inactivation together with lipid oxidation may promote the formation of C6/C9 aldehydes and alcohols, contributing to green and herbaceous notes. At higher drying intensity, terpene release and the formation of additional oxidation products become more relevant. Although carbohydrate-rich matrices can also generate furanic compounds through sugar degradation and Maillard-type reactions, this pathway seems to have a limited direct contribution under the experimental conditions of the present study. Indeed, in our samples, no typical markers of advanced sugar degradation/Maillard reactions, such as short-chain furanic compounds, pyrazines, or pyrroles, were detected. The furan compounds identified in the present study were mainly long-chain furans, such as 2-tridecylfuran and avocadynofuran, which are more plausibly associated with persin degradation and/or lipid-related pathways than with classical sugar-derived furan formation. Accordingly, the volatile changes were more consistent with lipid oxidation-related pathways and terpene modulation during drying, while the starch-rich matrix may also modulate volatile retention and release (Naknean & Meenune, 2010).

To provide a comprehensive overview of the combined chemical and sensory aspects, an integrated Principal Component Analysis (PCA) was performed on selected classes of volatile compounds and key odour descriptors from QDA (Fig. 7), offering a holistic view of the chemical - sensory landscape of avocado seed flour. The first two principal components accounted for 78.9% of the total variability, effectively discriminating between the drying treatments. Flour samples dried at 567 W and 50 °C were clustered in the region defined by “sweet”, “fruity”, and “orange/citrus” attributes, linked to more pleasant odour attributes. On the other hand, samples dried at 40 °C, 60 °C, and 400 W were more closely associated with herbaceous notes. The sample dried at 700 W was primarily differentiated along the second principal component (PC2), which was related to pungent notes and monoterpene hydrocarbons. Overall, these findings highlight the close relationship between volatile composition and sensory perception in avocado seed flour, while also addressing a gap in the literature through an integrated chemical-sensory approach. To the best of our knowledge, there is very limited information regarding the volatile composition of avocado seeds. Younis et al. (2022) studied the unsaponifiable fraction of avocado seeds, dried at 50 °C, from various regions around the world, focusing on the Red, Hass, Green, and Pinkerton varieties. They reported that the main compounds in the Pinkerton variety included α-cubebene, α-*trans*-bergamotene, (*E*)-caryophyllene, and α-elemene, along with the oxygenated sesquiterpenes caryophyllene oxide and epi-α-santalol. All these compounds were also identified in our samples. However, our study, providing a complete characterisation of seed flour volatile fraction, revealed the presence of many additional compounds belonging to various chemical classes. Furthermore, Bayomy et al. (2023) examined the composition of methanolic extracts from both raw and roasted Hass variety avocado seeds. They primarily detected alcohols, aldehydes, and hydrocarbons, including (*E*)-hex-2-en-1-ol, (*E*)-hept-2-enal, pentadecane, and cyclohex-3-ene-1-carbaldehyde, in the raw seeds, and they reported the formation of pyrroles and pyrazines in the roasted seeds as a processing result. These results differ from those reported in the present study, which is expected due to significant differences in both processing methods (roasting vs drying) and analysis procedures employed in the two studies. Finally, Arango et al. (2025) characterised the volatile profiles of unprocessed pulp, peel, and seed from Hass avocado using HS-SPME-GC–MS. The authors identified forty-two compounds in the seed, primarily consisting of terpene- and sesquiterpene-hydrocarbons, which contributed to a theoretical odour profile characterised by resinous, woody, and medicinal notes. Many of

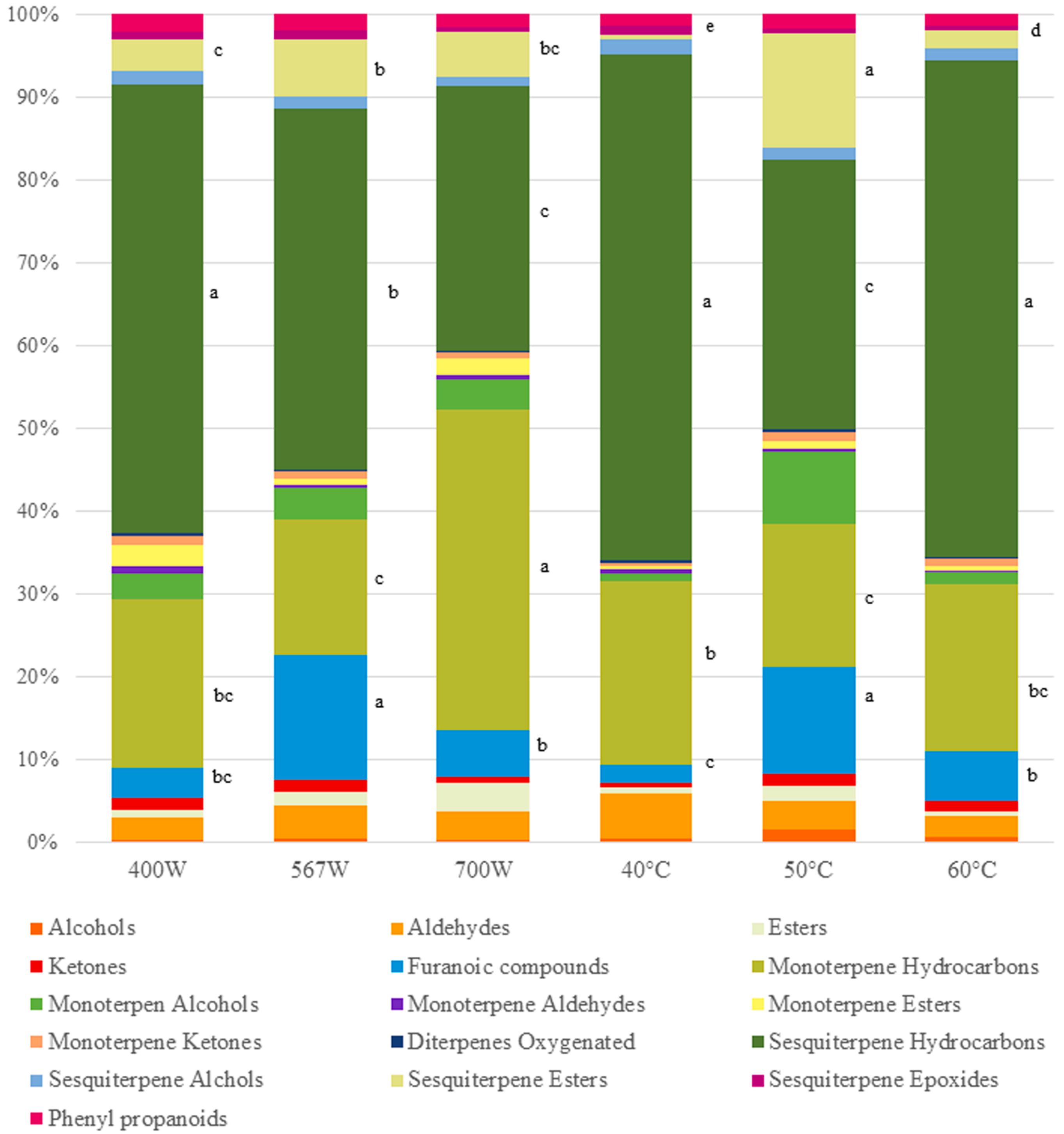

Fig. 5. Comparative percentage distribution as classes of volatile compounds in avocado seed flours obtained under different drying technologies and conditions. Different letters indicate statistically significant differences among samples by Duncan's multiple range test at $p < 0.05$.

the volatiles reported in untreated Hass avocado seeds were also found in our samples. However, our samples exhibited a more complex volatile composition, containing over a hundred compounds. This difference may be attributed to the variety of avocado seeds examined and, more significantly, to the drying process. This suggests that drying can enhance the volatile profile of the matrix, introducing more pleasant fruity, sweet, and citrus notes.

The potential of tropical seeds as flavouring ingredients has so far received limited attention, and tropical fruit seeds remain an underexplored source of aroma-active compounds despite their promising applications in food systems. In most cases, this aromatic potential is not fully expressed in the raw material itself, but rather emerges or is enhanced after roasting, fermentation, or other thermal treatments, mainly through Maillard reactions, lipid oxidation, and the release or transformation of bound aroma precursors. To the best of our knowledge, jackfruit and durian seeds are among the few tropical fruit seeds that have been specifically investigated for flavouring applications. In both cases, roasting promoted the formation of several pyrazines, which contributed to the development of cocoa-like and coffee-like sensory notes, respectively (Natania and Wijaya, 2022; Ravindran et al., 2020;

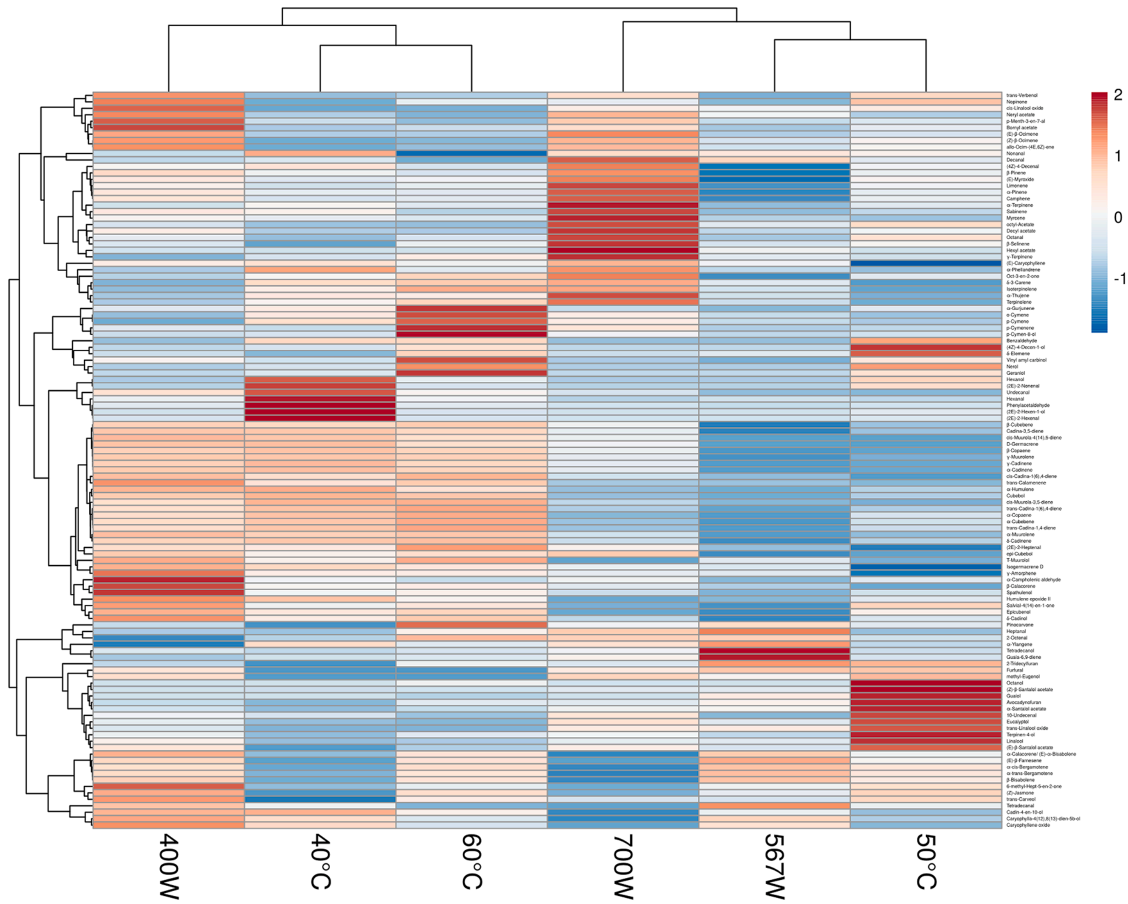

Fig. 6. Heatmap of volatile compounds detected in avocado seed flours obtained under different drying technologies and conditions.

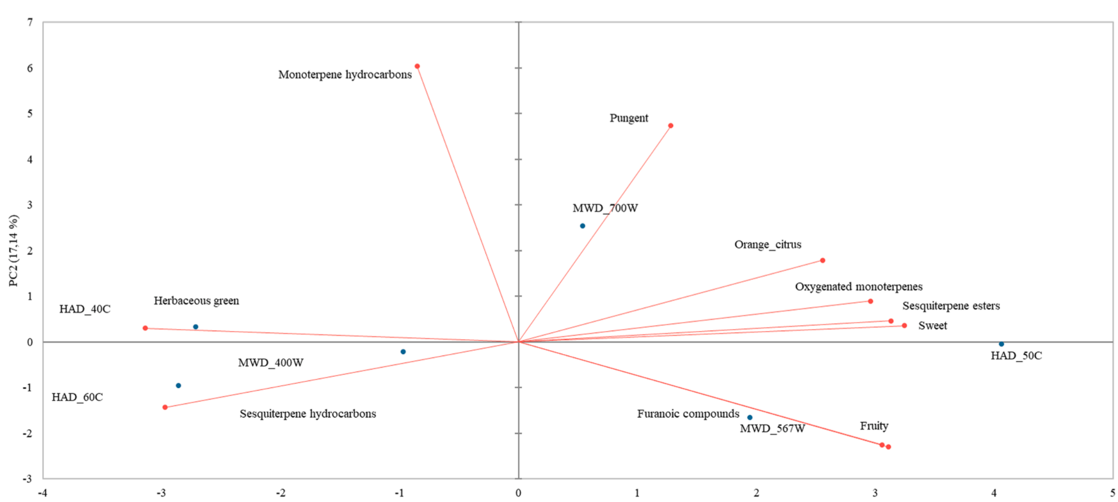

Fig. 7. Principal Component Analysis (PCA) biplot highlighting the correlation between volatile compounds (as chemical classes) and key odour descriptors (QDA) in avocado seed flours dried under different drying technologies and conditions.

Spada et al., 2020). By contrast, avocado seed flour exhibits a complex volatile profile that is particularly rich in terpenes and sesquiterpenes, even after mild thermal treatment. As shown by our data, this distinctive composition makes it possible to modulate the flavour profile of avocado seed flour through the application of different drying methods and processing conditions.

4. Conclusions

In this study, the suitability of avocado seed flour as a natural flavouring ingredient was assessed through a flavour-focused approach integrating drying-process characterisation, HS-SPME-GC–MS volatilomics, quantitative descriptive analysis by a trained panel, and consumer acceptability testing. The results show that both drying technology and process intensity play a key role in shaping the volatile composition and sensory properties of avocado seed flour, with aroma development being driven mainly by lipid oxidation-related pathways and terpene modulation during drying.

Microwave drying (MWD) was markedly faster and more energy-efficient than hot-air drying (HAD), substantially reducing processing time and potentially limiting thermal damage. Regardless of the drying technique, the drying behaviour of avocado seeds was satisfactorily described by an exponential-asymptotic model, consistent with the presence of a residual moisture fraction typical of dehydrated food materials.

The aroma of the seed flour was influenced more by process intensity than by drying technology itself. Intermediate drying intensities, namely 567 W for MWD and 50 °C for HAD, produced the most favourable aromatic profiles, characterised by sweet, fruity, and citrus notes, and resulted in the highest consumer liking scores. Volatilomic data and sensory evaluations were strongly aligned, confirming a clear correspondence between chemical markers and perceived aroma attributes.

This work delivers the first integrated evaluation of avocado seed flour as a potential natural flavouring ingredient and provides strong evidence that controlled drying strategies can be used to tailor its flavour profile.

The findings support the valorisation of avocado seed as a high-value and sustainable flavouring ingredient, contributing to the circular use of an underexploited agro-industrial by-product.

Based on these promising findings, additional avocado cultivars will be examined, prioritising those most widely processed. In parallel, ongoing studies are quantifying persin and related acetogenins in fresh and dried avocado seeds from common cultivars to better support future safety assessments and potential industrial applications.

Ethical statement

This manuscript reports sensory analyses (QDA and consumer acceptability test) carried out on avocado (*Persea americana* Mill.) seed flours with the voluntary participation of students and staff from the University of Messina. The panel was recruited and trained in accordance with ISO 8586:2023 guidelines. All participants were informed about the purpose and procedures of the study, and written informed consent was obtained before participation, with full assurance of data protection and privacy. Informed consent was obtained from all subjects involved in the study. The activity involved only sensory evaluation (odour/colour assessment) of food-derived samples and did not include clinical procedures, invasive interventions, administration of substances beyond normal dietary exposure, testing of health claims, or experimentation aimed at assessing physiological effects. Therefore, in line with the European Commission guidance on "Ethics Review and Food-Related Research" and in accordance with the World Medical Association Declaration of Helsinki, ethical committee approval was not required, and the study was not submitted for ethics committee evaluation.

Authorship contribution statement

All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Maria Merlino: Writing – review & editing, Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Fabrizio Cincotta:** Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation. **Martina Buda:** Formal analysis, Data curation. **Antonella Verzera:** Writing – review & editing, Validation, Supervision, Project administration, Conceptualization. **Concetta Condurso:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2026.102042.

Data availability

Data will be made available on request.

References

Arango, J. P. B., Ospina, A. P., Ladino, J. A. F., & Ocampo, G. T. (2025). Volatilomic Analysis in Peel, Pulp and Seed of Hass Avocado (*Persea americana* Mill.) From the Northern Subregion of Caldas by Gas Chromatography With Mass Spectrometry. *Food Science & Nutrition, 13*(7), Article e70489. https://doi.org/10.1002/fsn3.70489

Babiker, E. E., Ahmed, I. A. M., Uslu, N., Özcan, M. M., Al Juhaimi, F., Ghafoor, K., & Almusallam, I. A. (2021). Influence of drying methods on bioactive properties, fatty acids and phenolic compounds of different parts of ripe and unripe avocado fruits. *Journal of Oleo Science, 70*(4), 589–598. https://doi.org/10.5650/jos.ess20343

Bayomy, H. M., Alamri, E. S., & Rozan, M. A. (2023). Effect of roasting Hass avocado kernels on nutritional value and volatile compounds. *Processes, 11*(2), 377. https://doi.org/10.3390/pr11020377

Bhuyan, D. J., Alsherbiny, M. A., Perera, S., Low, M., Basu, A., Devi, O. A., Barooah, M. S., Li, C. G., & Papoutsis, K. (2019). The odyssey of bioactive compounds in avocado (*Persea americana*) and their health benefits. *Antioxidants, 8* (10), 426. https://doi.org/10.3390/antiox8100426

Cárceles Rodríguez, B., Durán Zuazo, V. H., Franco Tarifa, D., Cuadros Tavira, S., Sacristan, P. C., & García-Tejero, I. F. (2023). Irrigation alternatives for avocado (*Persea americana* Mill.) in the Mediterranean subtropical region in the context of climate change: A review. *Agriculture, 13*(5), 1049. https://doi.org/10.3390/agriculture13051049

Charles, A. C., Dadmohammadi, Y., & Abbaspourrad, A. (2022). Food and cosmetic applications of the avocado seed: A review. *Food & Function, 13*(13), 6894–6901. https://doi.org/10.1039/d1fo02438h

Chen, P., Zhao, S., Li, C., Zhang, T., Xing, Y., Zhang, K., Lv, J., & Zhu, W. (2025). Changes and Analytical Techniques in Volatile Flavor Compounds in Dried Agricultural Products: A Review. *Foods, 14*(20), 3531. https://doi.org/10.3390/foods14203531

Cincotta, F., Merlino, M., Condurso, C., Miller, A., Torre, M., & Verzera, A. (2024). Avocado leaf-waste management: Drying technology and quality of leaf herbal teas of different varieties cultivated in the Mediterranean area. *International Journal of Food Science and Technology, 59*(4), 2516–2523. https://doi.org/10.1111/ijfs.16987

Cincotta, F., Torre, M., Merlino, M., Condurso, C., Buda, M., & Verzera, A. (2025). Sustainable Herbal Teas from Fig (*Ficus carica* L.) Waste Leaves: Volatile Fingerprinting, Sensory Descriptors, and Consumer Acceptability. *Beverages, 11*(1), 16. https://doi.org/10.3390/beverages11010016

Condurso, C., Cincotta, F., Tripodi, G., Merlino, M., & Verzera, A. (2019). Influence of drying technologies on the aroma of Sicilian red garlic. *Lwt, 104*, 180–185. https://doi.org/10.1016/j.lwt.2019.01.026

Dabas, D., Shegog, R. M., Ziegler, G. R., & Lambert, J. D. (2013). Avocado (*Persea americana*) seed as a source of bioactive phytochemicals. *Current Pharmaceutical Design, 19*(34), 6133–6140.

Doymaz, I. (2007). The kinetics of forced convective air-drying of pumpkin slices. *Journal of Food Engineering, 79*(1), 243–248. https://doi.org/10.1016/j.jfoodeng.2006.01.049

Elsayed, S., & Elsayed, H. (2024). Boosting the nutritional value of stirred yogurt by adding nano-sized avocado seed powder and *Lactobacillus acidophilus*. *Egyptian Journal of Chemistry, 67*(13), 13–25. https://doi.org/10.21608/ejchem.2024.254083.8968

Fahs, H. Z., Refai, F. S., Gopinadhan, S., Moussa, Y., Gan, H. H., Hunashal, Y., Battaglia, G., Cipriani, P. G., Ciancia, C., Rahiman, N., Kremb, S., Xie, X., Pearson, Y. E., Butterfoss, G. L., Maizels, R. M., Esposito, G., Page, A. P., Gunsalus, K. C., & Piano, F. (2025). A new class of natural anthelmintics targeting lipid metabolism. *Nature communications, 16*(1), 305. https://doi.org/10.1038/s41467-024-54965-w

Féliz-Jiménez, A., & Sanchez-Rosario, R. (2024). Bioactive compounds, composition and potential applications of avocado agro-industrial residues: A review. *Applied Sciences, 14*(21), Article 10070. https://doi.org/10.3390/app142110070

Figueroa, J. G., Borrás-Linares, I., Lozano-Sánchez, J., Quirantes-Piné, R., & Segura-Carretero, A. (2025). Advanced recovery of bioactive polyphenols: Integrated optimization of drying and green extraction for avocado seed by-products. *Food Chemistry: X.* , Article 103216. https://doi.org/10.1016/j.fochx.2025.103216

Fufa, D. D., Bekele, T., Bultosa, G., & Tamene, A. (2025a). Avocado seeds valorization for sustainable food ingredient use: Quality attributes evaluation in the traditional fermented teff injera. *Discover Sustainability, 6*(1), 1–23. https://doi.org/10.1007/s43621-025-01144-6

Fufa, D. D., Bekele, T., Tamene, A., & Bultosa, G. (2025b). Drying kinetic models, thermodynamics, physicochemical qualities, and bioactive compounds of avocado (*Persea americana* Mill. Hass variety) seeds dried using various drying methods. *Heliyon, 11*(1). https://doi.org/10.1016/j.heliyon.2024.e41058

Henderson, S. M., & Pabis, S. (1961). Grain drying theory. 1. *Temperature Effect on Drying Coefficient*.

Hunashal, Y., Battaglia, G., Refai, F. S. M., Fahs, H. Z., Gunsalus, K. C., Esposito, G., & Piano, F. (2025). Analytical characterization and biological assay of avocado lipids with nematocidal activity. *Food Chemistry, 491*, Article 145215. https://doi.org/10.1016/j.foodchem.2025.145215

ISO 8586:2023. (2023). *Sensory analysis—selection and training of sensory assessors*. Geneva, Switzerland: ISO.

Jaramillo-De la Garza, J. S., Rodríguez-Sánchez, D. G., Hernández-Brenes, C., & Heredia-Olea, E. (2025). Development and Consumer Acceptability of Functional Bread Formulations Enriched with Extruded Avocado Seed Flour: Nutritional and Technological Properties. *Foods, 14*(24), 4282. https://doi.org/10.3390/foods14244282

Jimenez, P., Garcia, P., Quitral, V., Vasquez, K., Parra-Ruiz, C., Reyes-Farias, M., Garcia-Diaz, D. F., Robert, P., Encina, C., & Soto-Covasich, J. (2021). Pulp, Leaf, Peel and Seed of Avocado Fruit: A Review of Bioactive Compounds and Healthy Benefits. *Food Reviews International, 37*(6), 619–655. https://doi.org/10.1080/87559129.2020.1717520

Joardder, M. U., & Karim, A. (2023). Pore evolution in cell walls of food tissue during microwave-assisted drying: An in-depth investigation. *Foods, 12*(13), 2497. https://doi.org/10.3390/foods12132497

Karaaslan, S., & Ekinci, K. (2023). Determination and mathematical modeling of drying kinetics of avocado slices by tunnel type solar drying and microwave drying method. *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 27*(2), 305–312. https://doi.org/10.19113/sdufenbed.1237480

Laurentcya, T. D., Fergilang, J., Sari, N. K., & Nurherdiana, S. D. (2025). Optimization of Flavonoid Compounds from Avocado Seeds Using Ethanol Solvent through Response Surface Methodology (RSM). *AJARCDE (Asian Journal of Applied Research for Community Development and Empowerment), 9*(2), 394–405. https://doi.org/10.29165/ajarcde.v9i2.742

Lewis, W. K. (1921). The rate of drying of solid materials. *Industrial & Engineering Chemistry, 13*(5), 427–432.

Madamba, P. S., Driscoll, R. H., & Buckle, K. A. (1996). The thin-layer drying characteristics of garlic slices. *Journal of Food Engineering, 29*(1), 75–97. https://doi.org/10.1016/0260-8774(95)00062-3

Marra, A., Manousakis, V., Zervas, G. P., Koutis, N., Finos, M. A., Adamantidi, T., Panoutsopoulou, E., Ofrydopoulou, A., & Tsoupras, A. (2024). Avocado and its by-products as natural sources of valuable anti-inflammatory and antioxidant bioactives for functional foods and cosmetics with health-promoting properties. *Applied Sciences, 14*(14), 5978. https://doi.org/10.3390/app14145978

Maskan, M. (2000). Microwave/air and microwave finish drying of banana. *Journal of Food Engineering, 44*(2), 71–78. https://doi.org/10.1016/S0260-8774(99)00167-3

Merlino, M., Tripodi, G., Cincotta, F., Prestia, O., Miller, A., Gattuso, A., Verzera, A., & Condurso, C. (2022). Technological, nutritional, and sensory characteristics of gnocchi enriched with hemp seed flour. *Foods, 11*(18), 2783. https://doi.org/10.3390/foods11182783

Mokrzycki, W. S., & Tatol, M. (2011). Colour differenceΔ EA survey. *Mach. Graph. Vis, 20*(4), 383–411.

Naknean, P., & Meenune, M. (2010). Factors affecting retention and release of flavour compounds in food carbohydrates. *International Food Research Journal, 17*(1), 23–34.

Natania, K., & Wijaya, E. (2022). Optimization of roasting temperature and time of the durian seed (Durio zibethinus L.) as coffee substitution and its flavour profile. *Food Research, 6*(3), 279–287. https://doi.org/10.26656/fr.2017.6(3).413

Nyakang'i, C. O., Marete, E., Ebere, R., & Arimi, J. M. (2023). Physicochemical properties of avocado seed extract model beverages and baked products incorporated with avocado seed powder. *International Journal of Food Science, 2023*(1), Article 6860806. https://doi.org/10.1155/2023/6860806

Onwude, D. I., Hashim, N., Janius, R. B., Nawi, N. M., & Abdan, K. (2016). Modeling the thin-layer drying of fruits and vegetables: A review. *Comprehensive reviews in food science and food safety, 15*(3), 599–618. https://doi.org/10.1111/1541-4337.12196

Otero-Guzman, N., & Andrade-Pizarro, R. (2025). Bioactive compounds from tropical fruit by-products: Extraction, characterization and therapeutic potential. *Journal of Agriculture and Food Research.* , Article 101983. https://doi.org/10.1016/j.jafr.2025.101983

Paternina-Ricardo, S., Del Castillo, M. D., Sánchez-Martín, V., García-Espiñeira, M., Cervantes-Ceballos, L., Arroyo–Salgado, B., & Tejeda-Benitez, L. (2025). Exploring the Efficacy of the Biological Properties of Persea americana Mill Seed: Useful Studies and Perspectives in Functional Foods. *Journal of Agriculture and Food Research.* , Article 102428. https://doi.org/10.1016/j.jafr.2025.102428

Permal, R., Chia, T., Arena, G., Fleming, C., Chen, J., Chen, T., Chang, W. L., Seale, B., Hamid, N., & Kam, R. (2023). Converting avocado seeds into a ready to eat snack and analysing for persin and amygdalin. *Food Chemistry, 399*, Article 134011. https://doi.org/10.1016/j.foodchem.2022.134011

Ravindran, A., Raman, M., Babu, N., Dinakaran, A., Sankar, T. V., & Gopal, T. S. (2020). Diet chocolates and replacement of cocoa powder with jackfruit seed powder. *Food and Nutrition Sciences, 11*(03), 220–233. https://doi.org/10.4236/fns.2020.113017

Rodriguez-Saona, C., & Trumble, J. T. (2000). Biologically active aliphatic acetogenins from specialized idioblast oil cells. *Current Organic Chemistry, 4*(12), 1249–1260. https://doi.org/10.2174/1385272003375789

Siol, M., & Sadowska, A. (2023). Chemical composition, physicochemical and bioactive properties of avocado (*Persea americana*) seed and its potential use in functional food design. *Agriculture, 13*(2), 316. https://doi.org/10.3390/agriculture13020316

Spada, F. P., Mandro, G. F., da Matta Junior, M. D., & Canniatti-Brazaca, S. G. (2020). Functional properties and sensory aroma of roasted jackfruit seed flours compared to cocoa and commercial chocolate powder. *Food Bioscience, 37*, Article 100683. https://doi.org/10.1016/j.fbio.2020.100683

Süfer, Ö., Çalışkan Koç, G., Öztekin, S., Özkan Karabacak, A., Su, D., Wang, D., Eroğlu, S., Durgut Malçok, S., lkü Hilal Uslu, Ü., Adal, S., Jeevarathinam, G., Ramniwas, S., Rustagi, S., & Pandiselvam, R. (2025). Evaluation of the effect of sustainable drying techniques and intensification technologies on color profile of dehydrated fruits and vegetables. *Food and Bioprocess Technology, 18*(4), 3148–3194. https://doi.org/10.1007/s11947-024-03599-3

Tauhiduzzaman, M., Hafez, I., Bousfield, D., & Tajvidi, M. (2021). Modeling microwave heating and drying of lignocellulosic foams through coupled electromagnetic and heat transfer analysis. *Processes, 9*(11), 2001. https://doi.org/10.3390/pr9112001

Tesfaye, T., Ayele, M., Gibril, M., Ferede, E., Limeneh, D. Y., & Kong, F. (2022). Beneficiation of avocado processing industry by-product: A review on future prospect. *Current Research in Green and Sustainable Chemistry, 5*, Article 100253. https://doi.org/10.1016/j.crgsc.2021.100253

Wang, Y., Tuccillo, F., Lampi, A. M., Knaapila, A., Pulkkinen, M., Kariluoto, S., Coda, R., Edelmann, M., Jouppila, K., Sandell, M., Piironen, V., & Katina, K. (2022). Flavor challenges in extruded plant-based meat alternatives: A review. *Comprehensive Reviews in Food Science and Food Safety, 21*(3), 2898–2929. https://doi.org/10.1111/1541-4337.12964

Yagcioglu, A., Degirmencioglu, A., & Cagatay, F. (1999). Drying characteristics of laurel leaves under different drying conditions. In *Proceedings of the seventh international congress on agricultural mechanisation and energy* (pp. 565–569). May 26–27.

Younis, I. Y., Khattab, A. R., Selim, N. M., Sobeh, M., Elhawary, S. S., & Bishbishy, M. H. E. (2022). Metabolomics-based profiling of 4 avocado varieties using HPLC–MS/MS and GC/MS and evaluation of their antidiabetic activity. *Scientific reports, 12*(1), 4966. https://doi.org/10.1038/s41598-022-08479-4

Zhang, X., Liang, J., Lin, X., Chen, J., & Luo, X. (2025). A comprehensive review on the composition, processing methods, and sustainable utilization of tropical fruit seeds in food industry. *Food Frontiers, 6*(2), 644–669. https://doi.org/10.1002/fft2.493