



Influence of dielectric barrier discharge plasma processing on yellow passion fruit juice: effects on volatile compound composition and aromatic profile

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Abstract

Yellow passion fruit (*Passiflora edulis* Sims f. *flavicarpa* Deneger) is valued for its nutritional qualities and sensory attributes, which provide a fresh and fruity taste and aroma. This study presents a novel investigation into the effects of dielectric barrier discharge (DBD) plasma on the complex volatile profile of yellow passion fruit juice. The juice was subjected to cold plasma at different frequencies and exposure times, under a constant voltage. Plasma processing induced specific chemical modification in passion fruit juice that has not been previously reported in other plasma-treated juices. A key novel finding was the dehydrogenation of long-chain esters, increasing unsaturated esters. Isomerization, hydrolysis, and methylation were also observed to a lesser extent. These unique reactions were attributed to passion fruit's distinct composition, which is rich in long-chain esters. Furthermore, the study also reports on the discrepancy found between chemical analysis and human sensory perception. While chemical calculations (OAV) quantified significant changes in specific aroma descriptors, these modifications were not perceived by a trained Gas Chromatography-Olfactometry (GC-O) panel. This result demonstrates that the significant, measurable chemical modulations induced by plasma can be rendered sensorially irrelevant due to the powerful perceptual masking effect of the juice's dominant fruity esters. The 1000 Hz treatment reduced the waxy aroma of ethyl octanoate, mitigating juice rancidity when processed with its seeds. Therefore, DBD plasma presents a promising non-thermal application for the food industry to selectively modulate volatile profiles and improve the overall sensory quality of complex fruit juices.

Keywords Cold plasma · Passion fruit · Aroma · Sensory profile · Esters

Introduction

Yellow passion fruit (*Passiflora edulis* Sims f. *flavicarpa* Degener) is extensively cultivated in several countries [1]. It is considered the most important variety for the commercial production of passion fruit worldwide, accounting for approximately 95% of the market share [2]. Belonging to the Passifloraceae family, yellow passion fruit is consumed

in various forms, with juice being one of the most appreciated due to its nutritional benefits and sensory attributes, such as its fresh taste and pleasant aroma [3].

The predominant aroma of passion fruit is described as fruity, floral, and slightly sulfurous [4]. The sensory profile of passion fruit is attributed to its complex volatile compounds, particularly esters and terpenes [5]. However, maintaining these compounds during juice processing and storage remains a major challenge for the food industry.

Thermal processing, such as pasteurization, increases the shelf life of juices. However, this method degrades most volatile compounds, decreasing the concentration of bioactive components and compromising the sensory and nutritional quality of the product [6, 7]. In this scenario, non-thermal technologies such as cold plasma have been proposed as promising alternatives to reduce the degradation of thermolabile flavor and aroma compounds [8, 9]. Furthermore, this

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technology has the advantage of not leaving chemical residues on the processed product [10]. Cold plasma consists of a partially ionized gas generated at low temperature and composed of a mixture of reactive species such as free electrons, positive and negative ions, free radicals, and neutral particles [11–13].

The application of cold plasma in fruit juice processing has shown high potential to reduce undesirable aromas and off-flavors. In a study with pineapple juice, cold plasma processing at low frequencies reduced the concentration of methyl hexanoate, thereby diminishing the intensely sweet aroma [14]. Plasma treatment applied to camu-camu juice was also capable of altering its aromatic profile. Depending on the operational conditions, either an increase or a decrease in the odor activity of different aromatic descriptors was observed [15]. In a previous study using dielectric barrier discharge (DBD) plasma on pasteurized orange juice, the plasma treatment increased the concentration of terpenes and aldehydes, enhancing the fresh aroma of the juice. Although the DBD plasma treatment did not significantly reduce the compounds responsible for off-flavors, it maintained them at acceptable concentrations without further deteriorating the flavor [16].

In a study on red dragon fruit juice, cold plasma reduced the content of furan, a potentially toxic compound, while increasing desirable volatiles such as phenylethyl alcohol and acetoin, thereby improving the juice's flavor and making it more pleasant [17]. Although DBD plasma was not effective in mitigating the off-flavor caused by styrene in cashew apple juice, the internal cleavage of fatty acids and long-chain esters significantly reduced volatile acids by 73% and increased the odor activity value (OAV) by 22%, resulting in a more intense flavor [18]. These changes induced by cold plasma vary depending on the composition of the food matrix. Combining optimal operational conditions with the appropriate plasma technology can help improve different food matrices' sensory and nutritional characteristics [19–23].

Modifications in volatile compound profiles reported in the literature are attributed to reactive oxygen species (ROS) and reactive nitrogen species (RNS) generated during plasma treatment [19, 24–26]. These reactive species interact with the juice's volatile compounds, enabling reactions such as hydrolysis, isomerization, dehydrogenation, cleavage, hydrogenation, and ring opening or closing [27].

Recent comprehensive reviews of cold plasma applications have demonstrated its ability to selectively alter volatile compositions in various matrices, such as apple, mandarin, pineapple, and red dragon fruit juices, primarily by chemically transforming simpler esters, aldehydes, and alcohols [28–31]. However, some specific pathways of these reactive species are matrix-dependent [31, 32]. Given

that passion fruit has one of the most complex volatile profiles among tropical fruits, characterized by a high concentration of long-chain esters that are less prevalent in juices such as orange or pineapple, investigating its behavior under non-thermal processing presents a unique scientific opportunity. To date, the specific chemical pathways induced by cold plasma reactive species on the unique long-chain ester profile of passion fruit remain unexplored. Furthermore, while many studies report on the chemical changes induced by plasma, few have directly compared these quantitative data with the actual perceived aroma as determined by a trained sensory panel (GC-O). This leaves a critical gap in understanding the practical sensory implications of this technology, as it is unknown if chemical changes necessarily translate to a perceivable difference for the consumer.

The primary objective of this work is to provide a deeper understanding of the specific impacts of DBD plasma on yellow passion fruit juice, rather than merely cataloging volatile changes. Therefore, this study aims to identify the novel chemical transformations induced by plasma in this unique ester-rich matrix and to propose possible reaction pathways based on mass balance data; directly contrast the results of analytical-chemical analysis (OAV) with human sensory perception (GC-O) to determine if the measured chemical modifications are sensorially relevant; and investigate whether perceptual masking by the juice's dominant fruity aromas inhibits the perception of these chemical changes.

Materials and methods

The complete aromatic profile of the passion fruit juice was determined using a five-step approach, as visually detailed in Fig. 1, integrating theoretical OAV calculations and sensory GC-O analysis. Full descriptions of all steps are given in the following subsections.

Materials

Yellow passion fruits (*Passiflora edulis* Sims f. *flavicarpa* Degener) were purchased from a local supermarket (Fortaleza, Brazil). The fruits were selected at full commercial maturity, visually characterized by a completely yellow peel without green spots, representing the optimal ready-to-consume stage. The fruits were washed under running tap water and halved using a kitchen knife. The pulp, along with the seeds, was then blended for 1 min in a Walita model RI 7625/70 (Varginha, Brazil) and filtered through a sieve. The resulting juice was diluted with distilled water at a 1:1 (v/v) ratio to obtain the passion fruit juice. Prior to plasma processing, the basic physicochemical properties of the

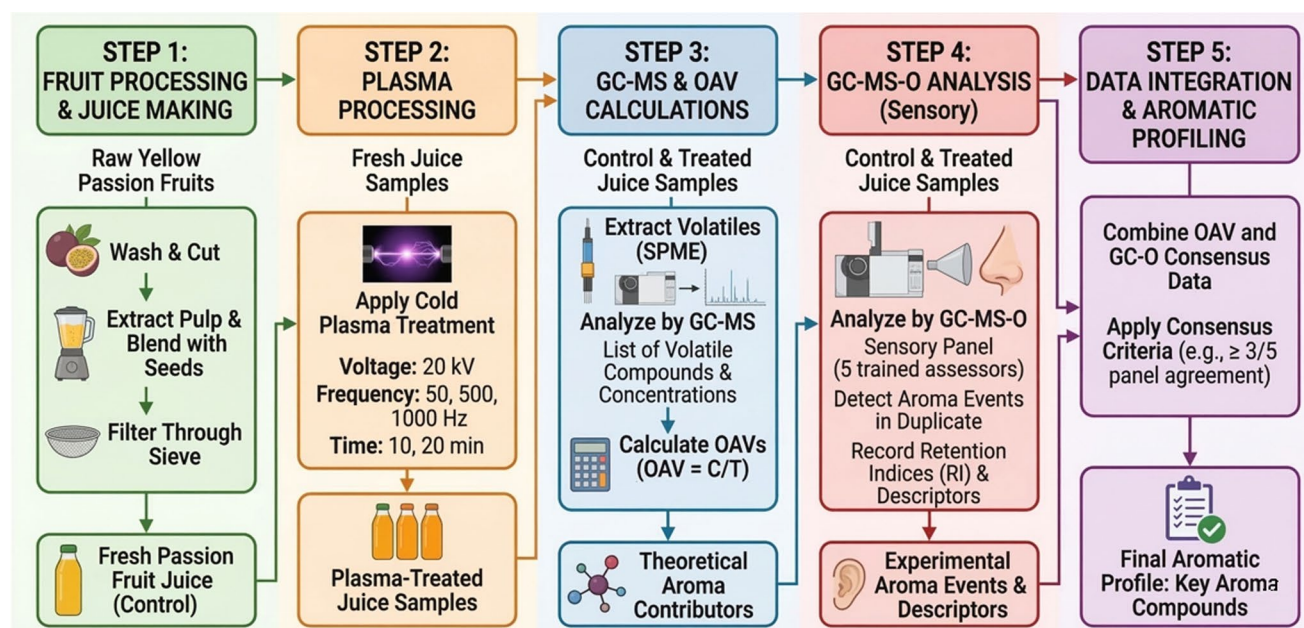


Fig. 1 Five-step approach for the aromatic profile methodology (OAV & GC-O) for passion fruit juice subjected to cold plasma treatment

formulated juice were characterized. The juice presented a total soluble solids of 39.2 g/L, and a titratable acidity of 32.3 g/L.

Commercial passion fruit juice production can be carried out in two ways: by processing only the pulp or by processing the pulp together with the seeds. Each manufacturer chooses one of these methods according to the desired sensory profile of the final product. In this study, the option was made to include the seeds in the processing.

Cold plasma juice processing

For sample processing, a dielectric barrier discharge (DBD)-type cold plasma generator (Inergiae, model PLS0130) was used. The equipment consisted of a generator connected to a chamber containing two aluminum electrodes (8 cm in diameter) spaced 15 mm apart. Two 5 mm-thick acrylic plates were used to insulate the aluminum electrodes. A 25 mL volume of passion fruit juice was placed in an acrylic Petri dish and subjected to direct plasma exposure in ambient atmospheric air for 10–20 min, under different frequency settings (50, 500, and 1000 Hz). The process was conducted at a fixed voltage of 20 kV, selected because it is the maximum voltage capacity of the equipment. Because applied voltage alone does not fully reflect the energy transferred to the sample, which varies across different equipment designs, the average power dissipated into the discharge was recorded to ensure reproducibility and comparability with other studies. The average power applied was 24.2 W for the 50 Hz treatment, 36.1 W for the 500 Hz treatment, and 48.0 W for the 1000 Hz treatment. Based on the volume

of juice that was processed, the energy density applied to the samples was calculated for each condition. For the 50 Hz treatments, the energy density was 580.8 J/mL (10 min) and 1161.6 J/mL (20 min). For the 500 Hz treatments, the values were 866.4 J/mL (10 min) and 1732.8 J/mL (20 min). Finally, for the 1000 Hz treatments, the energy density was 1152.0 J/mL (10 min) and 2304.0 J/mL (20 min).

The frequencies (50, 500, and 1000 Hz) were selected because they span the minimum, intermediate, and maximum operational ranges of the plasma generator used. The exposure times (10 and 20 min) were chosen based on previous experiments with other fruit juices, which showed that the main modifications in volatile compounds are perceived within this processing range [14, 18].

A sample of the unprocessed juice, referred to as the control, was held under the same laboratory conditions and analyzed to verify the modifications induced by the plasma processing. All treatments and the control analysis were conducted in triplicate.

SPME extraction and GC-MS analysis

Volatile organic compounds (VOCs) were extracted from the juice using solid-phase microextraction (SPME) followed by gas chromatography–mass spectrometry (GC-MS). A 5 mL aliquot of the juice was transferred to a 20 mL vial and equilibrated at 40 °C for 20 min. Volatile compounds were extracted using a 2 cm-long SPME fiber coated with 50/30 µm divinylbenzene/carboxen/polydimethylsiloxane (DVB/CAR/PDMS). The fiber was exposed to the vial headspace for 30 min at 40 °C

without agitation. After extraction, the fiber was retracted, removed from the vial, and inserted into the injector of the GC-MS system (Thermo Scientific, ISQ model) coupled with a mass spectrometer (Thermo, Waltham, MA, USA, Trace Ultra ISQ model) for desorption and analysis of the volatile compounds. The injector and interface temperatures were set at 250 °C in splitless mode. Separation of the compounds was carried out using an Equity-1 capillary column (30 m × 0.25 mm ID × 0.25 µm film thickness). Helium was used as the carrier gas. Chromatographic conditions and column temperature programming followed the protocol described by Porto et al. [14].

Compounds were tentatively identified by comparing their mass spectra with reference libraries NIST (Gaithersburg, MD, USA) and Wiley (Hoboken, NJ, USA). The identification was then confirmed by comparing their retention times and mass spectra with authentic standards for the following compounds: methyl butanoate, hexanol, methyl hexanoate, limonene, terpinene, octanol, terpinolene, linalool, undecane, 4-terpineol, ethyl octanoate, citronellol, tridecane, tetradecane, pentadecane, hexadecane, and β -pinene.

The quantification of volatile compounds was performed using two methods. For compounds where an authentic standard was available (as listed above), concentration was determined using an external standard calibration curve specific to that compound. For all other identified compounds, quantification was performed semi-quantitatively based on their chromatographic peak area, using the calibration curve of 1-octanol as a reference. The analytical limits of the method were established based on the signal-to-noise (S/N) ratio. Using 1-octanol as the reference standard, the limit of detection (LOD, $S/N=3$) was determined to be 0.01 µg/mL, and the limit of quantification (LOQ, $S/N=10$) was 0.03 µg/mL.

It is important to note that semi-quantification using 1-octanol introduces a minor degree of uncertainty regarding absolute concentrations. Acquiring authentic standards for all identified volatiles is severely constrained by commercial availability and prohibitive costs, making the use of reference standards a common and accepted practice in complex flavor profiling. While this approach can be problematic with GC-FID or GC-TCD detectors due to widely varying response factors, the error introduced in GC-MS, which relies on mass abundance (total ion current), is much lower. The variation in ionization efficiency among similar organic volatiles is relatively small, meaning the residual uncertainty is not significant in most cases. Furthermore, because this uniform analytical approach was applied consistently across all control and plasma-treated samples, the relative changes and mass balances used to deduce the mechanistic pathways in this study remain highly reliable.

Aromatic profile

The Odor Activity Value (OAV) was calculated by dividing the concentration of each volatile compound by its odor threshold in water [33]. Odor threshold values were obtained from published literature [34–36]. The six main odor descriptors responsible for the characteristic aroma of passion fruit juice were represented using radar charts: floral, fruity, green, waxy, woody, and herbal. Volatile compounds were categorized according to their primary odor descriptors.

Aromatic profile by olfactometry

A panel of 5 trained panelists assessed the aromatic profile of the passion fruit juice. The methodology for training the gas chromatography-olfactometry (GC-O) sensory panel was adapted from the five-step approach proposed by Vene et al. [37].

Panelists received theoretical training on the principles of human olfaction, odor thresholds, aroma compounds, and GC-O analysis procedures. In the second training step, we introduced the odor vocabulary and the assessment scale. A set of ten standard aroma compounds, selected for their relevance to fruit juices, was presented to the assessors on sniffing strips. Panelists were required to memorize the odor quality and description for each standard. For intensity training, a five-point integer scale was used, ranging from 1 (very weak, not identifiable) to 5 (extremely strong). This scale was taught using different concentrations of standard compounds (benzaldehyde, isoamylacetate, hexanal) to anchor the assessors' perceptions. In a third training step, assessors performed GC-O analysis on reference mixtures, which contained the previously memorized standard compounds. Each panelist analyzed the mixture to detect and recognize the compounds and determine their intensity.

Following the initial training, only the assessors who passed the selection criteria, which included good detection and recognition skills, motivation, availability, and ability to concentrate, were selected. Before the olfactory analysis, the selected panel's performance was monitored using our reference mixtures to ensure skill retention and evaluate each assessor's performance.

The analyses of the real product were conducted using the Posterior Intensity (PI) method, in which the assessor records the odor intensity on a scale after a peak has finished eluting from the GC column. In addition to rating the intensity, the assessor also records a description of the odor. To ensure panel consistency, robustness, and inter-panelist agreement, a strict consensus criterion was applied. An aroma event and its corresponding descriptor were

considered valid only if they were detected by at least 3 of the 5 assessors at the same retention time.

The extraction of volatile organic compounds (VOCs) was carried out following the same procedure described for the CG-MS analysis. After extraction, the fiber was retracted, removed from the vial, and inserted into the injector of the GC-MS-O system (Agilent GC 8890) coupled with a mass spectrometer (Agilent 5977 C MSD) and an olfactometry port (Gerstel ODP4) for desorption and analysis of the volatile compounds. The injector and interface temperatures were set at 250 °C in splitless mode. Separation of the compounds was carried out using a DB-5 capillary column (30 m × 0.25 mm ID × 0.25 µm film thickness). Helium was used as the carrier gas.

Statistical analysis

All treatments and the control analysis were conducted in triplicate. Results are expressed as mean ± standard deviation. The data were subjected to a one-way Analysis of Variance (ANOVA) to evaluate the effect of the different dielectric barrier discharge plasma treatments on the volatile compound concentrations. Significant differences between the means were determined using Tukey's HSD multiple-range test at the 5% significance level ($p < 0.05$). All statistical analyses were performed using Statistica version 12.0 (StatSoft Inc., Tulsa, OK, USA).

Results and discussion

Volatile composition of passion fruit juice

Table 1 presents the volatile compounds identified in the passion fruit juice, along with their retention times, Kovats retention indices, odor thresholds in water, and aroma descriptors. A total of 70 volatile compounds were identified in the juice by gas chromatography. The chemical composition of the passion fruit juice is characterized by a diverse range of volatile compounds, predominantly esters (48%), followed by terpenes (13.3%), acids (8%), alkanes (8%), alcohols (6.6%), and smaller amounts of other compound classes such as aldehydes, ketones, phenol, sesquiterpene, oxime, and pyran.

The volatile profile observed in this study is consistent with those reported in previous studies on passion fruit juice [3, 4, 38]. Based on the concentration of the compounds, the key volatile compounds found in passion fruit juice were ethyl hexanoate, hexyl hexanoate, hexyl butanoate, ethyl butanoate, and *m*-cymene. Based on their odor activity values, the compounds that contributed most significantly to the aroma of the juice were ethyl hexanoate, 3-hexenyl

butanoate, ethyl butanoate, β -ionone, *o*-cymene, *m*-cymene, hexyl butanoate, and linalool.

Changes in the volatile profile of passion fruit juice induced by DBD plasma

The application of DBD plasma to passion fruit juice resulted in several chemical modifications to its volatile compounds. Table 2 presents the mass fraction (% w/w) of each volatile compound under different treatment conditions. The absolute concentrations (µg/mL) of these compounds are available in Supplementary Table S1. The main volatile compounds in untreated passion fruit juice, based on concentration and mass fraction, were hexanol, *m*-cymene, limonene, ethyl hexanoate, hexyl acetate, hexyl butanoate, ethyl hexanoate, and ethyl butanoate. Mass balance analysis revealed that the most notable alterations, in terms of percentual change, in the volatile profile were observed in methyl butanoate, methyl hexanoate, benzaldehyde, ethyl 3-hydroxybutanoate, β -pinene, linalool, hexanoic acid, undecane, isobutyl hexanoate, 3-hexenyl butanoate, ethyl 4-octenoate, decanal, nonanoic acid, tridecane, 3-hexenyl hexanoate, tetradecane, butyl decanoate, dihydro- α -ionone, and hexadecanoic acid. In terms of total mass change, the most notable alterations were observed for ethyl butanoate, 1-hexanol, ethyl hexanoate, 1-octanol, 3-hexenyl butanoate, hexyl butanoate, and hexyl hexanoate.

Figures 2 and 3 display a heat map illustrating the changes in the mass fraction of volatile compounds, with untreated juice serving as the baseline. Lighter colors indicate changes between 0% and 50%, while darker colors represent changes greater than 50%. Red denotes a reduction in compound concentration, whereas blue indicates an increase in mass fraction.

Previous studies have reported a reduction in the concentration of long-chain esters due to demethylation, while short-chain esters were more stable [14]. Demethylation appears to have occurred in the chain attached to the carbon of the ester, which would tend to shorten the chain. The mass balance data suggest that the abstracted methyl group reacted with other esters, increasing the length of the chain attached to the oxygen of the ester. This pathway was observed in fruits containing mainly methyl and ethyl esters.

Passion fruit has a different ester composition. It contains several esters with long-chain hydrocarbons attached to the ester carbonyl and to the ester oxygen. For example, octyl butanoate, heptyl butanoate, hexyl hexanoate, and other long-chain esters. The mass balance analysis revealed an increase in the concentration of long-chain esters and a decrease in the concentration of short-chain esters. Demethylation of the esters at the side chain attached to the carbon was less evident in passion fruit juice. However, methylation

Table 1 Volatile compounds of yellow passion fruit juice with retention time, Kovats index, concentration, odor threshold in water, and aroma descriptors

Retention time (min)	Volatile compound	Class	Kovats index	Concentration ($\mu\text{g/mL}$)	Odor threshold in water(mg/L)	Odor descriptor
4.3	Acetic acid	Acid	726	0.93 ± 0.04	25.59	Acidic
5.2	Methyl butanoate	Ester	742	0.65 ± 0.02	0.076	Fruity
5.7	3-Amino, 2–3-dihydrobenzoic acid	Acid	751	20.78 ± 1.07	--	--
6.4	Toluene	Hydrocarbon	766	2.68 ± 0.12	0.330	Sweet
7.7	Ethyl butanoate	Ester	790	65.72 ± 3.32	0.020	Fruity
10.9	1-Hexanol	Alcohol	849	15.29 ± 0.84	2.500	Herbal
13.5	Methoxy-phenyl-oxime	Oxime	899	4.92 ± 0.22	--	--
13.6	Methyl hexanoate	Ester	901	5.10 ± 0.13	0.084	Fruity
14.4	Ethyl 3-hydroxybutanoate	Ester	915	0.27 ± 0.02	20.00	Fruity
14.6	β -pinene	Terpene	919	1.58 ± 0.09	2.540	Herbal
14.7	Benzaldehyde	Aldehyde	919	0.84 ± 0.03	0.028	Fruity
17.5	Hexanoic acid	Acid	974	0.68 ± 0.04	0.420	Fatty
18.3	Ethyl hexanoate	Ester	988	405.10 ± 20.28	0.001	Fruity
18.8	n-Hexyl acetate	Ester	997	21.39 ± 0.06	0.400	Fruity
19.3	α -Terpinene	Terpene	1006	0.80 ± 0.04	0.085	Woody
19.4	o-Cymene	Terpene	1009	0.62 ± 0.04	0.000	woody
19.9	Limonene	Terpene	1019	14.08 ± 0.78	1.040	Citrus
20.5	α -trans-Ocimene	Terpene	1030	1.71 ± 0.00	0.340	Floral
21.1	m-Cymene	Terpene	1041	34.48 ± 1.75	0.011	Floral
21.6	g-Terpinene	Terpene	1049	2.14 ± 0.11	0.260	Terpenic
22.2	1-Octanol	Alcohol	1061	6.14 ± 0.36	0.875	Waxy
22.8	p-Dimethyl styrene	Aromatic	1072	0.00 ± 0.07	--	--
23.0	Terpinolene	Terpene	1078	11.47 ± 0.64	0.200	Herbal
23.4	α -Linalool	Alcohol	1085	1.98 ± 0.09	0.006	Floral
23.7	Hexyl propanoate	Ester	1091	0.27 ± 0.02	0.008	Fruity
24.0	4-Methyl-2-(2-methylpropenyl) tetrahydro-2 H-pyran	Pyran	1095	0.48 ± 0.03	0.050	Floral
24.1	Undecane	Alkane	1100	0.00 ± 0.01	2.140	--
24.4	2-Ethenyl-1,1-dimethyl-3-methylene cyclohexane	Terpene	1105	3.75 ± 0.20	--	--
24.8	1,3,8-p-Menthatriene	Terpene	1116	1.87 ± 0.11	--	--
24.9	Allo-ocimene	Terpene	1119	0.99 ± 0.06	0.140	--
25.6	Benzyl acetate	Ester	1137	0.00 ± 0.01	0.270	--
25.7	Isobutyl hexanoate	Ester	1139	0.58 ± 0.02	0.020	Fruity
26.5	4-Terpinenol	Alcohol	1161	1.58 ± 0.10	6.400	Spicy
26.9	3-Hexenyl butanoate	Ester	1171	5.24 ± 0.28	0.001	Fruity
27.0	Ethyl 4-octenoate	Ester	1173	3.25 ± 0.01	0.050	
27.1	Hexyl butanoate	Ester	1177	134.30 ± 6.77	0.250	Green
27.3	Ethyl octanoate	Ester	1182	3.19 ± 0.17	0.005	Waxy
27.4	Decanal	Aldehyde	1186	0.13 ± 0.01	0.030	Aldehydic
27.7	n-Octyl acetate	Ester	1194	0.37 ± 0.02	0.047	Floral
27.9	1-Methylhexyl butanoate	Ester	1198	0.54 ± 0.03	--	--
28.2	α -Citronellol	Alcohol	1210	1.30 ± 0.06	0.062	Floral
28.4	Hexyl 2-butenate	Ester	1221	0.16 ± 0.01	--	--
28.5	Hexyl 2-methylbutanoate	Ester	1224	0.58 ± 0.04	0.022	Green
28.8	3-Methylbutyl hexanoate	Ester	1238	0.78 ± 0.04	0.900	--
29.3	Nonanoic acid	Acid	1262	0.21 ± 0.01	3.000	Waxy
29.6	Pentyl hexanoate	Ester	1279	1.46 ± 0.08	0.200	Apple
29.7	Heptyl butanoate	Ester	1283	0.39 ± 0.02	--	--
29.9	4-Methylpentyl hexanoate	Ester	1293	0.00 ± 0.01	--	--
30.2	Tridecane	Alkane	1300	0.00 ± 0.00	2.040	Chemical
30.4	3-Hydroxybutanoic acid	Acid	1314	0.14 ± 0.01	--	--

Table 1 (continued)

Retention time (min)	Volatile compound	Class	Kovats index	Concentration ($\mu\text{g}/\text{mL}$)	Odor threshold in water(mg/L)	Odor descriptor
30.9	Citronellol acetate	Ester	1341	0.59 ± 0.03	--	--
31.4	3-Hexenyl hexanoate	Ester	1364	4.56 ± 0.0	0.016	Green
31.6	Hexyl hexanoate	Ester	1371	147.73 ± 0.0	1.890	Fruity
31.6	Octyl butanoate	Ester	1373	1.35 ± 0.0	0.250	Fruity
31.9	1-Methylhexyl hexanoate	Ester	1385	0.46 ± 0.0	--	--
32.1	Tetradecane	Alkane	1400	0.22 ± 0.0	1.000	Waxy
32.3	Butyl 2-octenoate	Ester	1410	0.19 ± 0.0	--	--
32.4	Dihydro- α -ionone	Ketone	1416	0.19 ± 0.0	--	--
32.6	Ethyl cinnamate	Ester	1431	0.19 ± 0.0	0.001	fruity
33.1	β -Ionone	Ketone	1467	1.11 ± 0.0	0.000	Floral
33.5	2,4-Di-tert-butyl phenol	Phenol	1492	0.42 ± 0.0	0.500	--
33.5	α -Farnesene	Sesquiptene	1497	0.00 ± 0.0	0.087	Woody
33.6	Pentadecane	Alkane	1500	0.16 ± 0.0	--	--
33.7	3,7-Dimethyl-6-octenyl butanoate	Ester	1512	0.25 ± 0.0	--	--
34.5	Hexyl octenoate	Ester	1564	1.41 ± 0.0	--	--
34.8	Butyl decanoate	Ester	1590	0.41 ± 0.0	--	--
34.9	Hexadecane	Alkane	1600	0.10 ± 0.0	--	--
37.2	2-Ethylhexyl salicylate	Ester	1802	0.09 ± 0.0	--	--
38.1	Homomenthyl salicylate	Ester	1886	0.10 ± 0.0	--	--
38.7	Hexadecanoic acid	Acid	1941	0.11 ± 0.0	--	--

of the side chain attached to the oxygen appeared to occur, with significant increases in the concentrations of octyl butanoate, hexyl octanoate, and hexyl hexanoate.

Previous studies on plasma-treated juices have documented different primary reaction pathways for esters, depending on matrix composition. In pineapple juice, which predominantly contains methyl and ethyl esters, plasma induced ester demethylation. In cashew apple juice, ester isomerization and cleavage of long-chain esters and fatty acids were the primary mechanisms observed. The current study indicates a pathway consistent with ester dehydrogenation. This novelty is probably linked to the matrix specificity of passion fruit juice, which contains a high concentration of esters with long side chains (hexyl, heptyl, and octyl). These long chains serve as unique precursors that interact with plasma-generated reactive species to form unsaturated esters, a reaction pathway not previously reported in the plasma processing of other fruit juices.

Figure 4 illustrates the possible chemical transformation pathways of major esters during plasma processing of the juice. The increase in ethyl 4-octenoate under specific plasma conditions may result from the dehydrogenation of ethyl octanoate. The rise in hexyl 2-butenate may be due to the conversion of heptyl butanoate, which involves the removal of the methyl group from the heptyl chain, followed by molecular dehydrogenation. The isomerization of heptyl butanoate likely caused a slight increase in hexyl 2-methylbutanoate at 1000 Hz/10 min.

Maia et al. [39] observed that DBD plasma treatment of cashew juice induced ester isomerization, leading to

branched esters. Likewise, the substantial increase in (Z)-3-hexenyl butanoate content may be attributed to the dehydrogenation of hexyl butanoate (Fig. 4). Methyl hexanoate content also increased under plasma conditions of 50 Hz (10–20 min) and 1000 Hz (10–20 min), possibly due to demethylation of ethyl hexanoate.

The mass balance and heat map analysis indicated that the increase in methyl butanoate observed at 50 Hz/20 min and 1000 Hz/20 min may result from dehydration of the hydroxyl group in ethyl 3-hydroxybutanoate to form ethyl butanoate, followed by ethyl group demethylation. Figure 4 also illustrates a possible chemical pathway for the formation of the unsaturated ester 3-hexenyl hexanoate. Its increase could be associated with the transesterification of isobutyl hexanoate, which was significantly reduced, resulting in the formation of pentyl hexanoate. This intermediate may undergo methylation to form hexyl hexanoate, which could then be dehydrogenated to yield (E)-3-hexenyl hexanoate. A slight increase in 3-methylbutyl hexanoate may have occurred due to the isomerization of pentyl hexanoate under the 1000 Hz/20 min condition. Methyl hexanoate, methyl butanoate, decanal, hexanoic acid, and nonanoic acid may be degradation products derived from the cleavage of oleic and linoleic acids contained in the passion fruit seeds.

Among the terpenes with the highest mass fractions observed in passion fruit juice were *m*-cymene, limonene, and terpinolene, all of which showed a general decreasing trend across excitation frequencies. Reactive species generated during plasma treatment, combined with the high water

Table 2 Mass fraction of volatile compounds in yellow passion fruit juice subjected to dielectric barrier discharge plasma under different treatment conditions

Reten. time (min)	Volatile compound	Control (%)	50 Hz 10 min (%)	50 Hz 20 min (%)	500 Hz 10 min (%)	500 Hz 20 min (%)	1000 Hz 10 min (%)	1000 Hz 20 min (%)
4.3	Acetic acid	0.10	0.00	0.06	0.06	0.00	0.00	0.09
5.2	Methyl butanoate	0.07	0.00	0.06	0.00	0.00	0.00	0.06
5.7	3-Amino, 2–3-dihydrobenzoic acid	2.21	1.05	2.45	2.59	3.52	1.15	2.29
6.4	Toluene	0.28	0.44	0.35	0.34	0.28	0.47	0.26
7.7	Ethyl butanoate	6.97	6.71	4.87	5.17	2.55	5.96	7.11
10.9	1-Hexanol	1.62	2.26	1.41	1.90	1.39	2.43	1.79
13.5	Methoxy-phenyl-oxime	0.52	0.15	0.57	1.58	0.63	0.00	0.53
13.6	Methyl hexanoate	0.54	0.60	0.46	0.00	0.28	0.61	0.60
14.4	Ethyl 3-hydroxybutanoate	0.03	0.00	0.00	0.00	0.00	0.00	0.03
14.6	β -Pinene	0.17	0.00	0.00	0.00	0.00	0.00	0.19
14.7	Benzaldehyde	0.09	0.00	0.24	0.16	0.32	0.44	0.00
17.5	Hexanoic acid	0.07	0.07	0.14	0.17	0.13	0.00	0.09
18.3	Ethyl hexanoate	43.00	42.77	35.65	41.62	42.82	42.68	43.39
18.8	n-Hexyl acetate	2.27	2.45	2.32	2.20	2.19	2.36	2.28
19.3	α -Terpinene	0.09	0.08	0.10	0.10	0.09	0.11	0.08
19.4	o-Cymene	0.07	0.08	0.10	0.07	0.08	0.11	0.05
19.9	Limonene	1.49	1.40	1.56	1.53	1.40	1.61	1.26
20.5	α -trans-Ocimene	0.18	0.18	0.25	0.18	0.00	0.21	0.16
21.1	m-Cymene	3.66	3.29	3.71	3.29	3.29	3.26	3.10
21.6	g-Terpinene	0.23	0.23	0.30	0.18	0.22	0.29	0.18
22.2	1-Octanol	0.65	1.05	0.90	0.54	0.94	0.76	0.37
22.8	p-Dimethyl styrene	0.00	0.20	0.00	0.19	0.17	0.27	0.00
23.0	Terpinolene	1.22	1.15	1.34	1.03	1.12	1.24	1.16
23.4	α -Linalool	0.21	0.38	0.38	0.28	0.41	0.40	0.20
23.7	Hexyl propanoate	0.03	0.05	0.04	0.03	0.04	0.00	0.02
24.0	4-methyl-2-(2-methylpropenyl) tetrahydro-2 H-pyran	0.05	0.06	0.06	0.07	0.06	0.00	0.05
24.1	Undecane	0.00	0.03	0.00	0.03	0.04	0.04	0.00
24.4	2-Ethenyl-1,1-dimethyl-3-methylene cyclohexane	0.40	0.42	0.48	0.40	0.41	0.44	0.43
24.8	1,3,8-p-Menthatriene	0.20	0.21	0.24	0.20	0.20	0.25	0.15
24.9	Allo-ocimene	0.11	0.12	0.14	0.11	0.10	0.15	0.05
25.6	Benzyl acetate	0.00	0.02	0.02	0.02	0.01	0.00	0.01
25.7	Isobutyl hexanoate	0.06	0.05	0.06	0.00	0.00	0.00	0.02
26.5	4-Terpinenol	0.17	0.22	0.26	0.25	0.23	0.21	0.13
26.9	3-Hexenyl butanoate	0.56	0.69	1.31	1.24	1.09	0.69	1.01
27.0	Ethyl 4-octenoate	0.34	0.39	0.49	0.43	0.52	0.37	0.35
27.1	Hexyl butanoate	14.25	13.65	15.69	13.66	14.18	13.61	14.49
27.3	Ethyl octanoate	0.34	0.35	0.43	0.33	0.31	0.34	0.28
27.4	Decanal	0.01	0.03	0.06	0.03	0.03	0.04	0.02
27.7	n-Octyl acetate	0.04	0.05	0.05	0.04	0.04	0.04	0.03
27.9	1-Methylhexyl butanoate	0.06	0.09	0.09	0.06	0.06	0.09	0.05
28.2	α -Citronellol	0.14	0.18	0.21	0.16	0.16	0.17	0.13
28.4	Hexyl 2-butenate	0.02	0.02	0.04	0.02	0.03	0.03	0.02
28.5	Hexyl 2-methylbutanoate	0.06	0.07	0.08	0.06	0.07	0.08	0.05
28.8	3-Methylbutyl hexanoate	0.08	0.09	0.11	0.09	0.09	0.10	0.08
29.3	Nonanoic acid	0.02	0.02	0.06	0.05	0.09	0.04	0.03
29.6	Pentyl hexanoate	0.15	0.17	0.23	0.19	0.16	0.17	0.13
29.7	Heptyl butanoate	0.04	0.04	0.05	0.04	0.04	0.04	0.01
29.9	4-Methylpentyl hexanoate	0.00	0.01	0.02	0.03	0.02	0.01	0.02
30.2	Tridecane	0.00	0.02	0.01	0.02	0.02	0.00	0.00
30.4	3-Hydroxybutanoic acid	0.01	0.02	0.04	0.04	0.03	0.02	0.02
30.9	Citronellol acetate	0.05	0.07	0.08	0.08	0.09	0.07	0.00

Table 2 (continued)

Reten. time (min)	Volatile compound	Control (%)	50 Hz 10 min (%)	50 Hz 20 min (%)	500 Hz 10 min (%)	500 Hz 20 min (%)	1000 Hz 10 min (%)	1000 Hz 20 min (%)
31.4	3-Hexenyl hexanoate	0.48	0.50	0.69	0.57	0.57	0.57	0.33
31.6	Hexyl hexanoate	15.68	16.62	20.32	17.23	18.14	16.78	15.88
31.6	Octyl butanoate	0.14	0.31	0.38	0.34	0.37	0.38	0.26
31.9	1-Methylhexyl hexanoate	0.05	0.06	0.08	0.08	0.07	0.07	0.06
32.1	Tetradecane	0.02	0.03	0.04	0.05	0.05	0.05	0.03
32.3	Butyl 2-octenoate	0.02	0.02	0.03	0.03	0.03	0.03	0.02
32.4	Dihydro- α -ionone	0.02	0.03	0.04	0.03	0.03	0.03	0.03
32.6	Ethyl cinnamate	0.02	0.02	0.02	0.01	0.01	0.01	0.00
33.1	β -Ionone	0.12	0.13	0.16	0.14	0.14	0.12	0.11
33.5	2,4-Di-tert-butyl phenol	0.05	0.03	0.04	0.04	0.00	0.03	0.02
33.5	α -Farnesene	0.00	0.02	0.03	0.02	0.02	0.02	0.01
33.6	Pentadecane	0.02	0.01	0.03	0.02	0.02	0.02	0.00
33.7	3,7-Dimethyl-6-octenyl butanoate	0.03	0.03	0.04	0.03	0.03	0.03	0.03
34.5	Hexyl octenoate	0.15	0.16	0.20	0.18	0.15	0.17	0.12
34.8	Butyl decanoate	0.04	0.06	0.06	0.06	0.07	0.00	0.04
34.9	Hexadecane	0.01	0.02	0.02	0.02	0.03	0.03	0.01
37.2	2-Ethylhexyl salicylate	0.01	0.01	0.01	0.01	0.01	0.02	0.01
38.1	Homomenthyl salicylate	0.01	0.01	0.01	0.01	0.01	0.02	0.01
38.7	Hexadecanoic acid	0.01	0.01	0.00	0.01	0.00	0.02	0.00

content in the juice, likely contributed to the conversion of limonene into other compounds.

Figure 5 presents these changes and the proposed transformation pathways for terpenes under DBD plasma treatment. Limonene is proposed to have reacted with hydrogen radicals generated by plasma to form the α -terpenyl cation, which subsequently isomerized into the pinenyl cation. Subsequent hydrolysis, isomerization, and dehydrogenation reactions of limonene under specific plasma conditions have contributed to increased levels of 4-terpineol and, notably, linalool. Rodrigues et al. [16] demonstrated that cold plasma could convert limonene into 4-terpineol and linalool in orange juice.

The heat map analysis showed a significant increase in linalool content across most excitation frequencies, with the greatest increase (+130% compared to the control) observed at 500 Hz/20 min. Conversely, β -pinene, which also forms intermediate pinenyl and α -terpenyl radicals, exhibited a substantial reduction (−100%) under most conditions, suggesting its hydrolysis contributed to the increased levels of α -linalool and α -citronellol. The most significant increase in α -citronellol was observed at 50 Hz/20 min. Additionally, β -pinene oxidation by reactive species generated in the DBD plasma may have led to the formation of 4-terpineol. Dehydrogenation, isomerization, and partial ring-opening of limonene and terpinolene may also have contributed to the increased concentrations of *o*-cymene and α -terpinene at specific excitation frequencies.

At 1000 Hz/20 min, a substantial reduction (−62.6%) in allo-ocimene was observed. In contrast, trans-ocimene showed a slight increase under the same conditions,

suggesting it may have formed via isomerization of allo-ocimene (Fig. 4). The consistent reduction in terpinolene under most conditions, except for 1000 Hz/20 min, may have contributed to a slight increase in 4-terpineol content, following the same pathway as the conversion of limonene to this compound. Under the 50 Hz/20 min treatment, both terpinolene and limonene appear to have contributed to the increase (+54.6%) in α -citronellol.

During DBD plasma processing, benzaldehyde content increased under most plasma conditions, with the most pronounced elevation observed at 1000 Hz/10 min. In contrast, at this same excitation frequency, methoxy-phenyl-oxime and ethyl cinnamate showed considerable reductions in their mass fractions. This suggests that reactive oxygen species (ROS) generated by plasma likely induced oxidative cleavage of these compounds, leading to benzaldehyde formation.

Changes in the aromatic profile based on OAV analysis

Based on the odor activity values (OAV) of untreated passion fruit juice, the most relevant aroma notes in its sensory profile were fruity, floral, waxy, woody, and green. Figure 6 presents a radar chart depicting the five primary odor descriptors in the untreated and DBD plasma-treated passion fruit juice. Additional descriptors contributing to the aromatic profile included aldehydic, citrus, sweet, herbal, and terpenic notes. The volatile compounds contributing most significantly to the fruity aroma were the esters ethyl butanoate, ethyl hexanoate, 3-hexenyl butanoate, ethyl

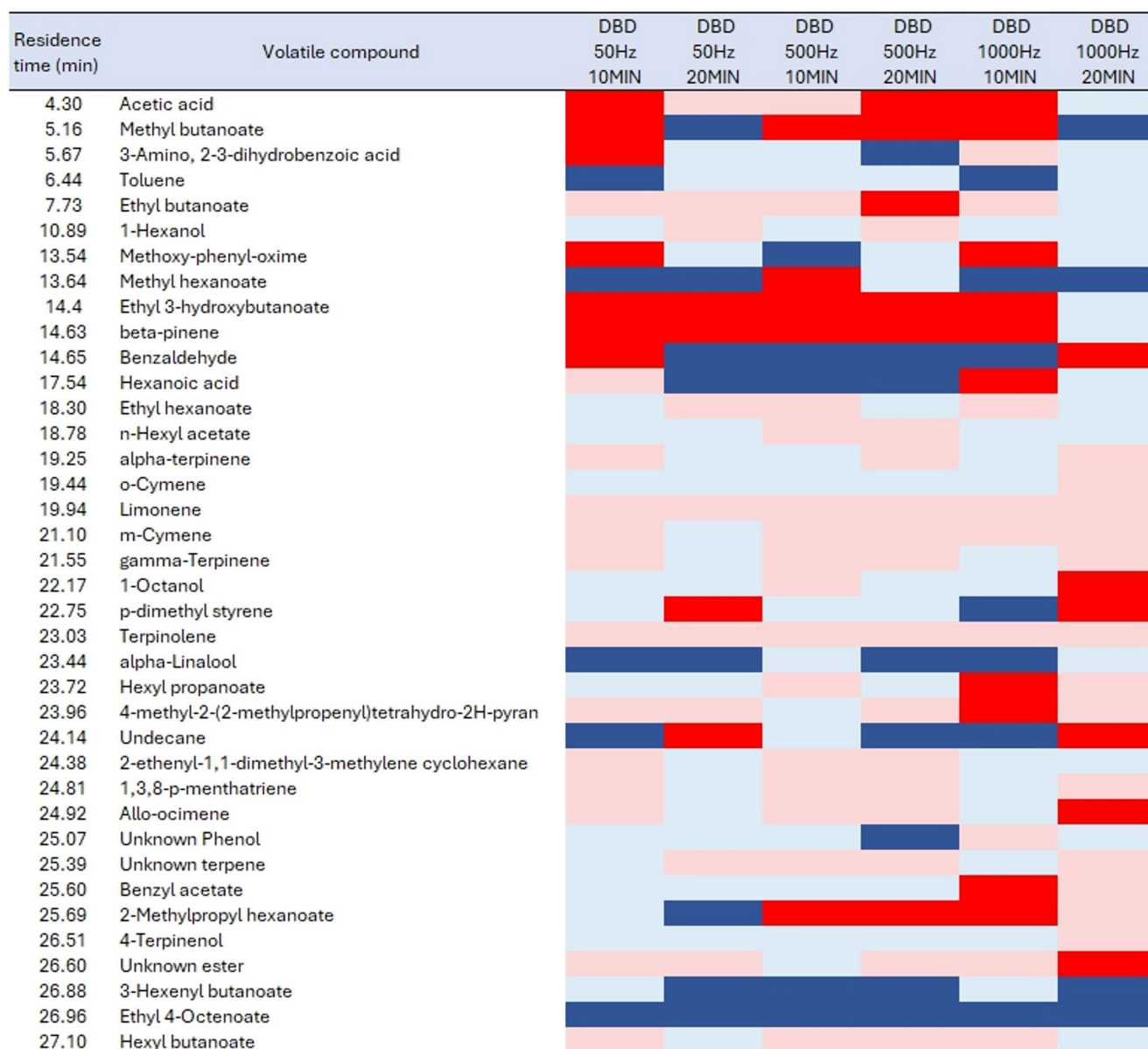


Fig. 2 Heat map showing changes in the mass fractions of volatile compounds, using untreated juice as the reference (residence times between 0 and 27.10 min)

cinnamate, and hexyl hexanoate. Except for ethyl cinnamate and 3-hexenyl butanoate, these compounds were also reported in a previous study on passion fruit aroma volatiles [4]. The floral aroma was mainly attributed to *m*-cymene, β -ionone, and α -linalool. The long-chain ester ethyl octanoate was primarily responsible for the waxy note, while the terpene *o*-cymene predominantly characterized the woody aroma.

Table 3 shows the odor activity values of untreated and plasma-treated passion fruit juice, organized by odor descriptor. Overall, no significant changes in total OAV were observed compared to the control, except under the 50 Hz/20 min condition, where a 12% decrease was observed.

Under the same conditions, the fruity descriptor showed a notable reduction of 14%, whereas the floral descriptor increased by 41%. Therefore, DBD plasma treatment under these conditions resulted in a less intense and slightly altered aroma, which may be appealing to certain consumers. A similar pattern was observed in pineapple juice [14], where the fruity aroma decreased with longer treatment durations (20 min).

This effect is due to a reduction in the concentration of esters responsible for fruity aromas, such as ethyl and methyl butanoate, and an increase in the concentration of compounds associated with floral notes, such as linalool. The reduction in fruity perception was mainly linked to

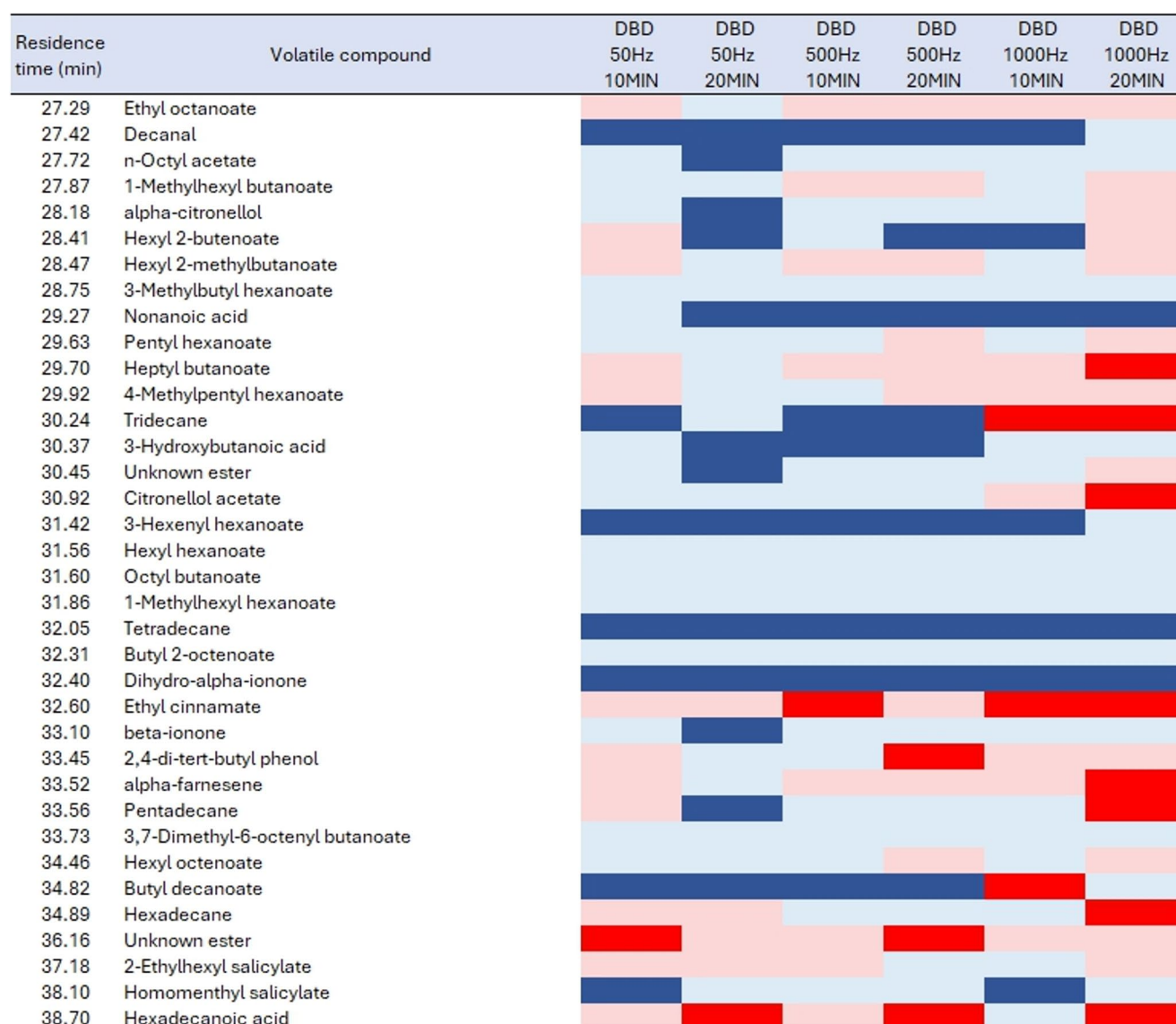


Fig. 3 Heat map showing changes in the mass fractions of volatile compounds, using untreated juice as the reference (residence times between 27.29 and 38.70 min)

the decreased concentration of ethyl hexanoate (−16.7%), ethyl butanoate (−30.6%), and ethyl cinnamate (−9.94%). The significant increase in floral aroma is mainly associated with the increased mass fractions of β -ionone (+52%) and linalool (+91.5%).

A similar change in aroma has been previously observed in a study on pasteurized orange juice, where notable changes in the floral descriptor were also associated with increased linalool content. Plasma processing at higher frequencies increased linalool levels, enhancing the floral aroma. While linalool generally has a positive impact on juice aroma, excessive levels may lead to the formation of compounds such as α -terpineol, which can negatively affect the aromatic quality [16].

The woody descriptor showed a substantial increase (+48.7%) under high-frequency and short-duration conditions (1000 Hz/10 min), likely due to a +49% increase in *o*-cymene content. The marked increase in woody notes could lead to a less characteristic aromatic profile, which may be undesirable depending on the intended sensory application. However, the contribution of the woody aroma to the overall aroma of passion fruit juice is very weak, and even such a significant increase does not change the more characteristic fruity aroma of the juice.

When the frequency was maintained at 1000 Hz but the exposure time was extended to 20 min, the woody note significantly decreased (−33.8%), along with a 33% reduction in *o*-cymene content. At the same frequency and duration,

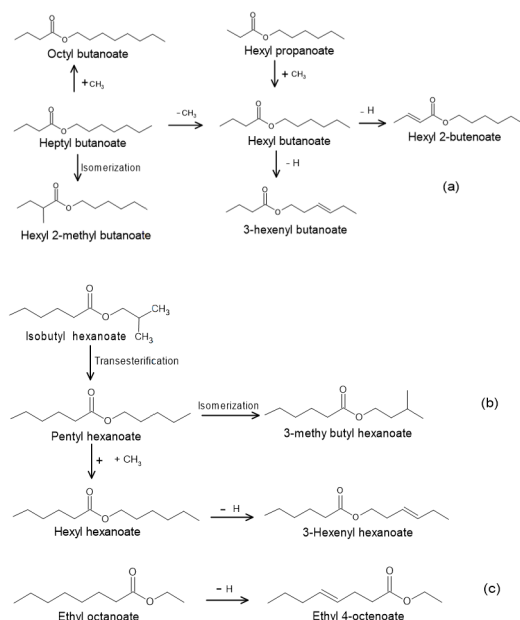


Fig. 4 Chemical modification pathway of the major esters in passion fruit induced by cold plasma treatment

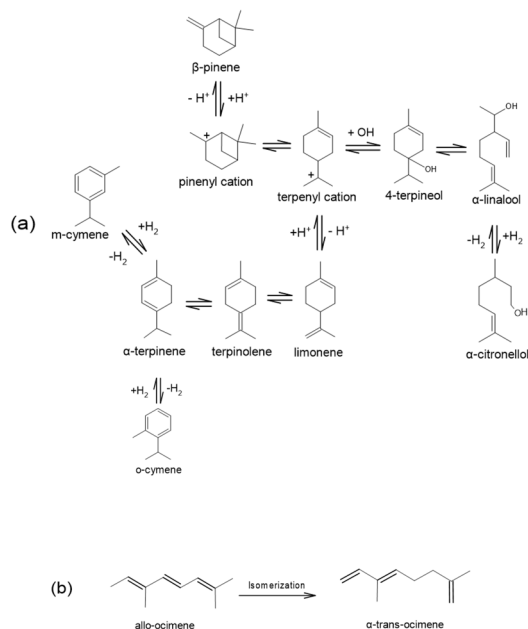


Fig. 5 Chemical changes and pathway of the main terpenes present in passion fruit induced by DBD plasma treatment

the intensity of the waxy aroma also declined (− 21%) due to the reduction in ethyl octanoate content (− 20.6%), a key compound contributing to this descriptor. However, when the juice was processed at a lower frequency (50 Hz) for the same duration (20 min), the waxy aroma increased (+

21.7%). A more pronounced increase in this note could result in an unpleasant, rancid aroma, which is generally undesirable. In contrast, DBD plasma processing of pineapple juice under the same conditions (50 Hz/20 min) reduced the waxy aroma, highlighting that the behavior of volatile compounds under plasma treatment can vary depending on the juice matrix [14].

Changes in the aromatic profile based on olfactometry assessment

Olfactometry assessment of the passion fruit juice showed that the most relevant aroma notes in its sensory profile were fruity, floral, and woody. Figure 7 presents a radar chart depicting the three primary odor descriptors in the untreated and DBD plasma-treated passion fruit juice.

The fruity aromas detected during olfactometry were correlated with ethyl butanoate, methyl hexanoate, ethyl hexanoate, hexyl butanoate, and hexyl hexanoate. The floral aroma was correlated with β -ocimene, while the woody aroma originated from a compound whose mass spectrum could not be identified.

The scores given by the panelists for the untreated and plasma-treated juices were similar. Although the panelists reported slight differences in the aroma of the juices, the scores for each peak observed in the olfactory assessment were consistent across all conditions.

Methodological differences in aroma analysis

A slight discrepancy was observed when comparing the results from the chemical-analytical approach (Odor Activity Value, OAV) with those from the human sensory assessment using Gas Chromatography-Olfactometry (GC-O). The OAV calculations, based on the concentration of volatile compounds, suggested that several plasma treatments induced changes to the aromatic profile. For example, the 50 Hz/20 min plasma treatment condition showed a 14% reduction in the fruity descriptor and a 41% increase in the floral descriptor based on OAVs. Similarly, the 1000 Hz/10 min treatment showed a 48.7% rise in the woody note's OAV.

In contrast, the trained sensory panel performing the GC-O assessment reported that the aroma scores for the untreated and plasma-treated juices were similar. The panelists' scores for the aroma peaks were consistent across all conditions, indicating that the chemical changes measured by the GC-MS were not potent enough to be perceived as a significant difference by the human assessors. However, it is worth noting that the three primary aroma descriptors in the overall scent were the same, as were their ranks in prevalence in the aroma profile.

Fig. 6 Aroma radar profile of passion fruit juice subjected to DBD plasma treatment: (a) 50 Hz/10 min; (b) 50 Hz/20 min; (c) 500 Hz/10 min; (d) 500 Hz/20 min; (e) 1000 Hz/10 min; and (f) 1000 Hz/20 min

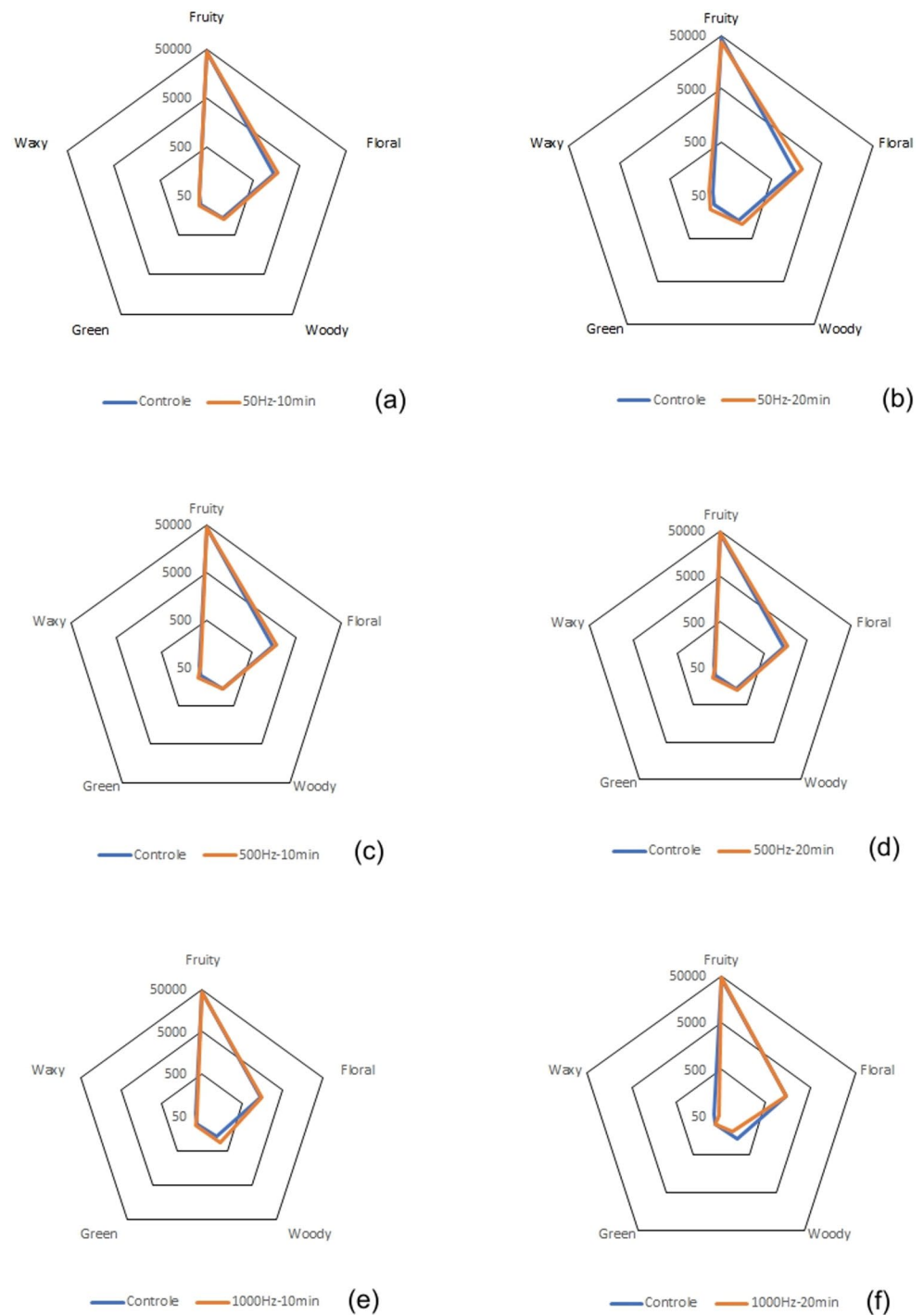


Table 3 Odor activity values of untreated and plasma-treated passion fruit juice presented by odor descriptors

Odor Descriptor	Control	DBD 50 Hz 10 min	DBD 50 Hz 20 min	DBD 500 Hz 10 min	DBD 500 Hz 20 min	DBD 1000 Hz 10 min	DBD 1000 Hz 20 min
Fruity	44,026	44,142	37,833	43,683	44,561	44,019	45,211
Floral	1444	1669	2042	1755	1742	1538	1408
Woody	186	202	240	186	203	277	123
Green	81	89	109	92	95	93	81
Waxy	71	71	86	67	63	67	56
Total OAV	45,810	46,175	40,313	45,785	46,666	45,997	46,881

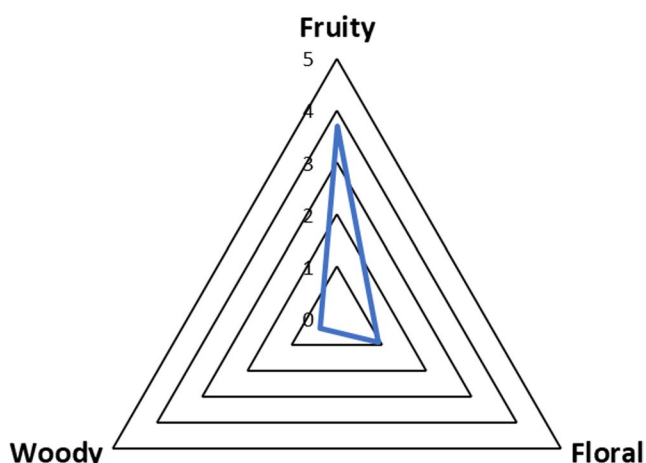


Fig. 7 Aroma radar profile of passion fruit juice subjected to DBD plasma treatment attained by olfactometry assessment

The slight divergence highlights the fundamental difference between a calculated chemical potency and integrated human perception. The OAV is a theoretical model that estimates the sensory contribution of an individual compound by dividing its concentration by its published odor threshold.

The OAV method has two key limitations in this context. OAVs are calculated using odor thresholds found in literature, which are often determined in a simple water matrix. The actual perception threshold of a compound within a complex food matrix like passion fruit juice, which contains acids, sugars, and other volatiles, can be slightly different. Also, the OAV model assesses each compound in isolation. The model is still not complex enough to account for complex perceptual phenomena such as masking, suppression, or synergistic effects that occur in the human olfactory system when a mixture of many compounds is smelled simultaneously.

The GC-O results suggest that such interactions may have played a role in the perception. While the plasma treatment did chemically increase the levels of compounds associated with floral (linalool, β -ionone) and woody (o-cymene) notes, these changes were likely masked or perceptually suppressed by the high concentration of the dominant fruity esters like ethyl hexanoate and hexyl butanoate. This interpretation is supported by the differences in the specific compounds identified by each method. The OAV analysis pointed to m-cymene, β -ionone, and linalool as key compounds for the floral note, while the GC-O panel correlated this aroma with β -ocimene. Likewise, the woody note was linked to o-cymene by OAV but to an unidentified compound by the panel, which could be o-cymene.

Regarding the olfactory assessment, when a scaled system is used, changes in aroma need to be substantial to be perceived and rated differently; otherwise, they will likely receive a score similar to the control. This characteristic

of sensory analysis can lead to both underestimation and overestimation of an aroma profile compared to purely chemical data. A scaled system, such as the one used in olfactometry assessment, relies on integer scores (from 1 to 5) to represent perceived intensity. This creates discrete steps rather than a continuous spectrum, which directly impacts the results. A scaled system is more likely to underestimate changes in an aroma profile. This occurs when chemical changes take place but are not strong enough to push the perceived intensity over the threshold into the next integer score.

In this work, gas chromatography-mass spectrometry (GC-MS) analysis revealed clear chemical changes in the juice following plasma treatment. For example, the OAV calculation, based on this continuous chemical data, showed a significant 41% increase in the floral descriptor for the 50 Hz/20 min plasma treatment. However, the trained sensory panel rated the treated and untreated juices as having similar aroma scores. The chemical reality was a more complex and altered aroma. Still, because these changes didn't cross the human perceptual threshold in a significant way, the scaled system reported no major difference, thereby possibly underestimating the extent of the chemical modification.

The ceiling effect of the scaled sensory analysis may explain this discrepancy between the OAV data and the GC-O assessment, particularly for the fruity descriptor, which showed an average 95% dominance in the OAV data and 74% in the GC-O data. The OAV calculations showed the fruity descriptor to be dominant at the chemical level, approximately 30 times more potent than the next-highest descriptor, floral. However, a human sensory panelist using a 5-point integer scale cannot perceive a 30-fold magnitude difference. The fruity aroma is so intense that it hits the maximum score of 5 (extremely strong), a phenomenon known as the ceiling effect. The consequence of this sensory saturation is the masking or perceptual suppression of the less-intense aroma notes. While the OAV data showed significant increases in chemical levels of floral and woody notes under certain plasma conditions, the panel's perception was already "maxed out" by the dominant fruity aroma. Therefore, these more subtle chemical changes were not perceived, leading the panel to report similar aroma scores for the treated and untreated juices.

The discrepancy arises because the OAV method creates a detailed, continuous chemical landscape, while the olfactometry method provides a simplified, contour-based map based on what a human can actually perceive. The sensory panel's results are arguably more practical for consumer products, as they reflect the real-world experience, even if they don't capture every subtle chemical reaction occurring in the background.

The OAV model assesses each compound in strict isolation. However, it is still not complex enough to account for the dynamic perceptual phenomena that occur in the human olfactory system when a mixture of many compounds is smelled simultaneously. This fact can lead to discrepancies between the methods. Mixture suppression is frequently observed in highly complex aromatic matrices such as passion fruit juice. The human olfactory epithelium has a finite number of receptors. High-concentration aliphatic esters (such as ethyl hexanoate and hexyl butanoate), which dominate the volatile profile, can physically outcompete minor compounds for receptor binding sites. Consequently, even though plasma treatment chemically increased the concentrations of floral and woody volatiles, their perceptual impact was likely suppressed by the ester background [40, 41].

Odor synergy and perceptual blending also contribute to the discrepancies. The OAV method assumes that aromas behave additively, but individual volatiles often integrate synergistically to form a singular perception [42]. The GC-O panelists may not have perceived the increased floral and woody notes as distinct, separate aromas, but rather as underlying contributors that simply reinforced the passion fruit identity. Furthermore, olfactory adaptation must be accounted for during the analytical process itself. During a 30- to 40-minute GC-O run, the continuous sniffing of high-intensity ester peaks can induce rapid peripheral adaptation (olfactory fatigue). This temporary reduction in receptor sensitivity can dull the panel's ability to accurately perceive and score the subtle increases in subsequent minor peaks [43]. Thus, both methods have their advantages and disadvantages: OAV does not account for receptor binding and perceptual blending effects, whereas the olfactory model is affected by olfactory fatigue.

Conclusions

This study evaluated the effects of dielectric barrier discharge (DBD) plasma on passion fruit juice. Plasma processing induced several modifications in the volatile profile of the juice, mainly through chemical reactions such as dehydrogenation, which led to an increase in unsaturated esters; isomerization, which contributed to the formation of branched esters; methylation, which led to an increase in long-chain esters; and hydrolysis, which contributed to the formation of terpene alcohols.

Despite these transformations, only minor changes were observed in the total odor activity value (OAV) and the predominance of the fruity descriptor, indicating that the characteristic aromatic profile of the juice was preserved under most treatment conditions. Olfactometry assessment

showed no perceived differences between the control and plasma-treated juices. Significant changes in the aroma of passion fruit juice would likely require longer exposure time to plasma or a higher-voltage treatment.

The DBD plasma represents a promising non-thermal processing technology capable of intentionally modulating volatile compounds. However, it also shows that these chemical modulations may not translate into a perceived sensory difference due to masking. For the food flavor industry, this provides a valuable tool for customizing and intensifying natural fruit profiles without the thermal degradation associated with traditional pasteurization. Specifically, plasma's ability to enhance desirable fresh and floral aromas, driven by increases in compounds such as linalool and β -ionone, offers significant potential for flavor formulation. From a practical standpoint, the ability to selectively reduce compounds such as ethyl octanoate under specific conditions (1000 Hz) has significant industrial value. Commercial passion fruit juice is often processed with its seeds to improve yield, which can introduce lipids that oxidize and generate undesirable waxy or rancid off-flavors. Applying targeted plasma treatments could serve as a mitigation strategy to suppress these specific off-notes, thereby protecting the juice's sensory quality.

However, some challenges remain before this technology can be scaled up for commercial implementation. The current study utilized a static batch system; industrial adoption will require the design and validation of continuous-flow plasma reactors capable of handling high throughputs. Additionally, future research must evaluate the energy efficiency of these scaled-up systems and conduct shelf-life studies to ensure that the plasma-induced modifications to the aromatic profile remain stable throughout the product's commercial storage period.

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Author contributions E.E.B.: Investigation, Formal analysis, Writing – original draft; D.L.H.M.: Investigation, Formal analysis; S.R.: Writing – review & editing, Supervision, Resources; F.A.N.F.: Formal analysis, Methodology, Writing – review & editing.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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