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# Characterisation of Volatile Compounds Associated With the Flavour of Flatbreads: Effect of Sorghum, Cassava and Whole or Dehulled Red and White Cowpea Flours

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## ABSTRACT

This study characterised the volatile compounds in flatbreads prepared from red non-tannin sorghum flour, cassava starch, whole and dehulled red and white cowpea flours and composite flours (30% cowpea flour and varying combinations of cassava starch and sorghum flour). Compounds were extracted using solid-phase microextraction (SPME) and determined by GC-TOF-HRMS. A wheat flatbread was used as the standard. Compounds that were correlated with aroma and flavour attributes were identified. Volatile compound classes included hydrocarbons, aldehydes, alcohols, acids, esters, ketones, benzene derivatives, sulphur- and nitrogen-containing compounds, terpenes and terpenoids. Adding sorghum flour to the composite reduced the generation of aldehydes and contributed 2-methoxyphenol and 2-methoxy-4-vinylphenol to the flatbreads. The cassava starch presented acetic acid and aldehydes, which contributed to the fermented and green aroma of cassava–cowpea composite-flour flatbreads. The cowpea variety influenced the volatile profile of flatbread. The red cowpea flatbreads had more 1-octen-3-ol, phenylethyl alcohol and decane, different from the white cowpea flatbreads. Soaking and dehulling the cowpeas reduced flour hexanal levels while increasing 1-hexanol and 1-octen-3-ol in derived flatbreads. Cowpea flatbreads were characterised by pyrazines, with higher levels contributed by dehulled flour. The main compounds responsible for beany flavour were dimethyl trisulphide, hexanal, nonanal, 1-octen-3-ol, 2-pentylfuran, heptanal and 1-(2-furanyl)-2-butanone. Characterising the aroma compounds of flatbreads prepared from sorghum, cassava and cowpea flours offers valuable insights that manufacturers can apply to improve the sensory quality of bread products made from these flours to meet specific consumer demands and preferences and diversify bread flour options.

## 1 | Introduction

War and conflict situations in major wheat-producing areas have had drastic effects on wheat exports to sub-Saharan African (SSA) countries (Glauber 2023), while climate change is significantly

impairing wheat productivity. Heavy reliance on wheat imports by SSA countries and the high cost of wheat and wheat products necessitate research on bakery products from locally available crops, including sorghum, cassava and cowpea. However, these wheat alternatives introduce flavour challenges (Dankwa et al. 2021).

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Aroma is an important aspect of bread flavour influencing consumer acceptance (Dong and Karboune 2021; Pico et al. 2015). Volatile compounds (VCs) contribute to aroma, and their presence largely determines the flavour quality of products (Small et al. 1997; Spence 2021). Gas chromatography has been widely used to analyse VCs of bread. Fan et al. (2021) found a higher number of VCs and concentration of volatiles in cooked sorghum than in corresponding raw sorghum flour, signifying the effect of the cooking process on the formation of new compounds. Fan et al. (2021) also found that for boiled sorghum, some varieties (e.g., Bazley and Liberty) contained more VCs than others (Apollo, Buster, G44 and MR43). Flatbreads prepared from dehulled cowpea flours were described as nuttier than those from whole flours (Dankwa et al. 2021). The effect of dehulling of legume flours such as faba bean (Rajhi, Boulaaba, et al. 2022), pea (flour and cooked forms) (Azarnia et al. 2011) and lentil (Rajhi, Baccouri, et al. 2022) on VC profiles has been reported, but not yet in cowpeas. Rajhi, Boulaaba, et al. (2022) found that dehulling faba bean decreased levels of monoterpenes and increased levels of alcohols. Azarnia et al. (2011) reported reduced total area values of VCs in dehulled pea flour and its cooked form compared to cooked whole pea flour. The change in the composition of volatiles due to dehulling will most probably influence the overall flavour of food products where the flour is used.

Flours used in preparing bread are the key raw materials that contain VCs that influence the generation of the final bread aroma and flavour (Boeswetter et al. 2019; Pico, Bernal, and Gómez 2017). Khrisanapant et al. (2019) used headspace solid-phase microextraction gas chromatography-mass spectrometry (HS-SPME-GC-MS) and reported 80 VCs in raw cowpea, with hydrocarbons and ketones found in lower percentages than aldehydes and alcohols. Specifically, they found hexanal, 4-(1-methylethyl)-benzaldehyde and 1-hexanol to have high percentage (%) of relative abundance in cowpea. Nonetheless, there is no published research on VCs in cowpea-based bread nor on the effect of dehulling cowpea.

Lu et al. (2020), using an electronic nose, reported nitrogen oxides, sulphur compounds, ammonia, aromatics and alkanes in cassava flour short biscuits. The researchers, however, did not provide details on the individual compounds within the groups. Sayaslan et al. (2000) using GC reported high contents of hexanal, 2-ethyl-1-hexanol, 2-propanol and methylbenzene among aldehyde, alcohols and benzene compounds in cassava starch.

To prepare good-quality non-gluten-containing bread with similar sensory (good flavour and texture) and nutritional properties to wheat bread, several non-gluten-containing flours such as corn, rice, oat, teff, buckwheat, amaranth, quinoa and potato starch with different functionalities are typically employed (Beltrão Martins et al. 2022; Pico, Bernal, and Gómez 2017; Rybicka et al. 2019). Sorghum, cassava and cowpea flours provide a source of starch, protein, fats, minerals, fibre and phenolic compounds that will affect the generation of VCs and impart specific flavour to products, e.g., flatbreads prepared from the flour. VCs influencing the flavour of wheat bread products have been reported by several researchers (Gancarz et al. 2021; Hor et al. 2021; Pacyński et al. 2015; Pico, Martínez, et al. 2017).

Studying the volatile profiles of flatbreads prepared from other flours that can be used for breadmaking in African countries is important to determine the contributions of each flour to the aroma and flavour of the flatbread.

In previous research (Dankwa et al. 2021), sorghum, cassava and cowpea single flours were composited to prepare flatbreads with protein content close to wheat flour. Flatbread prepared from 100% sorghum was described by a trained sensory panel as having a prominent sorghum aroma and bitter taste. The study also reported differences in the beany aroma intensity of flatbreads prepared from whole and dehulled red and white cowpea varieties. The red cowpea flatbreads smelled less beany than the white cowpea flatbreads. From these results, it was hypothesised that the cowpea variety would affect the volatile compound composition of flatbread. This may provide insights on the more suitable variety of cowpeas for bakery product development. Published research on VC profiles of bread prepared from one or a combination of sorghum, cassava and cowpea flours is yet to be reported.

This study is, therefore, a follow-up research to characterise VCs in sorghum, cassava and whole and dehulled cowpea flatbreads prepared from single and composite flours using GC-TOF-HRMS with a view to relate the compounds to flavour and aroma properties of the flatbreads. Aroma influences consumer perception and acceptance of baked products. In cowpea-based breads, it is often the earliest sensory cue perceived after appearance, even before the food is tasted or chewed. Aroma significantly contributes to the overall flavour experience and comes primarily from VCs.

With no prior knowledge of the volatile composition of sorghum, cassava and cowpea flatbreads, untargeted analysis was performed to allow comprehensive characterisation of a broad range of compounds. The volatile profiles of composite-flour flatbreads were compared to those of wheat.

## 2 | Materials and Methods

### 2.1 | Materials

Similar to the previous study (Dankwa et al. 2021), red, non-tannin sorghum meal (King Korn super fine sorghum; Mabele, Tiger Consumer Brands Limited, Johannesburg, South Africa) of particle size 500 µm, white bread wheat flour (Premier FMCG Limited, Johannesburg, South Africa) and sunflower oil were obtained from a local supermarket (Shoprite, Pretoria, South Africa). The red non-tannin sorghum flour was utilised due to its commercial availability in the South African market and its superior protein digestibility compared to tannin sorghum (Waniska 2000). Sorghum flour with a particle size of 500 µm was obtained by sifting 100g of flour for 10 min in vibrating sieves with mesh sizes of 500, 250, 212, 180 and 150 µm stacked in descending order. Sorghum flour with a particle size of 500 µm has been found to reduce dry appearance and residual particles in sorghum flatbreads. Cassava starch was sourced from DADTCO (Dutch Agricultural Development and Trading Company, Inhambane, Mozambique). White cowpea seeds (Bechuana white variety) and red cowpea seeds (Glenda variety)

were sourced from Agrinawar Agricol Pty, Pretoria, South Africa. Dehulled cowpea flours were prepared as described by Dankwa et al. (2021). Whole cowpea seeds in 250-g batches were soaked, manually dehulled and dried for 7 h at 45°C in a forced-air convection oven to obtain the dehulled cowpea flours.

## 2.2 | Methods

### 2.2.1 | Preparation of Flatbread From Single Flours and Composite Flours

The procedures described by Dankwa et al. (2021) were employed in preparing the single flours, composite flours and their corresponding flatbreads. Flatbreads were prepared by measuring 20-mL bottled spring water into a pre-coded plastic cup. Ten grams of flour was added and mixed with a battery-operated handheld frother until a homogeneous batter was formed. A Teflon-coated pan was greased with 1.25-mL sunflower oil using a basting brush and heated on an induction stove (ZC-6C1, Snappy Chef Trading Limited, Pretoria, South Africa) at control level P3. The batter was restirred, and 7.5 mL was dispensed

into the marked area of the pan, cooked for 1 min per side and turned with a spatula and cooked for another minute on the opposite side.

Flatbreads (Table 1) prepared from seven single flours (wheat, sorghum, cassava starch, red and whole white cowpea, whole red cowpea, dehulled white cowpea and dehulled red cowpea flours) and 12 composite flours were analysed using GC-TOF-HRMS. The same batch of flour stored at -20°C used for the sensory characterisation study by Dankwa et al. (2021) was subsequently used for the volatile characterisation of the flatbreads.

### 2.2.2 | Extraction of VCs Using SPME Fibre Coated With Divinylbenzene/Carboxen/Polydimethylsiloxanes (DVB/CAR/PDMS) and GC-TOF-HRMS Analysis

The samples were prepared and analysed according to the procedure described by Adebo, Gbashi, et al. (2022). Briefly, flatbread samples (2.5 g) were weighed into 20-mL dark-amber headspace sampling vials. Extraction of the VCs from flatbreads

TABLE 1 | Description of flatbread samples used for GC-TOF-HRMS analysis.

Sample group and sample abbreviation	Description	Composition (%)
<b>Single flatbread</b>		
XFSorg <sup>f</sup>	Sorghum	100
CS <sup>f</sup>	Cassava starch	100
WRC <sup>f</sup>	Whole red cowpea	100
WWC <sup>f</sup>	Whole white cowpea	100
DRC <sup>f</sup>	Dehulled red cowpea	100
DWC <sup>f</sup>	Dehulled white cowpea	100
WH <sup>f</sup>	Wheat (reference)	100
<b>Sorghum and cowpea composite</b>		
XFSorg-WRC <sup>f</sup>	Sorghum–whole red cowpea	70:30
XFSorg-WWC <sup>f</sup>	Sorghum–whole white cowpea	70:30
XFSorg-DRC <sup>f</sup>	Sorghum–dehulled red cowpea	70:30
XFSorg-DWC <sup>f</sup>	Sorghum–dehulled white cowpea	70:30
<b>Sorghum, cassava and cowpea composite</b>		
XFSorg-CS-WRC <sup>f</sup>	Sorghum–cassava–whole red cowpea	35:35:30
XFSorg-CS-WWC <sup>f</sup>	Sorghum–cassava–whole white cowpea	35:35:30
XFSorg-CS-DRC <sup>f</sup>	Sorghum–cassava–dehulled red cowpea	35:35:30
XFSorg-CS-DWC <sup>f</sup>	Sorghum–cassava–dehulled white cowpea	35:35:30
<b>Cassava and cowpea composite</b>		
CS-WRC <sup>f</sup>	Cassava–whole red cowpea	70:30
CS-WWC <sup>f</sup>	Cassava–whole white cowpea	70:30
CS-DRC <sup>f</sup>	Cassava–dehulled red cowpea	70:30
CS-DWC <sup>f</sup>	Cassava–dehulled white cowpea	70:30

was performed using SPME fibre coated with 1-cm 50-/30- $\mu$ m DVB/CAR/PDMS (Supelco Inc., Bellefonte, PA).

The samples were heated at 40°C for 20 min with intermittent agitation on for 10 s and off for 1 s at 250 rpm. The fibre was exposed to the sample's headspace for 20 min at an injection penetration depth of 54 mm. The SPME device was transferred to the inlet port of the Pegasus GC-TOF-HRMS system (LECO Corporation, St Joseph, Michigan, USA), operating in high resolution and equipped with a Gerstel MPS multipurpose autosampler (Gerstel GmbH & Co. KG, Mülheim an der Ruhr, Germany) that directly sampled 1  $\mu$ L from the headspace using an air-tight heated syringe.

Volatiles were injected in a splitless mode using helium as the carrier gas, pumped at 1 mL/min and desorbed for 60 s. The VCs were separated on an Rxi-5ms column (30 m  $\times$  0.25 mm ID  $\times$  0.25  $\mu$ m, Restek, Bellefonte, USA). The inlet and transfer temperatures were 250°C and 225°C, respectively, and were programmed as described by Adebo, Gbashi, et al. (2022). The mass spectral data acquisition was 13 spectra/s, with a mass-to-charge ratio range of 30–350 m/z, an ion source temperature at 250°C and an electron ionisation set at 70 eV as recommended by the manufacturer. Flatbreads were analysed in triplicate, and empty vials were used as blanks. Quantification of the compounds was not done in this study. Gas chromatography with an electronic ionisation source at 70 eV uses high-energy electrons, which leads to the production of ion fragments that aid in the determination of the compounds using spectral libraries. Moreover, GC-HRTOF-MS is a highly sensitive equipment that can detect unknown compounds without standards, and so the contents of the compounds were based on their peak areas. A similar methodology has been used in studies by Adebo, Njobeh, et al. (2018) and Oladimeji and Adebo (2024).

### 2.2.3 | GC-TOF-HRMS Data Processing and Analysis

VCs were tentatively identified for the flatbread samples. The raw data obtained from the ChromaTOF-HRT software (LECO Corporation, St Joseph, Michigan, USA) were filtered using a signal-to-noise ratio (S/N) of 100 to identify the peaks (analytes) from the background noise. Compounds were identified by searching their mass spectral fragmentation with reference spectra in the mainlib, replib, Leco-Fiehn Rtx5 database of the National Institute of Standards and Technology (NIST) library on ChromaTOF-HRT and comparing their retention times (RTs) and similarity indexes. Compounds with a similarity match of less than 70% to the NIST library, unknown peaks and solvent peaks were excluded using the DataPrep Solutions software. Data obtained from the empty vial were directly subtracted using the same software. A total of 283 compounds was identified across all the samples, with 80 of them being associated with flavour or aroma characteristics from literature. VCs that occurred at least twice in the three replications were used in calculating the mean peak area.

### 2.2.4 | Statistical Analysis

VCs detected in flatbreads were classified according to their chemical families. The 80 VCs associated with flavour or

aroma characteristics were used in the analysis. The principal component analysis (PCA) of a Pearson correlation matrix of standardised VC mean peak areas of cowpea flatbreads and single-flour flatbreads was performed with XLSTAT 2022 (Lumivero, Denver, Colorado). The quantification of flavour compounds calculated based on peak areas and relative concentration has also been reported by Adebo, Njobeh, et al. (2018) and Kewuyemi et al. (2020).

In this study, a two-sample *t*-test at  $p < 0.05$  was used to compare specific compounds (decane, 1-octen-3-ol and phenylethyl alcohol) that significantly contribute to compound level differences between the two cowpea varieties. The relative percentage mean peak area of a compound to the total mean peak area of compounds was calculated for the VCs in wheat flatbread and composite-flour flatbreads.

Mean intensities for aroma properties (earthy aroma, sorghum aroma, beany aroma, green aroma, nutty aroma and fermented aroma) and flavour attributes (beany flavour, bitter flavour, nutty flavour and fermented flavour) obtained by a trained sensory panel and reported earlier (Dankwa et al. 2021) were correlated with the relative percentage mean peak area of VCs using partial least squares regression (PLSR) analysis. The predictors and response variables were centred and standardised, and the model was cross-validated using the jackknife (LOO) method in XLSTAT. Variable importance in the projection (VIP) values were used to identify VCs that contributed to discriminating the sensory characteristics of the composite-flour flatbreads. PLSR has been used in studies to predict the relationship between VCs and sensory attributes in food products (Álvarez et al. 2011; Heiniö et al. 2003; Juric et al. 2003). VIP values from PLSR were set at 0.8 (Chong and Jun 2005; Seisonen et al. 2016) to obtain good correlations.

## 3 | Results and Discussion

### 3.1 | VCs Identified in Wheat, Sorghum, Cassava and Cowpea Flatbreads

Table 2 presents the compounds in sorghum, cassava starch, cowpea and wheat flatbread models in order of RT and their chemical classes. The VCs include hydrocarbons (31), ketones (9), alcohols (21), esters (41), aldehydes (20), acids (6), terpene and terpenoids (5), benzene derivatives (15), furans (2), pyrazines (8), a vitamin (1), sulphur and nitrogen compounds (7) and miscellaneous compounds (45). The mass spectra of the identified VCs and chromatograms obtained for the flatbreads are provided as Supporting Information S1.

### 3.2 | Effect of Cowpea Variety and Dehulling on the Aroma Profiles of Cowpea Flatbreads

Forty-five compounds were detected only in the cowpea flatbreads. Table 3 lists the total mean peak area for each chemical class detected in the whole and dehulled red and white cowpea flatbreads.

The red cowpea flatbreads (WRC<sup>f</sup>, DRC<sup>f</sup>) had more hydrocarbons (Table 3), a higher number and level of alcohols and esters

**TABLE 2** | Compounds detected in sorghum, wheat, cassava, cowpea (whole and dehulled) flatbread models analysed by GC-TOF-HRMS indicating retention time and flavour description reported in literature.

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
<b>Hydrocarbons</b>							
1	Spiro [2,4] hepta-4,6-diene	C <sub>7</sub> H <sub>8</sub>	92.0622	65.0387, 91.0544	4.392		
2	Decane	C <sub>10</sub> H <sub>22</sub>	142.1716	57.0700, 71.0856, 85.1013	8.055	Fruity, sweet	A
3	Undecane	C <sub>11</sub> H <sub>24</sub>	156.1874	43.0544, 57.0701, 71.0856	8.055		
4	2,6-Dimethylnonane	C <sub>11</sub> H <sub>24</sub>	141.1637	43.0545, 57.0701, 71.0857	8.428		
5	2,5-Dimethylheptane	C <sub>9</sub> H <sub>20</sub>	113.1324	43.0544, 56.0623, 57.0701	8.550		
6	2,2,3,3-Tetramethylbutane	C <sub>8</sub> H <sub>18</sub>	113.1325	43.0545, 56.0623, 57.0701,	8.552		
7	2,2,4,15,17-Hexamethyl-7,12-bis(3,5-trimethylhexyl) octadecane	C <sub>42</sub> H <sub>86</sub>	264.1694	57.0700, 58.0734, 99.1166	8.553		
8	5,5-Dimethyl-1,3-heptadiene	C <sub>9</sub> H <sub>16</sub>	124.0883	41.0338, 67.0542, 95.0856	8.631		
9	2,2,4,4-Tetramethyloctane	C <sub>12</sub> H <sub>26</sub>	171.1743	41.0388, 56.0623, 57.0701	8.763		
10	cis-1-Methyl-3-(1-methylethenyl)cyclohexane	C <sub>10</sub> H <sub>18</sub>	138.1404	67.0544, 81.0700, 96.0935	9.048		
11	2,4-Dimethyldecane	C <sub>12</sub> H <sub>26</sub>	131.0763	43.0544, 57.0701, 85.1013	9.688		
12	1,9-Tetradecadiene	C <sub>14</sub> H <sub>26</sub>	192.9998	67.0543, 69.0770, 81.0699	9.929		
12	2-Butyl-1-decene	C <sub>14</sub> H <sub>28</sub>	219.0486	39.0232, 41.0388, 43.0544	9.930		
14	1-Methyl-1-cyclodecene	C <sub>11</sub> H <sub>20</sub>	152.1560	67.0543, 81.0699, 95.0877	10.190		
15	Pentylcyclohexane	C <sub>11</sub> H <sub>22</sub>	154.1715	41.0388, 55.0544, 83.0856	10.238		
16	Hexylcyclohexane	C <sub>12</sub> H <sub>24</sub>	168.1877	55.0544, 67.0544, 83.0856	10.238		
17	2,6-Dimethyldecane	C <sub>12</sub> H <sub>26</sub>	140.1559	41.0388, 43.0545, 57.0701	10.492		
18	5-Methylundecane	C <sub>12</sub> H <sub>26</sub>	170.2028	43.0545, 71.0856, 85.1013	10.492		
19	2-Methyldodecane	C <sub>13</sub> H <sub>28</sub>	153.1611	57.0701, 71.0856, 85.1013	10.612		
20	5-Methyl-6-methylenedecane	C <sub>12</sub> H <sub>24</sub>	168.1872	41.0388, 56.0623, 69.0700	10.679		
21	3-Methylundecane	C <sub>12</sub> H <sub>26</sub>	141.1635	43.0544, 57.0701, 71.0857	10.719		
22	Hexadecane	C <sub>16</sub> H <sub>34</sub>	170.2028	43.0545, 57.0701, 71.0857	11.103	Fruity, sweet, pine	A

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
23	2,6,10,14-Tetramethylheptadecane	C <sub>21</sub> H <sub>44</sub>	269.0048	43.0545, 57.0701, 71.0856	11.147		
24	Tridecane	C <sub>13</sub> H <sub>28</sub>	170.2029	98.1090, 99.1169, 112.1245	11.148	Alkane	C
25	2,6-Dimethylundecane	C <sub>13</sub> H <sub>28</sub>	169.1950	43.0544, 57.0700, 71.0856	11.352		
26	2,3,7-Trimethyloctane	C <sub>11</sub> H <sub>24</sub>	155.1791	43.0545, 57.0701, 71.0857	12.192		
27	Octylcyclohexane	C <sub>14</sub> H <sub>28</sub>	182.2026	41.0388, 55.0544, 83.0856	13.226		
26	2,6,10,15-Tetramethylheptadecane	C <sub>21</sub> H <sub>44</sub>	224.0136	43.0544, 57.0701, 71.0856	13.525		
29	Eicosane	C <sub>20</sub> H <sub>42</sub>	225.4080	43.0545, 57.0701, 71.0857	13.907	Fuel-like	E
30	Pentadecane	C <sub>15</sub> H <sub>32</sub>	219.0750	43.0544, 57.0701, 71.0857	13.908	Waxy, mild	F
31	(2S)-1,3,4,5,6,7-Hexahydro-1,1,5,5-tetramethyl-2H-2,4a-methanonaphthalene	C <sub>15</sub> H <sub>24</sub>	204.1873	41.0387, 133.1011, 161.1325	14.022		
<b>Ketones</b>							
32	1,1,1-Trifluoro-2-propanone	C <sub>3</sub> H <sub>3</sub> F <sub>3</sub> O	69.0879	43.0312, 32.0728, 69.0766,	2.875		
33	2-Heptanone	C <sub>7</sub> H <sub>14</sub> O	114.1039	43.0181, 58.0415, 71.0593	6.284	Fruity, soapy, cinnamon	A, G
34	2-Octanone	C <sub>8</sub> H <sub>16</sub> O	131.0709	43.0180, 58.0415, 71.0492	6.285	Soapy, fruity	G
35	1-Hepten-3-one	C <sub>7</sub> H <sub>12</sub> O	111.0805	55.0180, 70.0414, 27.0233	7.720	Geranium-like	H
36	3-Octanone	C <sub>8</sub> H <sub>16</sub> O	128.1196	57.0337, 43.0545, 71.0856	7.852	Buttery, mushroom	D
37	Dihydro-2-methyl-3(2H)-thiophenone	C <sub>5</sub> H <sub>8</sub> OS	116.0292	44.9794, 60.0029, 116.0292	7.910	Cabbage	I
38	2-Nonanone	C <sub>9</sub> H <sub>18</sub> O	142.1350	43.0181, 58.0415, 71.0492	9.535	Fruity	G
39	2-Decanone	C <sub>10</sub> H <sub>20</sub> O	137.1288	58.0415, 71.0493, 93.0698	9.536	Fatty, fruity, cheesy, peach-fermented, peach-like, fruity	K
40	3-(Hydroxymethyl)-2-nonanone	C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	142.1353	43.1080, 50.0415, 71.0492	9.537		
<b>Alcohols</b>							
41	Ethanol	C <sub>2</sub> H <sub>6</sub> O	46.0400	19.0682, 31.0808, 45.0796	2.582	Strong alcohol, medicinal	C

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
42	Cyclobutanol	C <sub>4</sub> H <sub>8</sub> O	69.0923	28.0662, 43.0794, 69.0940	2.741	Roasted	C
43	(R)-Oxiranemethanol	C <sub>3</sub> H <sub>6</sub> O <sub>2</sub>	44.0651	16.0403, 28.0138, 44.0791	2.848		
44	2-Methyl-3-butyne-2-ol	C <sub>5</sub> H <sub>8</sub> O	70.0773	17.0028, 43.0890, 69.0939	3.103		
45	2-Undecen-4-ol	C <sub>11</sub> H <sub>22</sub> O	132.9228	34.9955, 47.0493, 71.0492	4.857		
46	2,3-Butanediol	C <sub>4</sub> H <sub>10</sub> O <sub>2</sub>	90.0676	43.0181, 45.0337, 57.0337	4.888	Neutral smelling	G
47	2-(Methylthio)ethanol	C <sub>3</sub> H <sub>8</sub> OS	92.0292	46.9951, 61.0108, 92.0291	5.615	French bean	R
48	(E)-3-Hexen-1-ol	C <sub>6</sub> H <sub>12</sub> O	97.0652	41.0388, 55.0544, 67.0543	5.761	Green	L
49	4-Methyl-1-pentanol	C <sub>6</sub> H <sub>14</sub> O	84.0934	43.0544, 56.0622, 69.0700	5.951		
50	1-Hexanol	C <sub>6</sub> H <sub>14</sub> O	102.0466	29.0389, 43.0544, 56.0622	5.957	Ethereal, alcohol, green, grass, fruity, sweet alcohol	A, C
51	1-Heptanol	C <sub>7</sub> H <sub>16</sub> O	120.0934	68.0621, 69.0700, 70.0778	7.609	Green, fatty	E
52	1-Nonen-3-ol	C <sub>9</sub> H <sub>18</sub> O	131.1579	43.0544, 57.0337, 72.0570	7.746	Woody, mushroom,	M
53	1-Octen-3-ol	C <sub>8</sub> H <sub>16</sub> O	131.0854	41.0338, 57.0337, 72.0571	7.747	Mushroom-like	P
54	1-Hepten-3-ol	C <sub>7</sub> H <sub>14</sub> O	110.1092	41.0388, 57.0337, 72.0571	7.748	Oily, green, metallic	O
55	β-Methoxy-α-phenylphenethyl alcohol	C <sub>15</sub> H <sub>16</sub> O <sub>2</sub>	136.0874	94.0526, 121.0761, 122.0837	8.100		
56	Benzyl alcohol	C <sub>7</sub> H <sub>8</sub> O	108.0570	77.0387, 79.0543, 108.0570	8.706	Pleasant aromatic, fruity, balsamic	G, E
57	1-Phenyl-1,2-propanediol	C <sub>9</sub> H <sub>12</sub> O <sub>2</sub>	137.9900	77.0387, 79.0543, 108.0571	8.709		
58	1-Octanol	C <sub>8</sub> H <sub>18</sub> O	131.0669	41.0388, 56.0623, 69.0700	9.207	Vegetable, earthy, mouldy	P
59	(5-Ethylcyclopent-1-enyl)methanol	C <sub>8</sub> H <sub>14</sub> O	126.1038	79.0543, 95.0856, 97.0648	9.340		
60	(E)-2-Hexen-1-ol	C <sub>6</sub> H <sub>12</sub> O	100.1168	43.0545, 67.0543, 82.0778	9.639	Floral, fruity, green, grassy, sweet	K
61	Phenylethyl alcohol	C <sub>8</sub> H <sub>10</sub> O	122.0727	65.0387, 91.0543, 92.0621	9.966	Rose, honey-like	G
<b>Esters</b>							
62	Ethenyl formate	C <sub>3</sub> H <sub>4</sub> O <sub>2</sub>	46.0365	20.5364, 43.0834, 44.0678	2.711		

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
63	Ethyl trifluoroacetate	C <sub>4</sub> H <sub>5</sub> F <sub>3</sub> O <sub>2</sub>	69.0843	31.0804, 43.0835, 62.0636	2.780		
64	Tridec-2-ynyl cyclopropanecarboxylate	C <sub>17</sub> H <sub>28</sub> O <sub>2</sub>	69.0942	18.0700, 43.0073, 69.0768	3.270		
65	Octyl phenyl carbonate	C <sub>15</sub> H <sub>22</sub> O <sub>3</sub>	94.0527	41.0262, 53.0262, 66.0338	5.304		
66	1,4-Diacetoxy-trans-2-butene	C <sub>8</sub> H <sub>12</sub> O <sub>4</sub>	131.1090	43.0181, 61.0286, 70.0778	6.053		
67	Ethyl 2-(benzyl amino)-2-(2-chloroacetamido)-3,3,3-trifluoropropionate	C <sub>14</sub> H <sub>16</sub> ClF <sub>3</sub> N <sub>2</sub> O <sub>3</sub>	223.6552	91.0543, 92.0577, 106.0778	6.226		
68	1,3-Propanediol, 2-methyl-dipropionate	C <sub>10</sub> H <sub>18</sub> O <sub>4</sub>	219.0250	57.0337, 75.0442, 109.0886	6.561		
69	Ethyl acetate	C <sub>4</sub> H <sub>8</sub> O <sub>2</sub>	87.0441	42.0466, 43.0180, 70.0778	6.653	Sweet, fruity, pineapple	G
70	Pentyl acetate	C <sub>7</sub> H <sub>14</sub> O <sub>2</sub>	131.0547	42.0466, 43.0181, 70.0078	6.656	Fresh banana	G
71	Ethyl 3-hydroxybutanoate	C <sub>6</sub> H <sub>12</sub> O <sub>3</sub>	131.1298	43.0180, 60.0207, 71.0128	7.063	Fruity, green, grape, winey	R
72	S-Methyl 3-methylbutanethioate	C <sub>6</sub> H <sub>12</sub> OS	132.0827	29.0390, 57.0701, 85.0649	7.103	Cheesy, dairy, creamy, fermented	Q
73	3-Methylbutyl propanoate	C <sub>8</sub> H <sub>16</sub> O <sub>2</sub>	135.0115	43.0545, 53.0337, 70.0778	7.563		
74	1,5-Pentanediol, O, O'-di(3-methylbut-2-enyl)	C <sub>15</sub> H <sub>24</sub> O <sub>4</sub>	265.9949	82.0778, 83.0856, 97.1013	7.825		
75	4-Hexen-1-ol acetate	C <sub>8</sub> H <sub>14</sub> O <sub>2</sub>	131.1061	43.0180, 67.0543, 82.0777	8.169		
76	(E)-2-Hexen-1-ol acetate	C <sub>8</sub> H <sub>14</sub> O <sub>2</sub>	137.1277	43.0181, 67.0543, 82.0778	8.170		
77	Hexyl acetate	C <sub>8</sub> H <sub>16</sub> O <sub>2</sub>	131.1139	43.0180, 56.0622, 84.0934	8.266	Fruity, spicy, herbal	P
78	Ethyl 2-chloro-3,3-trifluoro-2-propionamidopropionate	C <sub>8</sub> H <sub>11</sub> ClF <sub>3</sub> NO <sub>3</sub>	219.1604	56.0622, 57.0701, 99.1170	8.555		
79	Propane-1,1-diol dipropionate	C <sub>9</sub> H <sub>16</sub> O <sub>4</sub>	219.0955	57.0700, 59.0493, 115.1117	8.614		
80	Butanoic acid, 2-oxo-, methyl ester	C <sub>5</sub> H <sub>8</sub> O <sub>3</sub>	116.1152	57.0701, 59.0493, 115.1118	8.616		
81	Sulfurous acid, dibutyl ester	C <sub>8</sub> H <sub>18</sub> O <sub>3</sub> S	171.1742	41.0388, 56.0623, 57.0700	8.764		
82	Propanoic acid, 2-methyl-, pentyl ester	C <sub>9</sub> H <sub>18</sub> O <sub>2</sub>	131.1385	43.0544, 71.0492, 89.0597	8.859		

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
83	Oxalic acid, isohexyl neopentyl ester	C <sub>13</sub> H <sub>24</sub> O <sub>4</sub>	131.1242	43.0544, 57.0701, 71.0856	8.992		
84	1,6-Octadien-3-ol, 3,7-dimethyl formate	C <sub>11</sub> H <sub>18</sub> O <sub>2</sub>	139.1488	41.0388, 71.0492, 93.0701	9.680		
85	Linyl acetate	C <sub>12</sub> H <sub>20</sub> O <sub>2</sub>	142.9910	41.0388, 69.0700, 93.0699	9.680	Sweet, green, citrus	J
86	Hexyl propanoate	C <sub>9</sub> H <sub>18</sub> O <sub>2</sub>	137.1322	57.0337, 57.0442, 69.0700	9.723	Pear green, fruity, musty, overripe fruit	Q
87	Heptyl acetate	C <sub>9</sub> H <sub>18</sub> O <sub>2</sub>	134.9221	18.0426, 43.0181, 70.0078	9.825		
88	(Z)-4-Hexen-1-yl butanoate	C <sub>10</sub> H <sub>18</sub> O <sub>2</sub>	162.9973	43.0545, 67.0544, 82.0778	10.311		
89	Propanoic acid, 2-methyl-, 2-methylpentyl ester	C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	141.1634	57.0701, 69.0701, 71.0493	10.376		
90	Propanoic acid, 2-methyl-, hexyl ester	C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	168.1869	43.0544, 71.0492, 89.0598	10.378		
91	Benzyl acetate	C <sub>9</sub> H <sub>10</sub> O <sub>2</sub>	150.0676	43.0181, 91.0543, 108.0571	10.679	Floral, sweet	S
92	Decanoic acid, phenylmethyl ester	C <sub>17</sub> H <sub>26</sub> O <sub>2</sub>	151.0741	56.0622, 91.0543, 108.0571	10.679		
93	Ethyl octanoate	C <sub>10</sub> H <sub>20</sub> O <sub>2</sub>	129.0909	60.0209, 88.0598, 101.0598	11.104	Pineapple, apple	E
94	2-Phenylethyl acetate	C <sub>10</sub> H <sub>12</sub> O <sub>2</sub>	131.1222	43.0180, 91.0541, 104.0622	12.037	Floral, rose, honey	E
95	Propanoic acid, 2-methyl-, phenylmethyl ester	C <sub>11</sub> H <sub>14</sub> O <sub>2</sub>	178.0990	65.0387, 91.0543, 108.0571	12.607		
96	Pentanoic acid, 2,2,4-trimethyl-3-hydroxy-, isobutyl ester	C <sub>12</sub> H <sub>24</sub> O <sub>3</sub>	219.0247	43.0544, 55.0544, 71.0492	13.422		
97	Pentanoic acid, 2,2,4-trimethyl-3-carboxyisopropyl, isobutyl ester	C <sub>16</sub> H <sub>30</sub> O <sub>4</sub>	271.4759	43.0545, 55.0545, 71.0493	16.434		
98	Butanoic acid, 2,3-dihydroxypropyl ester	C <sub>7</sub> H <sub>14</sub> O <sub>4</sub>	155.1070	43.0545, 71.0493, 131.1017	16.435		
99	Dichloroacetic acid, 2-ethylhexyl ester	C <sub>10</sub> H <sub>18</sub> Cl <sub>2</sub> O <sub>2</sub>	225.5074	41.0388, 70.0778, 83.0856	18.694		
100	2-Ethylhexyldecanoate	C <sub>18</sub> H <sub>36</sub> O <sub>2</sub>	225.8385	41.0388, 57.0701, 70.0778,	18.694		
101	2-Methylbutyllaurate	C <sub>17</sub> H <sub>34</sub> O <sub>2</sub>	227.3017	43.0544, 57.0701, 70.0778	18.694		

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
102	Dodecanoic acid, isooctyl ester	C <sub>20</sub> H <sub>40</sub> O <sub>2</sub>	201.1844	43.0544, 57.0700, 70.0778	18.703		
<b>Aldehydes</b>							
103	Methyl glyoxal	C <sub>3</sub> H <sub>4</sub> O <sub>2</sub>	74.0727	28.0058, 31.9694, 43.0179	2.647		
104	Acetaldehyde	C <sub>2</sub> H <sub>4</sub> O	44.0389	31.0598, 44.0773, 69.0716	2.663	Fruity	G
105	Hexanal	C <sub>6</sub> H <sub>12</sub> O	101.0959	44.0259, 56.0622, 72.0571	4.842	Green, grassy,	G, B
106	2-Hexenal	C <sub>6</sub> H <sub>10</sub> O	98.0727	41.0388, 69.0336, 83.0492	5.687	Green, banana, cheesy, fatty	Q, T
107	Heptanal	C <sub>7</sub> H <sub>14</sub> O	131.0842	29.0389, 44.0259, 70.0778	6.446	Green, vegetable, rancid, aldehydic fatty, malty	O
108	(Z)-2-Heptenal	C <sub>7</sub> H <sub>12</sub> O	111.0805	41.0388, 55.0544, 83.0492	7.369	Fatty, green, fresh	U
109	Benzaldehyde	C <sub>7</sub> H <sub>6</sub> O	106.0414	51.0232, 77.0386, 105.0336	7.490	Bitter almond, sweet, nutty almond, caramel	G, O
110	Octanal	C <sub>8</sub> H <sub>16</sub> O	131.0647	58.0370, 58.0444, 58.0734	8.111	Citrus-like, green, flowery	O
111	Benzeneacetaldehyde	C <sub>8</sub> H <sub>8</sub> O	120.0570	65.0387, 91.0544, 12.0571	8.826	Honey-like	O
112	(E)-2-Octenal	C <sub>8</sub> H <sub>14</sub> O	125.0953	29.0389, 41.0388, 55.0544	9.014	Fatty, roasted, nutty	G
113	Nonanal	C <sub>9</sub> H <sub>18</sub> O	148.1248	41.0388, 56.0622, 57.0701	9.724	Waxy, green fatty, citrus, soapy	O
114	2,4-Dihydroxybenzaldehyde, 2TMS derivative	C <sub>13</sub> H <sub>22</sub> O <sub>3</sub> Si <sub>2</sub>	283.0304	125.9879, 250.9677, 266.9981	9.792		
115	2,5-Dihydroxybenzaldehyde, 2TMS derivative	C <sub>13</sub> H <sub>22</sub> O <sub>3</sub> Si <sub>2</sub>	283.0302	125.9879, 250.9677, 266.9989	9.794		
116	Decanal	C <sub>10</sub> H <sub>20</sub> O	145.9950	41.0388, 55.0544, 70.0778	11.256	Citrus	G
117	(E)-2-Nonenal	C <sub>9</sub> H <sub>16</sub> O	148.1245	41.0388, 55.0544, 70.0414	10.585	Green, tallow, fatty, cucumber	G, T
118	(Z)-2-Decenal	C <sub>10</sub> H <sub>18</sub> O	146.0722	41.0388, 55.0544, 85.0285	12.076	Citrusy, lemon, sour, rancid	P, X
119	(E)-2-Decenal	C <sub>10</sub> H <sub>18</sub> O	136.1240	41.0388, 55.0544, 85.0285	12.077	Metallic, geranium	X

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
120	2,4-Decadienal	C <sub>10</sub> H <sub>16</sub> O	152.1195	39.0231, 41.0388, 53.0387	12.634	Strong, fatty	A
121	( <i>E,E</i> )-2,4-Decadienal	C <sub>10</sub> H <sub>16</sub> O	152.1195	39.0231, 41.0387, 55.0544	12.812	Deep-fried, fatty	A, G, u
122	2,6,6-Trimethylcyclohexa-1,4-dienecarbaldehyde	C <sub>10</sub> H <sub>14</sub> O	150.1041	39.0232, 41.0388, 51.0232	12.933		
<b>Acids</b>							
123	[(Aminocarbonyl)amino] (oxo)acetic acid	C <sub>3</sub> H <sub>4</sub> N <sub>2</sub> O <sub>4</sub>	76.9451	31.0472, 44.0607, 69.0561	2.737		
124	Acetic acid	C <sub>2</sub> H <sub>4</sub> O <sub>2</sub>	60.0207	15.0235, 44.9972, 60.0207	2.995	Sour, pungent	O
125	3-Methylbutanoic acid	C <sub>5</sub> H <sub>10</sub> O <sub>2</sub>	87.0441	29.0389, 43.0545, 60.0208	5.623	Cheesy, dairy, creamy, sweaty	G, J
126	Heptanoic acid	C <sub>7</sub> H <sub>14</sub> O <sub>2</sub>	131.0745	43.0181, 58.0415, 128.0620	7.796	Rancid, fatty, sour, cheesy	T
127	Hexanoic acid	C <sub>6</sub> H <sub>12</sub> O <sub>2</sub>	107.0489	60.0207, 73.0285, 87.0442	7.805	Sweaty, fatty, sour, pungent, cheesy, fruity	G
128	Pentanoic acid	C <sub>5</sub> H <sub>10</sub> O <sub>2</sub>	89.0599	41.0892, 60.0207, 73.0285	7.809	Cheesy, sweaty, sour	P, W, T
<b>Terpene and terpenoids</b>							
129	( <i>S</i> )-1-Methyl-4-(1-methylethenyl)cyclohexene (L-limonene)	C <sub>10</sub> H <sub>16</sub>	136.1247	68.0621, 79.0542, 93.0699	8.584	Lemon-note, terpenic	Q
130	D-Limonene	C <sub>10</sub> H <sub>16</sub>	136.1247	68.0621, 79.0542, 93.0699	8.587	Fresh- citrus, orange-note	Q
131	<i>p</i> -Cymene	C <sub>10</sub> H <sub>14</sub>	134.1091	91.0543, 119.0855, 134.1091	8.754	Citrus	G
132	<i>m</i> -Cymene (Benzene, 1-methyl-3-(1-methylethyl))	C <sub>10</sub> H <sub>14</sub>	134.1091	91.0543, 119.0856, 134.1091	8.512	Citrus	G
133	$\beta$ -Caryophyllene	C <sub>15</sub> H <sub>24</sub>	190.1675	41.0388, 69.0700, 91.0543	14.396	Spicy, peppery, woody, hop	J
<b>Vitamin</b>							
134	<i>dl</i> -7-Azatryptophan	C <sub>10</sub> H <sub>11</sub> N <sub>3</sub> O <sub>2</sub>	131.1295	17.0260, 74.0180, 131.0747	6.965		
<b>Benzene derivatives</b>							

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
135	Toluene	C <sub>7</sub> H <sub>8</sub>	92.0621	51.0231, 91.0543, 92.0621	4.393	Benzene-like, painty	A, W
136	1-Ethyl-2-methylbenzene	C <sub>9</sub> H <sub>12</sub>	120.0935	17.0283, 105.0699, 120.0935	7.491		
137	1,2,3-Trimethylbenzene	C <sub>9</sub> H <sub>12</sub>	120.0934	77.0386, 105.0699, 120.0934	8.015		
138	1,2-Dichlorobenzene	C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub>	145.9685	75.0231, 110.9997, 145.9686	8.331		
139	1,4-Dichlorobenzene	C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub>	145.9685	75.0230, 110.9997, 145.9686	8.331		
140	1,3-Dichlorobenzene	C <sub>6</sub> H <sub>4</sub> Cl <sub>2</sub>	145.9685	75.0229, 110.9997, 145.9686	8.332		
141	1-Ethyl-2,4-dimethylbenzene	C <sub>10</sub> H <sub>14</sub>	134.1091	91.0543, 119.0857, 134.1091	9.353		
142	2-Methoxyphenol	C <sub>7</sub> H <sub>8</sub> O <sub>2</sub>	124.0520	81.0334, 109.0285, 124.0520	9.564	Sweet, medicinal	B
143	2-Methyldecalin	C <sub>11</sub> H <sub>20</sub>	152.1560	95.0856, 96.0935, 109.1013	9.928		
144	<i>trans</i> -4a-Methyl-decahydronaphthalene	C <sub>11</sub> H <sub>20</sub>	152.1560	95.0856, 96.0935, 109.1013	10.189		
145	2,6-Dimethyldecahydronaphthalene	C <sub>12</sub> H <sub>22</sub>	166.1717	67.0543, 81.0700, 95.0857	10.803		
146	Naphthalene	C <sub>10</sub> H <sub>8</sub>	128.0621	58.0414, 69.0602, 102.0464	11.077	Medical, musty, rubber	W
147	4-Ethyl-2-methoxyphenol	C <sub>9</sub> H <sub>12</sub> O <sub>2</sub>	152.0832	122.0363, 137.0597, 152.0832	12.381	Spice, clove-like	B
148	2-Methoxy-4-vinylphenol	C <sub>9</sub> H <sub>10</sub> O <sub>2</sub>	150.0676	77.0385, 135.0440, 150.0676	12.877	Spicy, clove-like, curry, cedar	A, B, W
149	2,6-Bis(1,1-dimethylethyl)-4-(1-oxopropyl)phenol	C <sub>17</sub> H <sub>26</sub> O <sub>2</sub>	262.2290	57.0701, 131.1537, 233.1901	16.895		
<b>Sulfur and nitrogen</b>							
150	2- <i>n</i> -Propylaziridine	C <sub>5</sub> H <sub>11</sub> N	132.9228	41.0388, 56.0623, 70.0778	4.857		
151	Dimethyl trisulphide	C <sub>2</sub> H <sub>6</sub> S <sub>3</sub>	125.9627	44.9794, 78.9670, 125.9627	7.64	Cooked cabbage-like	G, S
152	4-Methylthiazole	C <sub>4</sub> H <sub>5</sub> NS	99.0806	29.0390, 71.0856, 99.0805	7.852	Roasted beef	I
153	Sulfone, 2-hydroxybutyl <i>t</i> -butyl	C <sub>8</sub> H <sub>18</sub> O <sub>3</sub> S	192.9856	41.0388, 57.0701, 59.0493	8.764		
154	Sulfone, 2-hydroxyoctyl <i>t</i> -butyl	C <sub>12</sub> H <sub>26</sub> O <sub>3</sub> S	268.9810	57.0701, 70.0779, 83.0856	8.55		
155	1,2-Benzisothiazole	C <sub>7</sub> H <sub>5</sub> NS	135.0137	68.9793, 108.0028, 135.0137	11.695		

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
156	Benzothiazole	C <sub>7</sub> H <sub>5</sub> NS	135.0138	68.9794, 108.0030, 135.0138	11.695	Sulphury, rubbery, coffee-like odour, vegetable, meaty flavour	V, W, Q
<b>Furans</b>							
157	1-(2-Furanyl)-2-butanone	C <sub>8</sub> H <sub>10</sub> O <sub>2</sub>	138.1040	39.0232, 41.0388, 43.05445	7.939	Rum-like, sweet, floral, caramelised	Q, Y
158	2-Pentylfuran	C <sub>9</sub> H <sub>14</sub> O	138.1040	53.0386, 57.0701, 81.0335	7.939	Green bean, grassy, earthy, raw nuts, buttery	E, U, G
<b>Pyrazines</b>							
159	Methylpyrazine	C <sub>5</sub> H <sub>6</sub> N <sub>2</sub>	94.0527	39.0231, 67.0417, 94.0527	5.294	Roasted, popcorn	P
160	2,5-Dimethylpyrazine	C <sub>6</sub> H <sub>8</sub> N <sub>2</sub>	108.0683	42.0341, 81.0573, 108.0683	6.725	Crust-like, popcorn	P
161	2-Ethyl-6-methylpyrazine	C <sub>7</sub> H <sub>10</sub> N <sub>2</sub>	122.0839	56.0496, 94.0527, 121.0761	8.096	Nutty	P
162	Trimethylpyrazine	C <sub>7</sub> H <sub>10</sub> N <sub>2</sub>	122.0839	42.0340, 81.0574, 122.0839	8.19	Burnt	P
163	2-Ethyl-3-methylpyrazine	C <sub>7</sub> H <sub>10</sub> N <sub>2</sub>	122.0839	42.0341, 80.0495, 122.0839	8.203	Roasted, nutty, sweet, earthy	P
164	3-Ethyl-2,5-dimethylpyrazine	C <sub>8</sub> H <sub>12</sub> N <sub>2</sub>	136.0995	42.0341, 107.0605, 135.0918	9.39	Baked potato, earthy	P
165	2,6-Diethylpyrazine	C <sub>8</sub> H <sub>12</sub> N <sub>2</sub>	136.0994	42.0340, 119.0854, 135.0918	9.392	Green, spicy	P
166	2-Isoamyl-6-methylpyrazine	C <sub>10</sub> H <sub>16</sub> N <sub>2</sub>	164.1429	107.0604, 108.0683, 121.0761	11.962	Rubbery, sweet, meaty	P
<b>Miscellaneous</b>							
167	Hydroxyurea	CH <sub>4</sub> N <sub>2</sub> O <sub>2</sub>	44.0912	17.0143, 43.0867, 44.0886	2.675		
168	Glycidol	C <sub>3</sub> H <sub>6</sub> O <sub>2</sub>	45.0927	16.0265, 31.0657, 44.0457	2.698		
169	Methylsilane	CH <sub>6</sub> Si	46.0882	19.9813, 31.0658, 44.0807	2.756		
170	Fluoroethyne	C <sub>2</sub> HF	44.0388	16.0093, 28.0785, 44.0349	2.757		
171	2,2,2-Trifluoroacetamide	C <sub>2</sub> H <sub>2</sub> F <sub>3</sub> NO	69.0752	28.0566, 44.0770, 69.0615	2.872		
172	Dinocap	C <sub>10</sub> H <sub>9</sub> NO <sub>4</sub>	69.1162	18.0427, 43.0496, 45.0881	2.954		
173	Tris(trifluoromethyl)phosphine	C <sub>3</sub> F <sub>9</sub> P	219.1687	28.0566, 69.0568, 131.0882	2.982		

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
174	3-Fluoro-2-propynenitrile	C <sub>3</sub> FN	69.0552	17.0500, 69.0644, 69.1232	3.039		
175	1,2-Dimethylhydrazine	C <sub>2</sub> H <sub>8</sub> N <sub>2</sub>	60.0341	15.0236, 44.9973, 60.0208,	3.046		
176	Dimethylsilanediol	C <sub>2</sub> H <sub>8</sub> O <sub>2</sub> Si	92.0289	44.9793, 77.0054, 79.0023	3.808		
177	4-(2-Acetoxyphenyl)-1-ethyl-3-methyl-5-(4-nitrophenyl) pyrazole	C <sub>20</sub> H <sub>19</sub> N <sub>3</sub> O <sub>4</sub>	86.0363	43.0181, 45.0229, 28.0618	3.896		
178	2,2-Dichloroethyl methyl ether	C <sub>3</sub> H <sub>6</sub> Cl <sub>2</sub> O	132.0547	16.0314, 17.0205, 45.0337	4.722		
179	6-(4-Chlorophenyl) tetrahydro-2-methyl-2H-1,2-oxazine	C <sub>11</sub> H <sub>14</sub> ClNO	131.0640	43.0885, 45.0656, 45.5269	5.645		
180	Cyprodinil	C <sub>14</sub> H <sub>15</sub> N <sub>3</sub>	225.2530	17.0277, 69.0453, 223.6582	6.141		
181	4-(2,2-Dimethylpropanoate)-1,3,5-trideoxy-3-nitro- <i>d</i> -Xylitol	C <sub>10</sub> H <sub>19</sub> NO <sub>5</sub>	107.0730	57.0701, 84.0933, 85.1013	6.416		
182	Dipivefrine, N,O-bis (pentafluoropropionyl)	C <sub>25</sub> H <sub>27</sub> F <sub>10</sub> NO <sub>7</sub>	99.1169	57.0701, 84.0933, 85.1013	6.424		
183	Methoxyphenyl-oxime	C <sub>8</sub> H <sub>9</sub> NO <sub>2</sub>	151.0241	77.0053, 133.0135, 151.0241	6.576		
184	Phosphorus pentafluoride	F <sub>5</sub> P	131.1297	53.0261, 80.0370, 107.0605	6.745		
185	Ethanesulphonyl fluoride	C <sub>2</sub> H <sub>5</sub> FO <sub>2</sub> S	131.0802	18.0273, 54.0339, 67.0417	6.817		
186	4-Trimethylsilyloxybenzoic anhydride	C <sub>20</sub> H <sub>26</sub> O <sub>5</sub> Si <sub>2</sub>	211.0090	71.0856, 192.9803, 209.0116	7.333		
187	3-Trimethylsilyloxybenzoic anhydride	C <sub>20</sub> H <sub>26</sub> O <sub>5</sub> Si <sub>2</sub>	268.9817	96.9938, 192.9804, 209.0115	7.333		
188	1,1'-Oxybis hexane	C <sub>12</sub> H <sub>26</sub> O	219.1115	43.0545, 56.0623, 85.1013	7.404		
189	Succinic anhydride	C <sub>4</sub> H <sub>4</sub> O <sub>3</sub>	104.0621	31.0181, 56.0622, 88.0934	7.615		
190	Tris( <i>tert</i> -butyldimethylsilyloxy)arsane	C <sub>18</sub> H <sub>45</sub> AsO <sub>3</sub> Si <sub>3</sub>	230.1591	88.9511, 96.5044, 97.0029	7.704		
191	1-[6,8-Dichloro-2-phenyl-4-quinoly] hexahydro-3H-oxazolo[3,4- <i>a</i> ] pyridine	C <sub>22</sub> H <sub>20</sub> Cl <sub>2</sub> N <sub>2</sub> O	270.6437	83.0856, 96.0934, 97.1013	7.824		
192	Octamethylcyclotetrasiloxane	C <sub>8</sub> H <sub>24</sub> O <sub>4</sub> Si <sub>4</sub>	285.0466	248.9888, 265.0200, 281.0512	7.975		

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
193	1,1,1,5,5,5-Hexamethyl-3[(trimethylsilyl)oxy]-trisiloxane	C <sub>9</sub> H <sub>28</sub> O <sub>3</sub> Si <sub>4</sub>	285.0467	248.9886, 265.0200, 281.0512	7.975		
194	Pyrrrole, 2-(4-methyl-5-cis-phenyl-1,3-oxazolidin-2-yl)	C <sub>14</sub> H <sub>16</sub> N <sub>2</sub> O	266.9988	44.0258, 94.0526, 121.0761	8.103		
195	Phosphinothioic fluoride, (1,1-dimethylethyl)(pentafluorophenyl)	C <sub>10</sub> H <sub>9</sub> F <sub>6</sub> PS	223.6675	57.0700, 99.1169, 113.1325	8.552		
196	1-(1,1-Dimethylethoxy)-2-methylpropane	C <sub>8</sub> H <sub>18</sub> O	131.107	57.0701, 59.043, 115.1117	8.614		
197	1-(1,1-Dimethylethoxy)-2,2-dimethylpropane	C <sub>9</sub> H <sub>20</sub> O	136.9853	41.0388, 56.0622, 57.0701	8.764		
198	Di- <i>tert</i> -butyl dicarbonate	C <sub>10</sub> H <sub>18</sub> O <sub>5</sub>	172.1778	41.0388, 56.0623, 57.0700	8.765		
199	Ether, 2-ethylhexyl <i>tert</i> -butyl	C <sub>12</sub> H <sub>26</sub> O	172.1776	56.0623, 57.0700, 59.0493	8.765		
200	Hexamethylcyclotrisiloxane	C <sub>6</sub> H <sub>18</sub> O <sub>3</sub> Si <sub>3</sub>	219.1611	133.0136, 191.0011, 207.0324	9.278		
201	1,1,1,2,3,3,4,4,4-Nonafluoro-2-(trifluoromethyl)butane	C <sub>5</sub> F <sub>12</sub>	131.182	17.0276, 69.1064, 131.1376	9.315		
202	Butan-1-one, 4-chloro-1-(1,2,3,4,4a,9b-hexahydro-2,8-dimethylpyridol[4,3- <i>bj</i> ]indol-5-yl)	C <sub>17</sub> H <sub>23</sub> ClN <sub>2</sub> O	223.6215	43.0180, 58.0415, 71.0492	9.535		
203	Decamethylcyclopentasiloxane	C <sub>10</sub> H <sub>30</sub> O <sub>5</sub> Si <sub>5</sub>	359.066	73.0469, 266.9992, 355.0699	10.417		
204	1,1,1,5,5,5-Hexamethyl-3,3-bis[(trimethylsilyl)oxy] trisiloxane	C <sub>12</sub> H <sub>36</sub> O <sub>4</sub> Si <sub>5</sub>	283.049	73.0469, 147.0658, 281.0551	11.721		
205	<i>N,N</i> -Dibutylformamide	C <sub>9</sub> H <sub>19</sub> NO	128.107	44.0497, 72.0444, 114.0914	12.718		
206	Dodecamethylcyclohexasiloxane	C <sub>12</sub> H <sub>36</sub> O <sub>6</sub> Si <sub>6</sub>	434.0855	73.0468, 147.0657, 341.0182	12.890		
207	3,5-Diisopropoxy-1,1,1,7,7,7-hexamethyl-3,5-bis(trimethylsiloxy)tetrasiloxane	C <sub>18</sub> H <sub>50</sub> O <sub>7</sub> Si <sub>6</sub>	415.0352	73.0468, 324.9648, 326.9656	13.930		
208	3-Isopropoxy-1,1,1,7,7,7-hexamethyl-3,5,5-tris(trimethylsiloxy)tetrasiloxane	C <sub>18</sub> H <sub>52</sub> O <sub>7</sub> Si <sub>7</sub>	506.1059	73.0468, 147.0657, 281.0513	15.127		

(Continues)

TABLE 2 | (Continued)

No.	Compound and chemical class	Molecular formula	Observed ion (m/z)	Fragments (m/z)	RT (min)	Flavour or aroma description	Reference
209	Hexadecamethylcyclooctasiloxane	C <sub>16</sub> H <sub>48</sub> O <sub>8</sub> Si <sub>8</sub>	415.0363	73.0469, 147.0657, 355.0700	17.127		
210	Tris(trifluoromethyl) bromomethane	C <sub>4</sub> BrF <sub>9</sub>	131.1137	17.0340, 28.0310, 69.0642	17.913		
211	1,1,1,2,3,3,3-Heptafluoro-2-methoxypropane	C <sub>4</sub> H <sub>3</sub> F <sub>7</sub> O	131.1287	28.0491, 69.0593, 131.0617	18.997		

Note: m/z = mass-charge-ratio; Letters in Table 4.2.2 correspond to references found in literature. A = (Pico, Hansen, and Petersen 2017); B = (Jia et al. 2019); C = (Galoburda et al. 2020); D = (Cho et al. 2006); E = (Ali et al. 2022); F = (Hinge et al. 2016); G = (Pico et al. 2015); H = (Buettnner and Schiebert 1999); I = (X. Xu, Yu, et al. 2021); J = (Adebo, Njobeh, et al. 2018); K = (Derrail et al. 1999); L = (Morales and Aparicio 1999); M = (Sohail et al. 2022); N = (Lindsay et al. 2022); O = (De Luca et al. 2021); P = (Paraskevopoulou et al. 2012); Q = <http://www.thegoodscentscompany.com>; R = (Ye et al. 2016); S = (Fang and Qian 2005); T = (Song et al. 2019); U = (Bento-Silva et al. 2021); V = (Huang et al. 2022); W = (Fan et al. 2021); X = (Jiang et al. 2021); Y = (Laukaleja and Koppel 2021).

compared to the white cowpea flatbreads (Table 3). The peak area of ketones, furans, terpenes and terpenoids was larger for the red than for the white cowpea flatbreads. The terpenes and terpenoids are plant metabolites synthesised during plant growth (De Flaviis et al. 2021). No aldehyde was detected in the cowpea flatbreads.

Figure 1 further shows the differences in compounds extracted from the whole and dehulled red and white cowpea flatbreads. Decane, tridecane and hexadecane were the hydrocarbons detected. Alkanes like decane, tridecane and hexadecane may be derived from oxidative decomposition of lipids in the flours from the lipoxygenase pathway (Eriotou et al. 2021; Rajhi, Baccouri, et al. 2021).

F1 and F2 explain 84% of the variation in the cowpea flatbreads (Figure 1). F1 separates the whole red cowpea flatbread (WRC<sup>f</sup>) on the left side of F1 from the dehulled red cowpea flatbread (DRC<sup>f</sup>) on the right. The WRC<sup>f</sup> had abundant hexyl acetate, benzyl acetate, pentyl acetate, ethyl octanoate, 2-pentylfuran, 2-phenylethyl acetate, 2-ethyl-3-methylpyrazine, dimethyl trisulphide, 3-octanone, benzothiazole, *m*-cymene and L-limonene. F2 separates the red cowpea flatbreads (WRC<sup>f</sup> and DRC<sup>f</sup>) on top of F2 from the white cowpea flatbreads (WWC<sup>f</sup>, DWC<sup>f</sup>) based on significantly higher levels ( $p < 0.05$ ) of phenylethyl alcohol, 1-octen-3-ol and decane in the red cowpea flatbreads ( $p$ -values are supplied in Supporting Information S3).

1-Octen-3-ol has a fruity, buttery, mushroom-like aroma, whereas phenylethyl alcohol has a spicy, rose-like aroma (Pico, Bernal, and Gómez 2017) and decane exhibits a fruity, sweet aroma (Pico et al. 2015). The twofold increase of 1-octen-3-ol and decane and a higher level of phenylethyl alcohol in red compared to white cowpea flatbreads could contribute to reducing the perception of a beany aroma in the red cowpea flatbreads and potentially explain the more intense beany aroma of the white cowpea flatbreads.

1-Octen-3-ol and phenylethyl alcohol have been reported to have an odour threshold of 1 and 750–1100 ppb, respectively (Leffingwell and Associates 1991), whereas the odour threshold in water for alkanes such as decane could be higher and may not have a significant sensory impact as a result. The 1-octen-3-ol with a very low odour threshold could be the main compound differentiating the two cowpea varieties since its level was higher than phenylethyl alcohol in the red cowpea. Similar findings from Toya et al. (1974), Sun et al. (2022) and Lee and Shibamoto (2000) support this observation. Toya et al. (1974) found 1-octen-3-ol contents to differ in three cultivars of bush snap bean (*Phaseolus vulgaris* L.) in their raw and processed forms. Sun et al. (2022) found that an increase in 1-octen-3-ol in a fermented soybean beverage reduced the beany and green aroma to mushroom-like and aromatic compared to a soybean beverage from raw soybean with a lower 1-octen-3-ol content. Furthermore, Lee and Shibamoto (2000) reported the inhibitory effect of 1-octen-3-ol on the oxidation of hexanal into hexanoic acid in mung bean and soybean extracts, further elucidating the role of high levels of 1-octen-3-ol in limiting further oxidation and reducing the beany aroma of legumes.

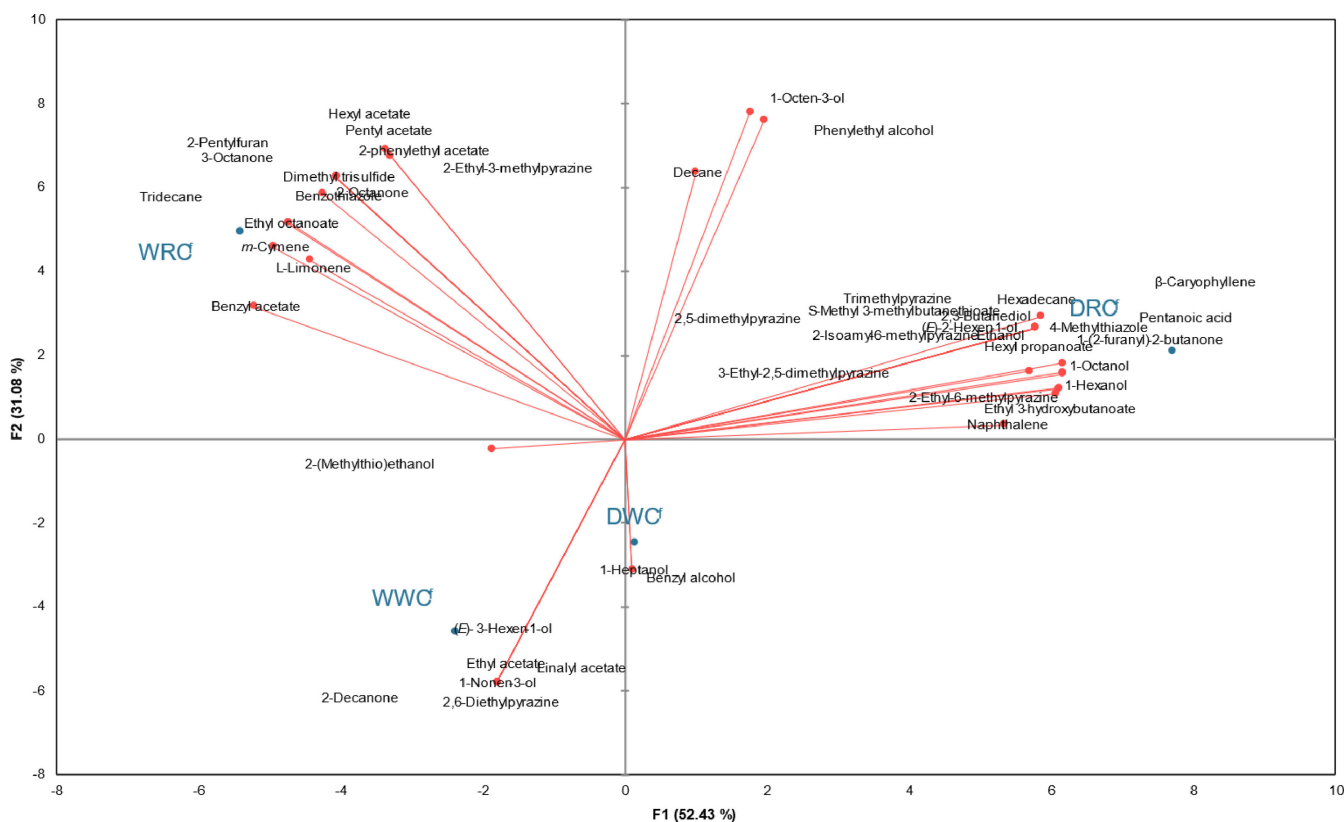
In this study, two furan compounds, 2-pentylfuran and 1-(2-furanyl)-2-butanone, were detected in the cowpea flatbreads. In soybean oil (Ho et al. 1978) and pea (Zhang et al. 2020), 2-pentylfuran has been characterised as beany and

**TABLE 3** | Comparison of mean peak area for compound chemical classes in whole and dehulled red and white cowpea flatbreads.

Class of compounds	No.	Flatbread			
		Whole cowpea		Dehulled cowpea	
		WWC <sup>f</sup>	WRC <sup>f</sup>	DWC <sup>f</sup>	DRC <sup>f</sup>
Hydrocarbons	3	494,338	1,112,264	—	1,031,150
Alcohols	12	2,638,695	4,120,324	8,789,068	32,472,374
Esters	10	1,312,328	10,305,018	770,315	3,653,487
Ketones	3	54,919	1,860,264	295,710	—
Acids	1	—	—	—	301,368
Sulphur compounds	3	—	202,843	—	77,188
Terpenes and Terpenoids	3	2,892,608	5,327,625	291,233	1,292,025
Benzene derivatives	1	13,281	—	—	33,022
Furans	2	—	2,480,063	798,495	2,612,641
Pyrazines	7	45,493	84,083	163,098	1,584,336

Note: — = not detected; No. = total number of compounds found within the class.

Abbreviations: WWC<sup>f</sup>, whole white cowpea; WRC<sup>f</sup>, whole red cowpea; DWC<sup>f</sup>, dehulled white cowpea; DRC<sup>f</sup>, dehulled red cowpea.



**FIGURE 1** | Principal component analysis biplot of compounds associated with cowpea flatbread models from whole and dehulled red and white cowpea flours. WWC<sup>f</sup>=Whole white cowpea flatbread; WRC<sup>f</sup>=Whole red cowpea flatbread; DWCF=Dehulled white cowpea flatbread; DRC<sup>f</sup>=Dehulled red cowpea flatbread.

grassy whereas 1-(2-furanyl)-2-butanone has a sweet, floral, caramelised-like aroma and is a Maillard reaction (MR) product resulting from the thermal degradation of sugars and has been identified in roasted coffee (Ribeiro et al. 2009).

The aroma character of 1-(2-furanyl)-2-butanone could be more intense in DRC<sup>f</sup>, as it was threefold more in the DRC<sup>f</sup> compared to DWCF. Thus, dehulling the red cowpea for breadmaking could potentially enhance its aroma.

Pyrazines are important compounds formed in MR that can positively influence the flavour of food products (Ribeiro et al. 2009). The dehulled flatbreads (DWC<sup>f</sup> and DRC<sup>f</sup>) had more pyrazines compared to their counterparts (Table 3). The DRC<sup>f</sup> compared to DWC<sup>f</sup> had the highest mean peak area for pyrazines. It seems that the higher pyrazine content in dehulled cowpea flatbreads could explain why the 100% dehulled cowpea flatbreads of the red and white cowpea varieties were nuttier than the whole cowpea flatbreads. 2-Ethyl-6-methylpyrazine and 3-ethyl-2,5-dimethylpyrazine were detected in dehulled cowpea flours. Paraskevopoulou et al. (2012) described 2-ethyl-6-methylpyrazine as nutty and 3-ethyl-2,5-dimethylpyrazine as baked in wheat bread enriched with lupin protein flour. Dehulling cowpeas is known to decrease the polyphenol content (Timitay et al. 2021), and this may explain why the dehulled cowpeas had more pyrazines than the whole cowpeas. According to Jinap et al. (2004), higher concentrations of polyphenols in cocoa limited the formation of pyrazines in roasted cocoa beans by binding and reducing the levels of free amino acids and reducing sugar degradation participating in MR. A similar observation was also reported in a model bread made from wheat flour with added phenolic compounds (Mildner-Szkudlarz et al. 2017).

Benzothiazole, dimethyl trisulphide and pyrazines found in cowpea flatbreads are products of MR as a result of the application of heat. Dimethyl trisulphide, with a cooked cabbage-like aroma, has been reported in cooked red kidney beans (Mishra et al. 2017) and is a product of the oxidation of sulphur-containing amino acids such as methionine and cysteine in Strecker degradation during MR (Kubec et al. 1998; Mishra et al. 2017). Benzothiazole was found in only WRC<sup>f</sup> and not in the dehulled counterpart, and this observation suggests that benzothiazole may be present due to the presence of the seed coat of the red cowpea variety.

### 3.3 | Aroma Compounds in Cassava Starch and Sorghum Flatbreads

Eighteen compounds were found in cassava flatbread. Table 4 presents the mean peak area for the chemical classes found for cassava and sorghum flatbread. Aldehydes, acids and furans were abundant in CS<sup>f</sup>. In XFSorg<sup>f</sup>, six compounds were detected. The levels of acetic acid and aldehydes were far greater than the levels of ketones in cassava flatbread. Also, the total VC compound content was lower in XFSorg<sup>f</sup> than in the cassava flatbread.

### 3.4 | Comparison of Compounds in Flatbreads Derived From Single Flours

The 53 compounds detected across all the single-flour flatbreads (Supporting Information S2) are compared and visualised using PCA (Figure 2). F1 and F2 explained 65% of the variation among the single-flour flatbreads. F1 separates the dehulled red cowpea flatbread (DRC<sup>f</sup>) on the right side from CS<sup>f</sup> on the left side. The dehulled red cowpea flatbread had more pyrazines and alcohols compared to the other single-flour flatbreads. Among the single-flour flatbreads, sorghum flatbread was close to the reference wheat (Figure 2). The closeness of XFSorg<sup>f</sup> and WH<sup>f</sup> was not explained by the VCs. F2 separates CS<sup>f</sup> and DRC<sup>f</sup>

**TABLE 4** | Comparison of mean peak area for aroma compounds chemical classes in cassava and sorghum flatbreads.

Class of compound	Cassava		Sorghum	
	No.	CS <sup>f</sup>	No.	XFSorg <sup>f</sup>
Hydrocarbons	0	—	1	785,344
Alcohols	2	327,065	2	974,313
Aldehydes	10	7,154,846	0	—
Esters	0	—	0	—
Ketones	2	981,434	0	—
Acids	2	6,884,202	0	—
Benzene derivatives	0	—	1	91,160
Terpenes and terpenoids	1	74,912	1	1,915,193
Furans	1	4,007,865	1	91,160
<b>Total</b>		<b>19,430,324</b>		<b>3,857,170</b>

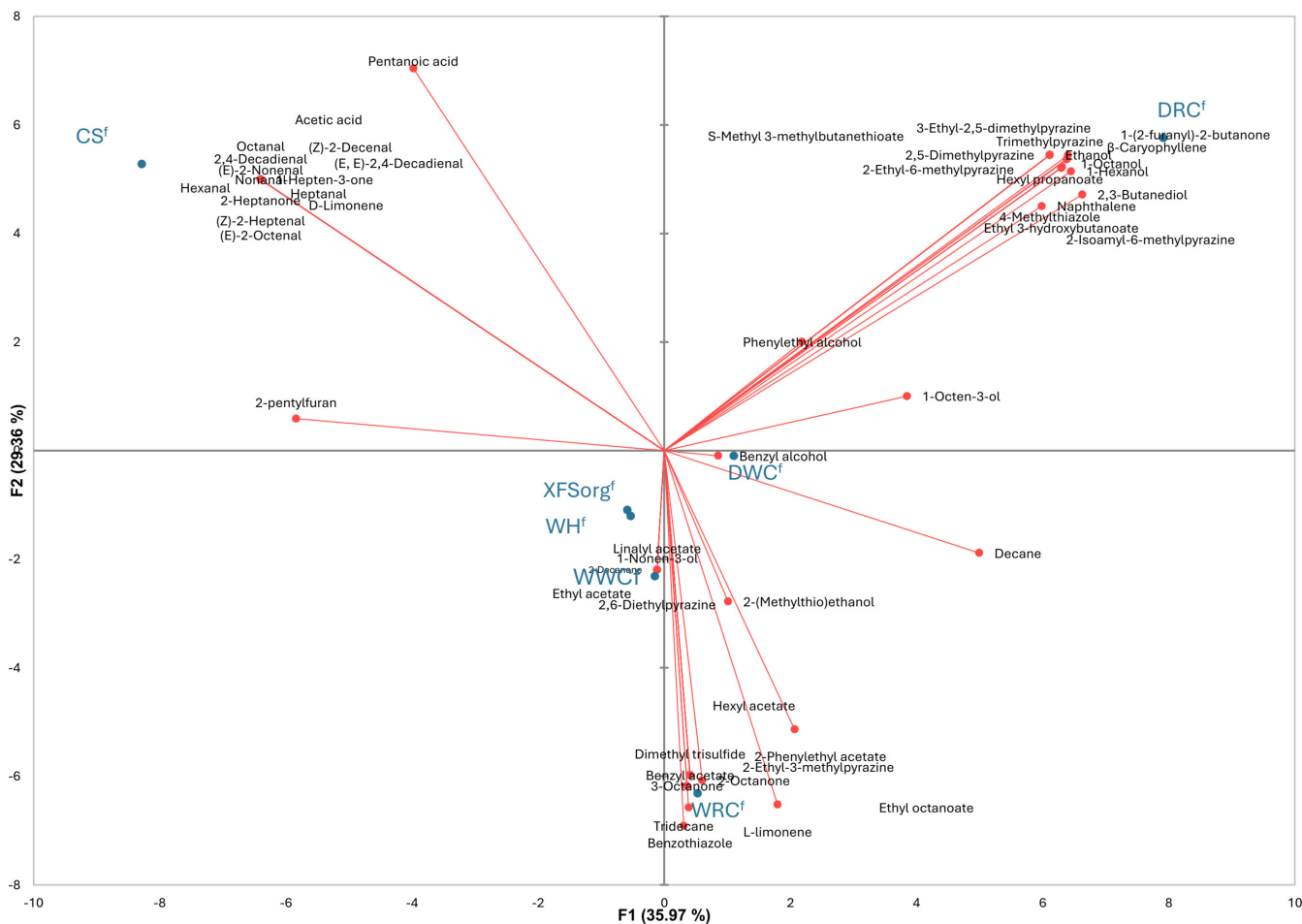
Note: — = not detected; No. = total number of compounds found within the class. Abbreviations: CS<sup>f</sup>, cassava-only flatbread; XFSorg<sup>f</sup>, sorghum-only flatbread.

at the top from WRC<sup>f</sup> at the bottom (Figure 2). The CS<sup>f</sup> had more acids (acetic acid, pentanoic acid), aldehydes ((*E,E*)-2,4-decadienal, 2,4-decadienal, hexanal, nonanal, octanal, heptanal, (*E*)-2-octenal, (*E*)-2-nonenal) and ketones (2-heptanone, 1-hepten-3-one) and D-limonene compared to flatbreads from sorghum, wheat and cowpea flours. Although the cassava starch had low fat content, almost negligible (not reported), abundant aldehydes were detected for cassava starch flatbread. The aldehydes observed in starches may have been formed in their tubers and absorbed by the starch during wet milling (Sayaslan et al. 2000). Misharina (2002) reported the sorption of VCs by amylose and amylopectin in cassava starch and other starches.

The level of acetic acid and aldehydes was far greater than the levels of ketones (1-hepten-3-one and 2-heptanone) in cassava flatbread. The presence of 1-hepten-3-one (geranium-like) and 2-heptanone (fruity) could impact cassava-only flatbread with a fruity aroma due to their lower odour threshold. The higher level of acetic acid generated in the cassava flatbread may be due to a higher content of free starch and glucosidase activity in the cassava, which may undergo glycolysis as a result of the application of heat to produce sugars needed for the formation of acetic acid in the MR. Pentanoic acid can occur naturally or be formed from fermentation (Goldberg and Rokem 2019). The pentanoic acid found in the cassava starch flatbread may be generated by fermentation during the extraction of the starch from the cassava tubers.

### 3.5 | Effect of Sorghum, Cassava Starch and Cowpea Flours on Aroma Compounds of Flatbreads Prepared From Sorghum, Cassava and Cowpea Compositeds Flours and the Relationship With Sensory Characteristics

Table 5 compares the relative % mean peak area for VCs detected in flatbreads from sorghum, cassava and cowpea composite



**FIGURE 2** | Principal component analysis biplot showing aroma compounds characterising sorghum, cowpea, and cassava starch flatbreads WH<sup>f</sup>= Wheat flatbread; XFSorg<sup>f</sup>= Sorghum flatbread; CS<sup>f</sup>= Cassava flatbread; WWC<sup>f</sup>= Whole white cowpea flatbread; WRC<sup>f</sup>= Whole red cowpea flatbread; DWC<sup>f</sup>= Dehulled white cowpea flatbread, DRC<sup>f</sup>= Dehulled red cowpea flatbread.

flour or wheat flour. Sixty compounds were detected in the composite-flour flatbreads. Of the 60 compounds, 39 were found in cassava–cowpea flatbreads, 28 in sorghum–cowpea flatbreads and 41 in sorghum–cassava–cowpea flatbreads.

Among the ester compounds, hexyl acetate and pentyl acetate, detected in the cowpea-only flatbread, dominated the composite-flour flatbreads. The CS-DRC<sup>f</sup> had the highest total ester content (41%) of the flatbreads prepared from composite flours. Hexyl acetate dominated the total esters in CS-DRC<sup>f</sup>. Three alcohols, 2,3-butanediol, 1-hexanol and 1-octen-3-ol were the main alcohols that contributed greatly to the total alcohols in the composite-flour flatbreads. The 1-hexanol level was between 2 and 9%. The 2,3-butanediol was the most abundant alcohol in the sorghum–cowpea flatbreads (XFSorg-WWC<sup>f</sup>, XFSorg-WRC<sup>f</sup>, XFSorg-DWC<sup>f</sup>, XFSorg-DRC<sup>f</sup>), whereas 1-hexanol was the most abundant alcohol in the cassava–cowpea flatbreads (CS-WWC<sup>f</sup>, CS-WRC<sup>f</sup> and CS-DWC<sup>f</sup>) except for CS-DRC<sup>f</sup>. Among composite-flour flatbreads, 1-hepten-3-ol and 2-(methylthio) ethanol were detected in XFSorg-WWC<sup>f</sup> (2%) and XFSorg-DRC<sup>f</sup> (2%), respectively.

The aldehydes, hexanal, 2,4-decadienal, nonanal and heptanal found in the cassava-only flatbread were more prominent in the flatbreads prepared from the cassava-containing composite

flours. Cassava–whole red cowpea flatbread (CS-WRC<sup>f</sup>) was the only flatbread with eicosane, a fuel-like aroma comprising 0.2% of the aroma compounds. Sorghum–cassava–cowpea and cassava–cowpea flatbreads had higher levels of aldehydes than sorghum–cowpea flatbreads. The total aldehyde was least in sorghum–cowpea flatbreads (0.1%) compared to the cassava–cowpea flatbread and sorghum–cassava–cowpea flatbread (Table 5). Acetaldehyde was the only aldehyde detected in sorghum–cowpea flatbread. The CS-DRC<sup>f</sup> and XFSorg-CS-WRC<sup>f</sup> had the lowest level of aldehydes among the cassava–cowpea and sorghum–cassava–cowpea flatbread groups.

In general, cassava–cowpea flatbreads were characterised by a higher relative % mean peak area of acids, furans, terpenes and terpenoids compared to sorghum–cowpea and sorghum–cassava–cowpea flatbreads. Although pentanoic acid and acetic acid were detected in the cassava-only flatbread, compositing cassava and cowpea led to the formation of other acids (hexanoic acid and 3-methyl butanoic acid). Of all the acids in the flatbreads, acetic acid was generally higher in cassava–cowpea flatbreads compared to sorghum–cassava–cowpea flatbreads and was not detected in the sorghum–cowpea flatbreads. Interestingly, acids contributed by the cassava starch were not detected in CS-DRC<sup>f</sup> (Table 5). The 1-(2-furanyl)-2-butanone found in the cowpea flatbreads was also detected in all three

TABLE 5 | Relative % of the mean peak area for aroma compounds in wheat flatbread, sorghum, cassava and cowpea composite flatbreads.

Compounds	Relative % mean peak area												
	Wheat			Cassava-cowpea flatbread			Sorghum-cowpea flatbread			Sorghum-cassava-cowpea flatbread			
	WH <sup>f</sup>	CS-DWC <sup>f</sup>	CS-DRC <sup>f</sup>	CS-WWC <sup>f</sup>	CS-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-WWC <sup>f</sup>	XFSorg-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-CS-WWC <sup>f</sup>	XFSorg-CS-WRC <sup>f</sup>
<b>Hydrocarbons</b>													
Decane	—	2.28	2.81	4.61	—	3.70	8.33	5.46	7.57	—	5.67	—	3.29
Tridecane	7.44	0.63	0.85	2.20	0.67	1.01	3.70	5.33	—	1.48	—	1.80	—
Eicosane	—	—	—	—	0.20	—	—	—	—	—	—	—	—
Hexadecane	—	—	—	—	—	0.77	—	—	2.42	1.40	—	—	—
Pentadecane	—	—	—	—	—	—	—	—	—	—	0.64	0.32	—
<b>Ketones</b>													
2-Heptanone	—	8.00	—	—	—	—	—	14.06	—	—	—	—	4.88
2-Octanone	—	—	—	—	4.95	—	8.88	—	21.73	—	5.05	3.26	—
3-Octanone	6.04	—	—	—	—	—	—	—	—	5.34	—	—	—
Dihydro-2-methyl-3 (2H)-thiophenone	—	—	—	—	—	0.59	—	—	—	—	—	—	1.05
2-Nonanone	—	—	—	—	—	—	—	—	—	—	—	—	0.83
<b>Esters</b>													
Heptyl acetate	—	—	0.37	—	—	0.23	—	—	—	—	—	—	—
Hexyl acetate	—	—	22.28	—	—	11.72	6.52	7.08	2.53	—	—	—	0.63
Pentyl acetate	—	—	15.51	—	—	16.40	5.97	8.97	3.50	—	—	—	—
Benzyl acetate	—	—	1.60	—	—	—	—	—	—	—	—	—	—
Hexyl propanoate	—	—	1.62	—	—	—	—	—	—	—	—	—	—
Ethyl	—	—	—	—	—	—	—	—	—	—	—	—	1.08
3-hydroxybutanoate	—	—	—	—	—	—	—	—	—	—	—	—	—
Linalyl acetate	—	—	—	—	—	—	0.28	—	—	—	—	—	—
S-Methyl	—	—	0.90	—	—	—	—	—	—	—	—	—	—
3-methylbutanethioate	—	—	—	—	—	—	—	—	—	—	—	—	—

(Continues)

TABLE 5 | (Continued)

Compounds	Relative % mean peak area																			
	Wheat					Cassava-cowpea flatbread					Sorghum-cowpea flatbread					Sorghum-cassava-cowpea flatbread				
	WH <sup>f</sup>	CS-DWC <sup>f</sup>	CS-DRC <sup>f</sup>	CS-WWC <sup>f</sup>	CS-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-WWC <sup>f</sup>	XFSorg-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-WWC <sup>f</sup>	XFSorg-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-WWC <sup>f</sup>	XFSorg-WRC <sup>f</sup>			
<b>Alcohols</b>																				
1-Octen-3-ol	—	2.27	2.14	3.85	3.11	1.35	0.00	0.00	1.92	4.02	4.46	1.95	2.12	—	—	—	—			
Phenylethyl alcohol	—	—	0.67	1.69	0.71	0.58	1.88	1.23	1.04	—	—	—	0.99	—	—	—	—			
1-Hexanol	66.69	9.93	—	4.74	7.01	—	—	—	—	6.43	5.28	2.29	8.29	—	—	—	—			
2,3-Butanediol	11.26	—	31.62	—	—	43.65	22.52	28.68	15.51	—	—	—	44.97	—	—	—	—			
Benzyl alcohol	—	—	1.02	—	—	—	—	—	—	—	—	—	0.59	—	—	—	—			
1-Hepten-3-ol	8.57	—	—	—	—	—	—	1.93	—	—	—	—	—	—	—	—	—			
Cyclobutanol	—	—	—	—	—	—	—	—	—	—	—	—	0.12	—	—	—	—			
2-(Methylthio) ethanol	—	—	—	—	—	—	2.07	—	—	—	—	—	—	—	—	—	—			
<b>Aldehydes</b>																				
2,4-Decadienal	—	—	—	1.04	1.32	—	—	—	—	—	—	—	—	—	—	0.73	—			
(E, E)-2,4-Decadienal	—	0.52	—	3.14	5.72	—	—	—	—	—	—	—	—	2.05	2.05	1.46	—			
(Z)-2-Decenal	—	—	—	—	0.43	—	—	—	—	—	—	—	—	—	—	—	—			
(E)-2-Nonenal	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.23	—			
(E)-2-Octenal	—	—	—	0.70	0.66	—	—	—	—	—	—	—	—	—	—	0.39	—			
Heptanal	—	—	—	—	—	—	—	—	—	2.26	—	—	—	—	—	1.85	—			
Hexanal	—	36.40	—	—	32.15	—	—	—	—	35.62	45.97	42.41	—	—	—	—	—			
Nonanal	—	2.00	—	3.37	1.73	—	—	—	—	2.38	2.30	1.44	—	—	—	—	—			
Octanal	—	—	—	0.92	0.78	—	—	—	—	—	—	—	—	—	—	—	—			
2-Hexenal	—	—	—	3.47	—	—	—	—	—	—	—	—	—	—	—	—	—			
Benzaldehyde	—	—	—	1.98	—	—	—	—	—	—	—	—	—	1.13	—	—	—			
Benzeneacetaldehyde	—	—	—	1.00	0.81	—	—	—	—	—	—	—	—	—	—	0.37	—			
(E)-2-Decenal	—	—	—	—	0.43	—	—	—	—	—	—	—	—	—	—	—	—			

(Continues)

TABLE 5 | (Continued)

Compounds	Relative % mean peak area																				
	Wheat			Cassava-cowpea flatbread						Sorghum-cowpea flatbread						Sorghum-cassava-cowpea flatbread					
	WHf	CS-DWCf	CS-DRCf	CS-WWCf	CS-WRCf	XFSorg-DWCf	XFSorg-DRCf	XFSorg-WWCf	XFSorg-WRCf	XFSorg-DWCf	XFSorg-DRCf	XFSorg-WWCf	XFSorg-WRCf	XFSorg-DWCf	XFSorg-DRCf	XFSorg-WWCf	XFSorg-WRCf				
Acetaldehyde	—	—	—	—	—	—	—	—	0.07	—	—	—	—	—	—	—	—				
Decanal	—	—	—	—	—	—	—	—	0.00	0.24	—	—	—	—	—	—	—				
<b>Acids</b>																					
Acetic acid	—	—	—	12.23	1.73	—	—	—	—	0.89	—	—	—	—	—	—	—				
Pentanoic acid	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.87				
Hexanoic acid	—	1.67	—	—	1.51	—	—	—	—	—	—	—	—	—	—	—	—				
3-Methylbutanoic acid	—	—	—	—	1.81	—	—	—	2.53	—	—	—	—	—	—	—	2.68				
Heptanoic acid	—	—	—	—	—	—	—	—	—	—	—	—	—	1.47	—	—	—				
<b>Benzene derivatives</b>																					
2-Methoxyphenol	—	—	—	—	—	1.23	—	1.77	1.71	—	—	—	—	—	—	—	2.08				
2-Methoxy-4-vinylphenol	—	—	—	—	—	1.55	—	—	—	1.56	—	—	—	—	—	—	1.05				
4-Ethyl-2-methoxyphenol	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.22				
Toluene	—	—	—	—	—	—	—	—	—	—	—	—	—	—	25.80	—	—				
<b>Terpenes and terpenoids</b>																					
D-Limonene	—	—	—	—	6.03	—	—	—	—	—	—	—	—	—	—	—	—				
<i>p</i> -Cymene	—	—	—	—	—	0.32	—	—	—	—	—	—	0.85	—	—	—	—				
<i>m</i> -Cymene	—	—	—	0.70	—	—	—	—	0.87	—	—	—	—	—	—	—	0.57				
L-limonene	—	10.33	7.38	14.04	—	3.70	8.80	5.71	7.52	13.93	7.33	3.37	—	—	—	—	4.79				
<b>Sulphur and nitrogen compounds</b>																					
Dimethyl trisulphide	—	0.67	0.48	—	—	0.31	0.24	0.36	—	0.50	0.51	—	—	—	—	—	—				

(Continues)

TABLE 5 | (Continued)

Compounds	Relative % mean peak area																			
	Wheat					Cassava-cowpea flatbread					Sorghum-cowpea flatbread					Sorghum-cassava-cowpea flatbread				
	WH <sup>f</sup>	CS-DWC <sup>f</sup>	CS-DRC <sup>f</sup>	CS-WWC <sup>f</sup>	CS-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-WWC <sup>f</sup>	XFSorg-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-WWC <sup>f</sup>	XFSorg-WRC <sup>f</sup>	XFSorg-DWC <sup>f</sup>	XFSorg-DRC <sup>f</sup>	XFSorg-WWC <sup>f</sup>	XFSorg-WRC <sup>f</sup>			
Benzothiazole	—	—	—	—	0.24	—	—	—	—	—	—	—	—	—	—	—	—			
<b>Furans</b>																				
2-Pentylfuran	—	24.78	—	39.57	27.98	—	—	—	31.09	—	—	—	—	—	—	12.31	18.90			
1-(2-Furanyl)-2-butanone	—	—	10.75	—	—	12.22	26.01	19.44	—	—	—	—	—	24.67	18.14	—	—			
3-Ethyl-2,5-dimethylpyrazine	—	—	—	—	—	0.68	—	—	—	—	—	—	—	—	—	—	—			
Methylpyrazine	—	—	—	—	—	1.46	—	—	—	—	—	—	—	—	—	—	—			

Note: — = not detected. Please refer to Table 1 for the sample name.

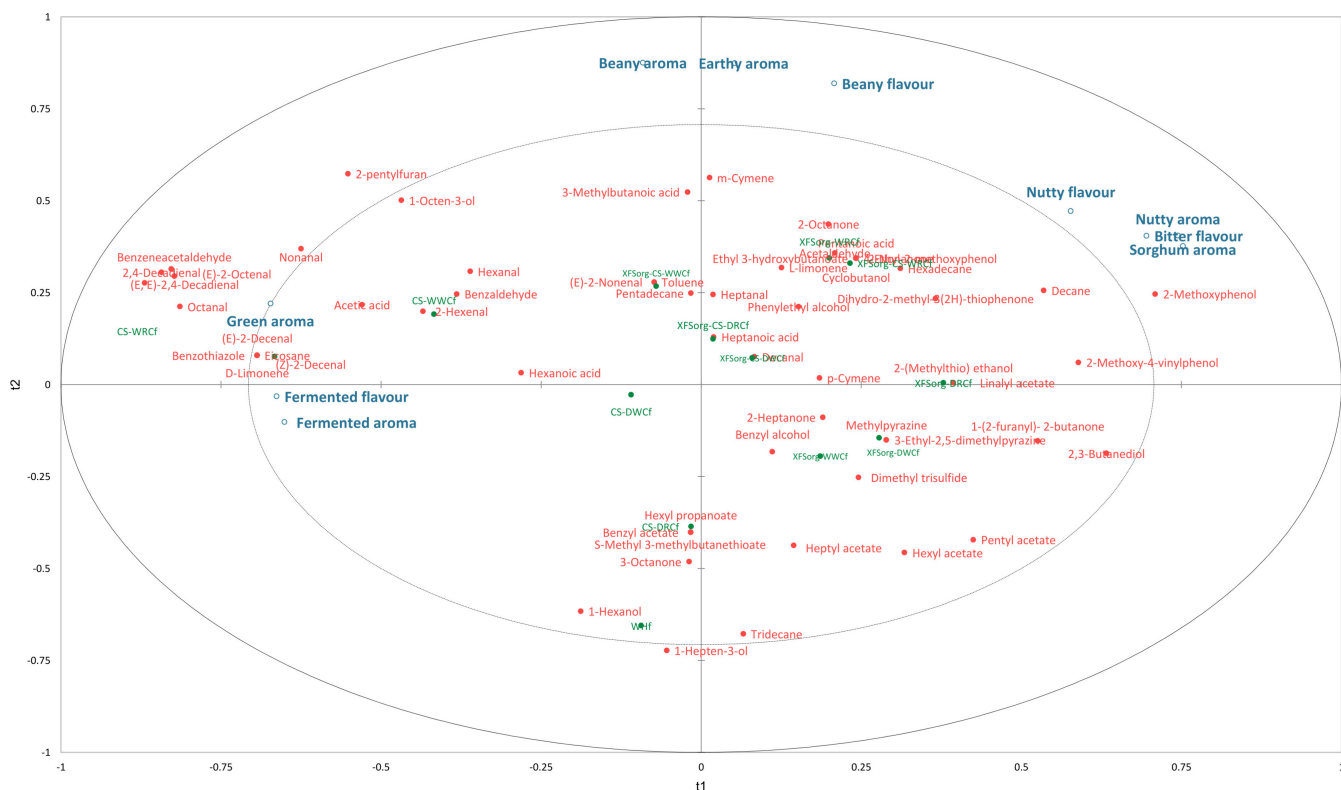
flatbread groups prepared from the composite flours. The 2-pentylfuran was higher in the cassava-cowpea flatbreads compared to the sorghum-cassava-cowpea flatbreads.

Among the benzene derivatives, terpenes and terpenoids found for the single flatbreads, only 2-methoxyphenol and L-limonene were detected in the composite-flour flatbreads. Dimethyl trisulphide was prominent in all three flatbread groups prepared from the composite flours, irrespective of whether they contained red or white cowpea in the whole or dehulled form. The dimethyl trisulphide level in the three flatbread groups was less than 1%. The benzothiazole that was detected in WRC<sup>f</sup> was found in only CS-WRC<sup>f</sup>. Of the 7 pyrazines detected in cowpea-only flatbreads, only 2 pyrazines, methylpyrazine and 3-ethyl-2,5-dimethylpyrazine were detected in flatbreads from the composite flours.

Figure 3A, 3B and 3C present the VCs associated with the sensory descriptions of the flatbreads. The first four components explain 82% of the total variation in the flatbreads with cumulated Q<sup>2</sup>, R<sup>2</sup>Y, R<sup>2</sup>X of 0.17, 0.83 and 0.52, respectively.

Forty-six VCs were found with VIP ≥ 0.8. Fifteen compounds (3-methylbutanoic acid, pentanoic acid, 4-ethyl-2-methoxyphenol, 2-nonanone, 2-heptanone, cyclobutanol, dihydro-2-methyl-3(2H)-thiophenone, 2-hexenal, benzaldehyde, phenylethyl alcohol, p-cymene, heptanoic acid, decanal, 3-ethyl-2,5-dimethylpyrazine and methylpyrazine) had VIP values < 0.8. The goodness of fit 'R<sup>2</sup>' for PLSR models was 0.76 for sorghum aroma, 0.77 for earthy aroma, 0.78 for beany aroma, 0.80 for green aroma, 0.87 for nutty aroma, 0.83 for fermented aroma, 0.82 for beany flavour, 0.83 for bitter flavour, 0.87 for nutty flavour and 0.92 for fermented flavour.

Sorghum aroma on the right side of component 1 (t1) in the upper quadrant was associated with 2-methoxyphenol (smoky, medicinal, sweet), 2-methoxy-4-vinylphenol (spicy and clove-like) and decane (Figure 3A). These three compounds were detected to be closely related to sorghum aroma characterising flatbreads containing 70% or 35% red non-tannin sorghum. Among the three compounds, 2-methoxyphenol and 2-methoxy-4-vinylphenol are the main compounds that may contribute to sorghum aroma. The odour thresholds of 2-methoxyphenol and 2-methoxy-4-vinylphenol in water have been reported as 3–21 ppb and 3 ppb, respectively (Leffingwell and Associates 1991), which are lower compared to decane. Alkanes do not contribute much to flavour or aroma but may, however, influence the flavour and aroma-imparting characteristics of other VCs by controlling their release (Chigwedere et al. 2019; Fu et al. 2022). 2-methoxy-4-vinylphenol has been reported to contribute to the overall aroma of boiled sorghum grains (Chen et al. 2021). In addition, Cao et al. (2020) reported both 2-methoxyphenol and 2-methoxy-4-vinylphenol to contribute to the aroma of liquor prepared from some Chinese sorghum cultivars. 2-methoxy-4-vinyl phenol is reported as the product of thermal decomposition of *p*-coumaric acid and ferulic acid (Hu et al. 2020; Maga and Katz 1978; Miraji et al. 2022) and 2-methoxyphenol is also a product from ferulic acid (Maga and Katz 1978). Flatbreads prepared from 70% sorghum flour had the least aldehydes among the composite-flour flatbreads, the cassava-cowpea flatbreads having the highest (Figure 3A, 3B and



**FIGURE 3** | (A) Partial least square regression loading plot illustrating the volatile compounds (X-matrix) and intensities of aroma and flavour attributes evaluated by a trained panel (Y-matrix) associated with the first two components (t1 and t2). The t1 and t2 explained 33% and 29%, respectively, of the total variation. The percentages of the variances in X and Y explained by each variable are indicated on the t1, t2 axes. Flatbread is denoted in green, sensory attributes = blue; volatile flavour and aroma compounds are denoted in red. Please refer to Table 1 for the abbreviations used for the different flatbreads. (B) Partial least square regression correlation loading plot illustrating the volatile compounds (X-matrix) and intensity of aroma and flavour attributes evaluated by a trained panel (Y-matrix) associated with first and third components (t1 and t3). The t1 and t3 explained 33% and 15% respectively of the total variation. The percentages of the variances in X and Y explained by each variable are indicated on t1 and t3. Flatbread is denoted in green, sensory attributes = blue; volatile flavour and aroma compounds are denoted in red. Please refer to Table 1 for the abbreviations used for the different flatbreads. (C) Partial least square regression correlation loading plot illustrating the volatile compounds (X-matrix) and intensity of aroma and flavour attributes evaluated by a trained panel (Y-matrix) associated with the first and fourth components (t1 and t4). The t1 and t4 explained 33% and 5%, respectively, of the total variation. The t1, t2, t3 and t4 explained a total variation 82% in the flatbreads. The percentages of the variances in X and Y explained by each variable are indicated on t1 and t4. Flatbread is denoted in green, sensory attributes = blue; volatile flavour and aroma compounds are denoted in red. Please refer to Table 1 for the abbreviations used for the different flatbreads.

3C). Precursors for 2-methoxyphenol (Mukherjee et al. 2021) and 2-methoxy-4-vinyl phenol (Kiliç and Yeşiloğlu 2013) are reported to be strong antioxidants and thus may potentially limit the formation of aldehydes in flatbread containing sorghum. A study by Mukherjee et al. (2021) revealed strong antioxidant activity for arabinogalactan-protein of fruit gum grafted chemically with ferulic acid. *p*-Coumaric acid was found to have 71% effect on reducing lipid oxidation in 45 µg/mL linoleic acid emulsion prepared by mixing linoleic acid (155 µL), 0.04 M potassium phosphate buffer and (175 µg) and Tween-20 (Kiliç and Yeşiloğlu 2013).

Nutty aroma and nutty flavour on the side of t1 were closely related to 2-methoxyphenol (Figure 3A) and 1-(2-furanyl)-2-butanone (Figure 3 C). 2-methoxyphenol was described as smoky, burnt (Yin et al. 2021) and sweet which may explain an association with nuttiness. 1-(2-furanyl)-2-butanone so far not reported in bread, has been described as caramelised by Laukaleja and Koppel (2021) in roasted coffee. The caramelised nature of

the 1-(2-furanyl)-2-butanone may impact the nuttiness of the flatbreads.

The earthy aroma on the right side of t1 was closely related to 2-pentylfuran (Figure 3A) and 2-octanone (Figure 3C) whereas the fermented aroma and flavour on the left of t1 were related to hexanoic acid, acetic acid and 2-hexenal (Figure 3C). 2-pentylfuran has been described in the literature as earthy (Ali et al. 2022) whereas 2-octanone is soapy and fruity (Pico et al. 2015). Other researchers have also described 2-octanone as earthy, weedy and woody in mushrooms (X. Xu, Xu, et al. 2019). 2-octanone has an odour threshold in water of 50 ppb compared to 6 ppb for 2-pentylfuran. 2-pentylfuran, compared to 2-octanone, may have a greater impact on earthy aroma due to its high level and low odour threshold.

Green aroma was related to octanal, nonanal, benzothiazole, (*E*)-2-octenal, (*Z*)-2-decenal, (*E*)-2-decenal, eicosane, benzeneacetaldehyde, 2,4-decadienal, (*E,E*)-2,4-decadienal and





## 4 | Conclusions

This study documents VCs of flatbreads prepared from sorghum, cassava and cowpea flours and highlights the effect of cowpea variety and dehulling on the aroma profiles of cowpea flatbreads. High levels of 1-octen-3-ol in cowpeas potentially masked the beany aroma of 100% cowpea flatbread. Dehulling cowpeas can affect aroma by increasing alcohols, esters and pyrazines in flatbreads. VCs linked to aroma and flavour attributes of flatbreads revealed that sorghum, cassava and cowpea composite-flour flatbreads contain potentially attractive compounds that differ from the reference wheat flatbread. Overall, about 46 VCs contributed to the flavour of sorghum–cassava and cowpea composite-flour flatbreads. As expected, phenolic compounds, 2-methoxyphenol and 2-methoxy-4-vinylphenol contributed sorghum aroma to flatbreads. The beany flavour of cowpea in the composite-flour flatbread was associated with hexanal, 1-octen-3-ol, nonanal, dimethyl trisulphide, 2-pentylfuran, 1-(2-furanyl)-2-butanone and heptanal. Cassava-dehulled red cowpea and cassava-dehulled white cowpea flatbreads were closest to wheat flatbread, characterised by fewer VCs. Information on VCs of the red and white cowpea varieties, red non-tannin sorghum and cassava starch flatbreads would be useful to food product developers seeking to utilise the flours in food products. The insights could facilitate the realisation of industrial production of flavour-attractive flatbreads from sorghum, cassava and cowpea composite flours. Follow-up research to determine consumer acceptance of cassava-dehulled cowpea flatbreads compared to wheat flatbread, is needed.

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### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### References

Adebo, O. A., S. Gbashi, Y. O. Kewuyemi, et al. 2022. "SPME-GC-HRTOF-MS Dataset of Fermented Maize Flour Volatilome." *F1000Research* 11, no. 1198: 1198. <https://doi.org/10.12688/f1000research.126604.1>.

Adebo, O. A., P. B. Njobeh, S. C. Desobgo, M. Pieterse, E. Kayitesi, and D. T. Ndinteh. 2018. "Profiling of Volatile Flavor Compounds in Nkui (A Cameroonian Food) by Solid Phase Extraction and 2D Gas Chromatography Time of Flight Mass Spectrometry (SPME-GC× GC-TOF-MS)." *Food Science & Nutrition* 6, no. 8: 2028–2035. <https://doi.org/10.1002/fsn3.736>.

Ali, B., K. Y. Khan, H. Majeed, et al. 2022. "Impact of Soy-Cow's Mixed Milk Enzyme Modified Cheese on Bread Aroma." *LWT-Food Science & Technology* 154: 112793. <https://doi.org/10.1016/j.lwt.2021.112793>.

Álvarez, M. G., C. González-Barreiro, B. Cancho-Grande, and J. Simal-Gándara. 2011. "Relationships Between Godello White Wine Sensory Properties and Its Aromatic Fingerprinting Obtained by GC-MS." *Food Chemistry* 129, no. 3: 890–898. <https://doi.org/10.1016/j.foodchem.2011.05.040>.

Amann, L. S., O. Frank, C. Dawid, and T. F. Hofmann. 2022. "The Sensory-Directed Elucidation of the Key Tastants and Odorants in Sourdough Bread Crumb." *Food* 11, no. 15: 2325. <https://doi.org/10.3390/foods11152325>.

Azarnia, S., J. I. Boye, T. Warkentin, L. Malcolmson, H. Sabik, and A. S. Bellido. 2011. "Volatile Flavour Profile Changes in Selected Field Pea Cultivars as Affected by Crop Year and Processing." *Food Chemistry* 124, no. 1: 326–335. <https://doi.org/10.1016/j.foodchem.2010.06.041>.

Beltrão Martins, R., M. C. Nunes, I. Gouvinhas, et al. 2022. "Apple Flour in a Sweet Gluten-Free Bread Formulation: Impact on Nutritional Value, Glycemic Index, Structure and Sensory Profile." *Food* 11, no. 20: 3172. <https://doi.org/10.3390/foods11203172>.

Bento-Silva, A., N. Duarte, M. Belo, et al. 2021. "Shedding Light on the Volatile Composition of Broa, a Traditional Portuguese Maize Bread." *Biomolecules* 11, no. 10: 1396. <https://doi.org/10.3390/biom11101396>.

Boatright, W. L., and Q. Lei. 1999. "Compounds Contributing to the "Beany" Odor of Aqueous Solutions of Soy Protein Isolates." *Journal of Food Science* 64, no. 4: 667–670. <https://doi.org/10.1111/j.1365-2621.1999.tb15107.x>.

Boeswetter, A. R., K. A. Scherf, P. Schieberle, and P. Koehler. 2019. "Identification of the Key Aroma Compounds in Gluten-Free Rice Bread." *Journal of Agricultural & Food Chemistry* 67, no. 10: 2963–2972. <https://doi.org/10.1021/acs.jafc.9b00074>.

Bott, L., and E. Chambers Iv. 2006. "Sensory Characteristics of Combinations of Chemicals Potentially Associated With Beany Aroma in Foods." *Journal of Sensory Studies* 21, no. 3: 308–321. <https://doi.org/10.1111/j.1745-459X.2006.00067.x>Citations:71.

Buettner, A., and P. Schieberle. 1999. "Characterization of the Most Odor-Active Volatiles in Fresh, Hand-Squeezed Juice of Grapefruit (*Citrus paradisi* Macfayden)." *Journal of Agricultural & Food Chemistry* 47, no. 12: 5189–5193. <https://doi.org/10.1021/jf9900711>.

Cao, S., L. Wang, Q. Wu, D. Ni, Y. Xu, and L. Lin. 2020. "Regional Aroma Characteristics of Sorghum for Chinese Liquor Production." *Journal of the Institute of Brewing* 126, no. 3: 306–315. <https://doi.org/10.1002/jib.613>.

Chambers, E., and K. Koppel. 2013. "Associations of Volatile Compounds With Sensory Aroma and Flavor: The Complex Nature of Flavor." *Molecules* 18, no. 5: 4887–4905. <https://doi.org/10.3390/molecules18054887>.

Chen, S., L. Wang, D. Ni, L. Lin, H. Wang, and Y. Xu. 2021. "Characterization of Aroma Compounds in Cooked Sorghum Using Comprehensive Two-Dimensional Gas Chromatography-Time-of-Flight Mass Spectrometry and Gas Chromatography-Olfactometry-Mass Spectrometry." *Molecules* 26, no. 16: 4796. <https://doi.org/10.3390/molecules26164796>.

Chigwedere, C. M., W. W. Tadele, J. Yi, et al. 2019. "Insight Into the Evolution of Flavor Compounds During Cooking of Common Beans Utilizing a Headspace Untargeted Fingerprinting Approach."

- Food Chemistry* 275: 224–238. <https://doi.org/10.1016/j.foodchem.2018.09.080>.
- Cho, I. H., S. Y. Kim, H.-K. Choi, and Y.-S. Kim. 2006. “Characterization of Aroma-Active Compounds in Raw and Cooked Pine-Mushrooms (*Tricholoma matsutake* Sing.).” *Journal of Agricultural and Food Chemistry* 54, no. 17: 6332–6335. <https://doi.org/10.1021/jf060824l>.
- Chong, I.-G., and C.-H. Jun. 2005. “Performance of Some Variable Selection Methods When Multicollinearity Is Present.” *Chemometrics and Intelligent Laboratory Systems* 78, no. 1–2: 103–112. <https://doi.org/10.1016/j.chemolab.2004.12.011>.
- Dankwa, R., H. Aisala, E. Kayitesi, and H. L. De Kock. 2021. “The Sensory Profiles of Flatbreads Made From Sorghum, Cassava, and Cowpea Flour Used as Wheat Flour Alternatives.” *Food* 10, no. 12: 3095. <https://www.mdpi.com/2304-8158/10/12/3095>.
- De Flaviis, R., G. Sacchetti, and D. Mastrocola. 2021. “Wheat Classification According to Its Origin by an Implemented Volatile Organic Compounds Analysis.” *Food Chemistry* 341: 128217. <https://doi.org/10.1016/j.foodchem.2020.128217>.
- De Luca, L., A. Aiello, F. Pizzolongo, G. Blaiotta, M. Aponte, and R. Romano. 2021. “Volatile Organic Compounds in Breads Prepared With Different Sourdoughs.” *Applied Sciences* 11, no. 3: 1330. <https://doi.org/10.3390/app11031330>.
- Derail, C., T. Hofmann, and P. Schieberle. 1999. “Differences in Key Odorants of Handmade Juice of Yellow-Flesh Peaches (*Prunus persica* L.) Induced by the Workup Procedure.” *Journal of Agricultural & Food Chemistry* 47, no. 11: 4742–4745. <https://doi.org/10.1021/jf990459g>.
- Di Donfrancesco, B., and K. Koppel. 2017. “Sensory Characteristics and Volatile Components of Dry Dog Foods Manufactured With Sorghum Fractions.” *Molecules* 22, no. 6: 1012. <https://doi.org/10.3390/molecules22061012>.
- Dong, Y., and S. Karboune. 2021. “A Review of Bread Qualities and Current Strategies for Bread Bioprotection: Flavor, Sensory, Rheological, and Textural Attributes.” *Comprehensive Reviews in Food Science & Food Safety* 20, no. 2: 1937–1981. <https://doi.org/10.1111/1541-4337.12717>.
- Eriotou, E., I. K. Karabagias, S. Maina, D. Koulougliotis, and N. Kopsahelis. 2021. “Geographical Origin Discrimination of “Ntopia” Olive Oil Cultivar From Ionian Islands Using Volatile Compounds Analysis and Computational Statistics.” *European Food Research and Technology* 247, no. 12: 3083–3098. <https://doi.org/10.1007/s00217-021-03863-2>.
- Fan, X., X. Jiao, J. Liu, M. Jia, C. Blanchard, and Z. Zhou. 2021. “Characterizing the Volatile Compounds of Different Sorghum Cultivars by Both GC-MS and HS-GC-IMS.” *Food Research International* 140: 109975. <https://doi.org/10.1016/j.foodres.2020.109975>.
- Fang, Y., and M. Qian. 2005. “Aroma Compounds in Oregon Pinot Noir Wine Determined by Aroma Extract Dilution Analysis (AEDA).” *Flavour and Fragrance Journal* 20, no. 1: 22–29. <https://doi.org/10.1002/ffj.1551>.
- Fischer, E., N. Cayot, and R. Cachon. 2022. “Potential of Microorganisms to Decrease the “Beany” Off-Flavor: A Review.” *Journal of Agricultural and Food Chemistry* 70, no. 15: 4493–4508. <https://doi.org/10.1021/acs.jafc.1c07505>.
- Fu, Y., Y. Zhang, S. Zeng, et al. 2022. “The Effect of Long-Chain Alkanes on Flavour Release and Olfactory Characteristics of Rose Essential Oil.” *Flavour and Fragrance Journal* 37, no. 1: 72–80. <https://doi.org/10.1002/ffj.3681>.
- Galoburda, R., E. Straumite, M. Sabovics, and Z. Kruma. 2020. “Dynamics of Volatile Compounds in Triticale Bread With Sourdough: From Flour to Bread.” *Food* 9, no. 12: 1837. <https://doi.org/10.3390/foods9121837>.
- Gancarz, M., U. Malaga-Toboła, A. Oniszczuk, et al. 2021. “Detection and Measurement of Aroma Compounds With the Electronic Nose and a Novel Method for MOS Sensor Signal Analysis During the Wheat Bread Making Process.” *Food and Bioprocess Technology* 127: 90–98. <https://doi.org/10.1016/j.fbp.2021.02.011>.
- Glauber, J. 2023. *Ukraine One Year Later: Impacts on Global Food Security. The Russian-Ukraine Conflict and Global Security*. International Food Policy Research Institution (IFPRI). <https://doi.org/10.2499/9780896294394>.
- Goldberg, I., and J. S. Rokem. 2019. “Organic and Fatty Acid Production, Microbial.” In *Encyclopedia of Microbiology*, edited by T. M. Schmidt, Fourth ed., 358–382. Academic Press. <https://doi.org/10.1016/B978-012373944-5.00156-5>.
- Heiniö, R.-L., K. Katina, A. Wilhelmson, et al. 2003. “Relationship Between Sensory Perception and Flavour-Active Volatile Compounds of Germinated, Sourdough Fermented and Native Rye Following the Extrusion Process.” *LWT-Food Science and Technology* 36, no. 5: 533–545. [https://doi.org/10.1016/S0023-6438\(03\)00057-4](https://doi.org/10.1016/S0023-6438(03)00057-4).
- Hinge, V. R., H. B. Patil, and A. B. Nadaf. 2016. “Aroma Volatile Analyses and 2AP Characterization at Various Developmental Stages in Basmati and Non-Basmati Scented Rice (*Oryza sativa* L.) Cultivars.” *Rice* 9, no. 1: 1–22. <https://doi.org/10.1186/s12284-016-0113-6>.
- Ho, C. T., M. S. Smagula, and S. S. Chang. 1978. “The Synthesis of 2-(1-Pentenyl) Furan and Its Relationship to the Reversion Flavor of Soybean Oil.” *Journal of the American Oil Chemists’ Society* 55, no. 2: 233–237.
- Hor, P. K., K. Ghosh, S. K. Halder, et al. 2021. “Evaluation of Nutrient Profile, Biochemical Composition and Anti-Gastric Ulcer Potentialities of Khambir, a Leavened Flat Bread.” *Food Chemistry* 345: 128824. <https://doi.org/10.1016/j.foodchem.2020.128824>.
- Hu, X., L. Lu, Z. Guo, and Z. Zhu. 2020. “Volatile Compounds, Affecting Factors and Evaluation Methods for Rice Aroma: A Review.” *Trends in Food Science & Technology* 97: 136–146. <https://doi.org/10.1016/j.tifs.2020.01.003>.
- Huang, C., and J. Zayas. 1991. “Phenolic Acid Contributions to Taste Characteristics of Corn Germ Protein Flour Products.” *Journal of Food Science* 56, no. 5: 1308–1310. <https://doi.org/10.1111/j.1365-2621.1991.tb04759.x>.
- Huang, Y., J. Wan, Z. Wang, et al. 2022. “Variation of Volatile Compounds and Corresponding Aroma Profiles in Chinese Steamed Bread by Various Yeast Species Fermented at Different Times.” *Journal of Agricultural and Food Chemistry* 70, no. 12: 3795–3806. <https://doi.org/10.1021/acs.jafc.2c00550>.
- Jia, X., Q. Zhou, J. Wang, C. Liu, F. Huang, and Y. Huang. 2019. “Identification of Key Aroma-Active Compounds in Sesame Oil From Microwaved Seeds Using E-Nose and HS-SPME-GC× GC-TOF/MS.” *Journal of Food Biochemistry* 43, no. 10: e12786. <https://doi.org/10.1111/jfbc.12786>.
- Jiang, Y., M. R. Boorboori, Y. Xu, and W. Lin. 2021. “The Appearance of Volatile Aromas in Tieguanyin Tea With Different Elevations.” *Journal of Food Science* 86, no. 10: 4405–4416. <https://doi.org/10.1111/1750-3841.15898>.
- Jinap, S., B. Jamilah, and S. Nazamid. 2004. “Effect of Polyphenol Concentration on Pyrazine Formation During Cocoa Liquor Roasting.” *Food Chemistry* 85, no. 1: 73–80. <https://doi.org/10.1016/j.foodchem.2003.06.005>.
- Juric, M., G. Bertelsen, G. Mortensen, and M. A. Petersen. 2003. “Light-Induced Colour and Aroma Changes in Sliced, Modified Atmosphere Packaged Semi-Hard Cheeses.” *International Dairy Journal* 13, no. 2–3: 239–249. [https://doi.org/10.1016/S0958-6946\(02\)00156-5](https://doi.org/10.1016/S0958-6946(02)00156-5).
- Kewuyemi, Y. O., P. B. Njobeh, E. Kayitesi, et al. 2020. “Metabolite Profile of Whole Grain Ting (A Southern African Fermented Product) Obtained Using Two Strains of *Lactobacillus fermentum*.”

- Journal of Cereal Science* 95: 103042. <https://doi.org/10.1016/j.jcs.2020.103042>.
- Khrisanapant, P., B. Kebede, S. Y. Leong, and I. Oey. 2019. "A Comprehensive Characterisation of Volatile and Fatty Acid Profiles of Legume Seeds." *Food* 8, no. 12: 651. <https://doi.org/10.3390/foods8120651>.
- Kiliç, I., and Y. Yeşiloğlu. 2013. "Spectroscopic Studies on the Antioxidant Activity of *p*-Coumaric Acid." *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 115: 719–724. <https://doi.org/10.1016/j.saa.2013.06.110>.
- Kubec, R., V. Drhová, and J. Velišek. 1998. "Thermal Degradation of S-Methylcysteine and Its Sulfoxideimportant Flavor Precursors of Brassica and Allium Vegetables." *Journal of Agricultural and Food Chemistry* 46, no. 10: 4334–4340.
- Laukaleja, I., and K. Koppel. 2021. "Aroma Active Compound Perception in Differently Roasted and Brewed Coffees by Gas Chromatography–Olfactometry." *Journal of Sensory Studies* 36, no. 6: e12708. <https://doi.org/10.1111/joss.12708>.
- Lee, K.-G., and T. Shibamoto. 2000. "Antioxidant Properties of Aroma Compounds Isolated From Soybeans and Mung Beans." *Journal of Agricultural and Food Chemistry* 48, no. 9: 4290–4293. <https://doi.org/10.1021/jf000442u>.
- Leffingwell and Associates. 1991. "Odor & Flavor Detection Thresholds in Water (in Parts per Billion)". <http://www.leffingwell.com/odorthre.htm> (accessed 22 September, 2023).
- Lindsay, M. A., N. Granucci, D. R. Greenwood, and S. G. Villas-Boas. 2022. "Identification of New Natural Sources of Flavour and Aroma Metabolites From Solid-State Fermentation of Agro-Industrial by-Products." *Metabolites* 12, no. 2: 157. <https://doi.org/10.3390/metabo12020157>.
- Lu, H., L. Guo, L. Zhang, et al. 2020. "Study on Quality Characteristics of Cassava Flour and Cassava Flour Short Biscuits." *Food Science & Nutrition* 8, no. 1: 521–533. <https://doi.org/10.1002/fsn3.1334>.
- Maga, J. A., and I. Katz. 1978. "Simple Phenol and Phenolic Compounds in Food Flavor." *Critical Reviews in Food Science & Nutrition* 10, no. 4: 323–372. <https://doi.org/10.1080/10408397809527255>.
- Mildner-Szkudlarz, S., A. Siger, A. Szwengiel, K. Przygoński, E. Wojtowicz, and R. Zawirska-Wojtasiak. 2017. "Phenolic Compounds Reduce Formation of Nε-(Carboxymethyl) Lysine and Pyrazines Formed by Maillard Reactions in a Model Bread System." *Food Chemistry* 231: 175–184. <https://doi.org/10.1016/j.foodchem.2017.03.126>.
- Min, S., Y. Yu, S. Yoo, and S. S. Martin. 2005. "Effect of Soybean Varieties and Growing Locations on the Flavor of Soymilk." *Journal of Food Science* 70, no. 1: C1–C11. <https://doi.org/10.1111/j.1365-2621.2005.tb09009.x>.
- Miraji, K. F., E. Capuano, H. S. Laswai, and A. R. Linnemann. 2022. "Degree of Maturity and Dry-Heat Processing Affect Visual Quality and Volatile Profile of Roasted Immature Rice Grains." *LWT-Food Science and Technology* 167: 113831. <https://doi.org/10.1016/j.lwt.2022.113831>.
- Misharina, T. 2002. "Sorption of Monoterpenoids and Sesquiterpenoids by Natural Polysaccharides." *Applied Biochemistry and Microbiology* 38, no. 5: 480–486.
- Mishra, P. K., J. Tripathi, S. Gupta, and P. S. Variyar. 2017. "Effect of Cooking on Aroma Profile of Red Kidney Beans (*Phaseolus vulgaris*) and Correlation With Sensory Quality." *Food Chemistry* 215: 401–409. <https://doi.org/10.1016/j.foodchem.2016.07.149>.
- Morales, M., and R. Aparicio. 1999. "Effect of Extraction Conditions on Sensory Quality of Virgin Olive Oil." *Journal of the American Oil Chemists' Society* 76, no. 3: 295–300. <https://doi.org/10.1007/s11746-999-0234-9>.
- Mukherjee, S., K. Bera, S. Jana, et al. 2021. "Conjugation Reaction With Ferulic Acid Boosts the Antioxidant Property of Arabinogalactan-Protein and Enhances Its Ability to Form Complex With β-Lactoglobulin." *International Journal of Biological Macromolecules* 167: 587–594. <https://doi.org/10.1016/j.ijbiomac.2020.11.181>.
- Murat, C., K. Gourrat-Pernin, and N. Cayot. 2014. "The Off-Flavor of Pea Flour: Sensory Representation of Headspace Extracts." *Flavour* 679–682. <https://doi.org/10.1016/B978-0-12-398549-1.00124-0>.
- Oladimeji, B. M., and O. A. Adebo. 2024. "Properties and Metabolite Profiling of Bambara Groundnut Flour as Affected by Different Food Processing Conditions." *Applied Food Research* 4, no. 1: 100389. <https://doi.org/10.1016/j.afres.2024.100389>.
- Pacyński, M., R. Z. Wojtasiak, and S. Mildner-Szkudlarz. 2015. "Improving the Aroma of Gluten-Free Bread." *LWT-Food Science and Technology* 63, no. 1: 706–713.
- Paraskevopoulou, A., A. Chrysanthou, and M. Koutidou. 2012. "Characterisation of Volatile Compounds of Lupin Protein Isolate-Enriched Wheat Flour Bread." *Food Research International* 48, no. 2: 568–577. <https://doi.org/10.1016/j.foodres.2012.05.028>.
- Pico, J., J. Bernal, and M. Gómez. 2015. "Wheat Bread Aroma Compounds in Crumb and Crust: A Review." *Food Research International* 75: 200–215. <https://doi.org/10.1016/j.foodres.2015.05.051>.
- Pico, J., J. L. Bernal, and M. Gómez. 2017. "Influence of Different Flours and Starches on Gluten-Free Bread Aroma." *Journal of Food Science and Technology* 54, no. 6: 1433–1441. <https://doi.org/10.1007/s13197-017-2562-3>.
- Pico, J., Å. S. Hansen, and M. A. Petersen. 2017. "Comparison of the Volatile Profiles of the Crumb of Gluten-Free Breads by DHE-GC/MS." *Journal of Cereal Science* 76: 280–288. <https://doi.org/10.1016/j.jcs.2017.07.004>.
- Pico, J., M. M. Martínez, J. Bernal, and M. Gómez. 2017. "Impact of Frozen Storage Time on the Volatile Profile of Wheat Bread Crumb." *Food Chemistry* 232: 185–190. <https://doi.org/10.1016/j.foodchem.2017.04.026>.
- Rajhi, I., B. Baccouri, F. Rajhi, et al. 2022. "HS-SPME-GC-MS Combined With Chemometrics to Assess the Impact of Germination, Dehulling, and Milling on Flavor Attributes of Brown and Green Lentils (*Lens culinaris* subsp. *culinaris*)." *South African Journal of Botany* 150: 1102–1110. <https://doi.org/10.1016/j.sajb.2022.09.013>.
- Rajhi, I., B. Baccouri, F. Rajhi, H. Mhadhbi, and G. Flamini. 2021. "Monitoring the Volatile Compounds Status of Whole Seeds and Flours of Legume Cultivars." *Food Bioscience* 41: 101105. <https://doi.org/10.1016/j.fbio.2021.101105>.
- Rajhi, I., M. Boulaaba, B. Baccouri, et al. 2022. "Assessment of Dehulling Effect on Volatiles, Phenolic Compounds and Antioxidant Activities of Faba Bean Seeds and Flours." *South African Journal of Botany* 147: 741–753. <https://doi.org/10.1016/j.sajb.2022.03.010>.
- Ribeiro, J. S., F. Augusto, T. J. Salva, R. A. Thomaziello, and M. Ferreira. 2009. "Prediction of Sensory Properties of Brazilian Arabica Roasted Coffees by Headspace Solid-Phase Microextraction-Gas Chromatography and Partial Least Squares." *Analytica Chimica Acta* 634, no. 2: 172–179. <https://doi.org/10.1016/j.aca.2008.12.028>.
- Rybicka, I., K. Doba, and O. Bińczak. 2019. "Improving the Sensory and Nutritional Value of Gluten-Free Bread." *International Journal of Food Science & Technology* 54, no. 9: 2661–2667. <https://doi.org/10.1111/ijfs.14190>.
- Sayaslan, A., O. K. Chung, P. A. Seib, and L. M. Seitz. 2000. "Volatile Compounds in Five Starches." *Cereal Chemistry* 77, no. 2: 248–253. <https://doi.org/10.1094/CCHEM.2000.77.2.248>.
- Seisonen, S., K. Vene, and K. Koppel. 2016. "The Current Practice in the Application of Chemometrics for Correlation of Sensory and Gas Chromatographic Data." *Food Chemistry* 210: 530–540. <https://doi.org/10.1016/j.foodchem.2016.04.134>.

- Small, D., M. Jones-Gotman, R. Zatorre, M. Petrides, and A. Evans. 1997. "Flavor Processing: More Than the Sum of Its Parts." *Neuroreport* 8, no. 18: 3913–3917.
- Sohail, A., S. Al-Dalali, J. Wang, et al. 2022. "Aroma Compounds Identified in Cooked Meat: A Review." *Food Research International* 157: 111385. <https://doi.org/10.1016/j.foodres.2022.111385>.
- Song, J., J. Bi, Q. Chen, X. Wu, Y. Lyu, and X. Meng. 2019. "Assessment of Sugar Content, Fatty Acids, Free Amino Acids, and Volatile Profiles in Jujube Fruits at Different Ripening Stages." *Food Chemistry* 270: 344–352. <https://doi.org/10.1016/j.foodchem.2018.07.102>.
- Spence, C. 2021. "What Is the Relationship Between the Presence of Volatile Organic Compounds in Food and Drink Products and Multisensory Flavour Perception?" *Food* 10, no. 7: 1570. <https://doi.org/10.3390/foods10071570>.
- Sun, T., H. Jiang, K. Yang, et al. 2022. "Nutritional Function and Flavor Evaluation of a New Soybean Beverage Based on *Naematelia aurantialba* Fermentation." *Food* 11, no. 3: 272. <https://doi.org/10.3390/foods11030272>.
- Suo, B., W. Nie, Y. Wang, et al. 2020. "Microbial Diversity of Fermented Dough and Volatile Compounds in Steamed Bread Prepared With Traditional Chinese Starters." *LWT-Food Science and Technology* 126: 109350. <https://doi.org/10.1016/j.lwt.2020.109350>.
- Timitey, A., L. Adinsi, Y. E. Madodé, F. Cissé, N. Akissoé, and D. J. Hounhouigan. 2021. "Technological, Physico-Chemical and Sensory Changes During Cowpea Processing Into Shô Basi, a Couscous-Like Product From Sahelian Africa." *Legume Science* 4, no. 1: e115. <https://doi.org/10.1002/leg3.115>.
- Toya, D., W. Frazier, M. Morgan, and J. Baggett. 1974. "The Influence of Processing and Maturity on Volatile Components in Bush Snap Beans, *Phaseolus Vulgaris* L. 1." *Journal of the American Society for Horticultural Science* 99, no. 6: 493–497. <https://doi.org/10.21273/JASHS.99.6.493>.
- Vara-Ubol, S., E. Chambers, and D. H. Chambers. 2004. "Sensory Characteristics of Chemical Compounds Potentially Associated With Beany Aroma in Foods 1." *Journal of Sensory Studies* 19, no. 1: 15–26. <https://doi.org/10.1111/j.1745-459X.2004.tb00133.x>.
- Wang, L.-F., J.-Y. Lee, J.-O. Chung, J.-H. Baik, S. So, and S.-K. Park. 2008. "Discrimination of Teas With Different Degrees of Fermentation by SPME–GC Analysis of the Characteristic Volatile Flavour Compounds." *Food Chemistry* 109, no. 1: 196–206. <https://doi.org/10.1016/j.foodchem.2007.12.054>.
- Waniska, R. D. 2000. "Structure, Phenolic Compounds, and Antifungal Proteins of Sorghum Caryopses." In *Technical and Institutional Options for Sorghum Grain Mold Management: Proceedings of an International Consultation, 18–19 May 2000, ICRISAT, Patancheru, India*, edited by A. Chandrashekar, R. Bandyopadhyay, and A. J. Hall, 72–106. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT).
- Xiang, L., W. Zhu, B. Jiang, J. Chen, L. Zhou, and F. Zhong. 2023. "Volatile Compounds Analysis and Biodegradation Strategy of Beany Flavor in Pea Protein." *Food Chemistry* 402: 134275. <https://doi.org/10.1016/j.foodchem.2022.134275>.
- Xu, J., W. Zhang, K. Adhikari, and Y.-C. Shi. 2017. "Determination of Volatile Compounds in Heat-Treated Straight-Grade Flours From Normal and Waxy Wheats." *Journal of Cereal Science* 75: 77–83. <https://doi.org/10.1016/j.jcs.2017.03.018>.
- Xu, X., R. Xu, Q. Jia, et al. 2019. "Identification of Dihydro- $\beta$ -Ionone as a Key Aroma Compound in Addition to C8 Ketones and Alcohols in *Volvariella volvacea* Mushroom." *Food Chemistry* 293: 333–339. <https://doi.org/10.1016/j.foodchem.2019.05.004>.
- Xu, X., M. Yu, J. Raza, H. Song, L. Gong, and W. Pan. 2021. "Study of the Mechanism of Flavor Compounds Formed via Taste-Active Peptides in Bovine Bone Protein Extract." *LWT-Food Science and Technology* 137: 110371. <https://doi.org/10.1016/j.lwt.2020.110371>.
- Ye, D.-Q., X.-T. Zheng, X.-Q. Xu, Y.-H. Wang, C.-Q. Duan, and Y.-L. Liu. 2016. "Evolutions of Volatile Sulfur Compounds of Cabernet Sauvignon Wines During Aging in Different Oak Barrels." *Food Chemistry* 202: 236–246. <https://doi.org/10.1016/j.foodchem.2016.01.139>.
- Yin, W.-T., X.-T. Ma, S.-J. Li, X.-D. Wang, H.-M. Liu, and R. Shi. 2021. "Comparison of Key Aroma-Active Compounds Between Roasted and Cold-Pressed Sesame Oils." *Food Research International* 150: 110794. <https://doi.org/10.1016/j.foodres.2021.110794>.
- Yoo, S.-H., and Y. H. Chang. 2016. "Volatile Compound, Physicochemical, and Antioxidant Properties of Beany Flavor-Removed Soy Protein Isolate Hydrolyzates Obtained From Combined High Temperature Pre-Treatment and Enzymatic Hydrolysis." *Preventive Nutrition and Food Science* 21, no. 4: 338–347. <https://doi.org/10.3746/pnf.2016.21.4.338>.
- Zhang, C., Y. Hua, X. Li, X. Kong, and Y. Chen. 2020. "Key Volatile Off-Flavor Compounds in Peas (*Pisum sativum* L.) and Their Relations With the Endogenous Precursors and Enzymes Using Soybean (*Glycine max*) as a Reference." *Food Chemistry* 333: 127469. <https://doi.org/10.1016/j.foodchem.2020.127469>.

### Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** GC-TOF-HRMS chromatograms of flatbreads from sorghum, cassava starch and cowpea flours. **Figure S1:** GC-TOF-HRMS chromatogram of red non-tannin sorghum flatbread (XFSorg<sup>f</sup>). **Figure S2:** GC-TOF-HRMS chromatogram of cassava starch flatbread (CS<sup>f</sup>). **Figure S3:** GC-TOF-HRMS chromatogram of whole red cowpea flatbread (WRC<sup>f</sup>). **Figure S4:** GC-TOF-HRMS chromatogram whole white cowpea flatbread (WWC<sup>f</sup>). **Figure S5:** GC-TOF-HRMS chromatogram dehulled red cowpea flatbread (DRC<sup>f</sup>). **Figure S6:** GC-TOF-HRMS chromatogram of dehulled white cowpea flatbread (DWC<sup>f</sup>). **Figure S7:** GC-TOF-HRMS chromatogram wheat flatbread (WH<sup>f</sup>). **Figure 8:** GC-TOF-HRMS chromatogram sorghum–whole red cowpea flatbread. **Figure S9:** GC-TOF-HRMS chromatogram sorghum–dehulled red cowpea flatbread. **Figure S10:** GC-TOF-HRMS chromatogram of sorghum–whole white cowpea flatbread. **Figure S11:** GC-TOF-HRMS chromatogram of sorghum–dehulled white cowpea flatbread. **Figure S12:** GC-TOF-HRMS chromatogram of sorghum–cassava–whole red cowpea flatbread (XFSorg-CS-WRC<sup>f</sup>). **Figure S13:** GC-TOF-HRMS chromatogram of sorghum–cassava–dehulled red cowpea flatbread (XFSorg-CS-DRC<sup>f</sup>). **Figure S14:** GC-TOF-HRMS chromatogram of sorghum–cassava–whole white cowpea flatbread (XFSorg-CS-WWC<sup>f</sup>). **Figure S15:** GC-TOF-HRMS chromatogram of sorghum–cassava–dehulled white cowpea flatbread (XFSorg-CS-DWC<sup>f</sup>). **Figure S16:** GC-TOF-HRMS chromatogram of cassava–whole red cowpea flatbread (CS-WRC<sup>f</sup>). **Figure S17:** GC-TOF-HRMS chromatogram of cassava–dehulled red cowpea flatbread (CS-DRC<sup>f</sup>). **Figure S18:** GC-TOF-HRMS chromatogram of cassava–whole white cowpea flatbread (CS-WWC<sup>f</sup>). **Figure S19:** GC-TOF-HRMS chromatogram of cassava–dehulled white cowpea flatbread (CS-DWC<sup>f</sup>). **Table S2:** Mean peak area of volatile compounds detected in single-flour flatbreads. **Table S3:** Mean values of volatile compounds differentiating flatbreads from the white cowpea and red cowpea variety.