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## Research Article

# Mango Cultivars Uncovers Aroma Diversity and Chemotaxonomic Insights

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## Abstract

**Background and Objective:** Mango (*Mangifera indica* L.) aroma is a key quality trait, yet the chemical diversity of volatile compounds across Vietnamese cultivars remains poorly characterized. This study aimed to profile volatile organic compounds (VOCs) responsible for aroma diversity and assess their potential for chemotaxonomic differentiation. **Materials and Methods:** Eight Vietnamese mango cultivars were analyzed using headspace gas chromatography-mass spectrometry (HS-GC/MS) to identify and quantify VOCs. Identified compounds were classified into major chemical groups and multivariate analyses were used to explore cultivar-specific profiles and potential chemotaxonomic markers. **Results:** A total of 95 VOCs was identified, grouped into alcohols, aldehydes and ketones, acids and esters, terpenes and terpenoids, hydrocarbons and miscellaneous compounds. The  $\beta$ -Terpinolene dominated six cultivars, notably Xoai Keo, Xoai Cat Chu and Xoai Cat Hoa Loc. Other cultivars exhibited distinctive markers: Xoai Thanh Ca was enriched in 3-carene and alpha-terpinolene, while Xoai Uc showed high D-limonene levels. Several terpenes were unique to individual cultivars, enabling chemical fingerprinting and differentiation. **Conclusion:** Volatile profiles, particularly monoterpenoid composition, effectively distinguish Vietnamese mango cultivars and serve as biochemical markers for breeding, authentication and conservation. These findings reveal untapped aroma diversity and support integrating aroma profiling into mango improvement programs.

**Key words:** Aroma, *Mangifera indica*, mango, terpene, volatile compound

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**Competing Interest:** The authors have declared that no competing interest exists.

**Data Availability:** All relevant data are within the paper and its supporting information files.

## INTRODUCTION

Mango (*Mangifera indica* L.) is a globally important tropical fruit crop, often hailed as the “King of Fruits” and valued for its rich aroma and delicious flavour<sup>1</sup>. The complex aroma of mango arises from a very large and chemically diverse set of volatile organic compounds (VOCs). In fact, hundreds of individual volatile compounds have been identified in ripe mangoes<sup>2</sup>. Recent reviews note that over 270 distinct aroma volatiles have been reported across different mango cultivars<sup>3</sup>. These include numerous monoterpenes and sesquiterpenes such as 3-carene, myrcene,  $\beta$ -ocimene, limonene, sesquiterpene hydrocarbons, as well as diverse esters, alcohols, aldehydes, ketones and lactones<sup>2,3</sup>. Such chemical complexity underlies the characteristic “green”, “woody”, “fruity” and “sweet” notes of many mango varieties. Importantly, the volatile profile of the fruit can differ markedly by cultivar for example Shimizu *et al.*<sup>4</sup> detected 59 VOCs in a panel of 17 cultivars and used multivariate analysis to group them into four distinct clusters, reflecting cultivar lineage and heritage<sup>4</sup>. The fact that individual cultivars possess unique VOC fingerprints underscores the breadth of mango aroma chemistry and its varietal specificity.

Asia and especially South and Southeast Asia is the centre of origin and diversity for mango. Approximately 1000 mango cultivars are cultivated globally<sup>2</sup>, with India alone accounting for about 40% of the world’s mango area and China about 17%. Over millennia of cultivation in India, Myanmar, Vietnam, Thailand and neighbouring countries, numerous local landraces have been selected for desirable traits, including flavour. Many Asian cultivars (Vietnamese Cat Hoa Loc, Thai Nam Dok Mai, Indian Alphonso) are renowned for their intense, floral and fruity aromas. This rich genetic and geographic diversity has translated into great chemical diversity. For example, Xin *et al.*<sup>5</sup> reported that more than 400 volatiles have been isolated from different mango varieties across Asia. In practice, fruit from local Vietnamese cultivars often has a distinct aromatic profile compared to imports. Thus, the *Mangifera* genetic resource in Vietnam and Asia harbours substantial aromatic variation that remains to be fully characterized.

The chemical diversity of mango aroma is important for several reasons. First, aroma is a key component of flavour quality and consumer preference. The fruit’s bouquet is often the most immediate indicator of ripe quality and differences in volatile content can directly affect marketability<sup>6</sup>. Breeders are increasingly aware that flavour and aroma traits (in addition to yield and disease resistance) should be targeted. Modern genomic studies have begun to identify genes and

quantitative trait loci (QTL) underlying volatile production, suggesting that marker-assisted breeding could be used to enhance aroma. For example, Abbas *et al.*<sup>3</sup> note that QTL mapping and metabolic engineering have been proposed to transfer desirable aroma traits from highly aromatic lines into commercial cultivars. Second, unique aroma profiles can aid germplasm conservation and authentication. Volatile fingerprinting is increasingly used as a biochemical marker: Mango accessions and even mutated lines can be distinguished by their VOC profiles<sup>4,7</sup>. Because volatile blends are often cultivar-specific and relatively stable, profiling can validate varietal identity or reveal novel chemotypes<sup>4,7</sup>. Therefore, documenting aroma diversity in Vietnamese and Asian mangoes supports *in situ* and *ex situ* germplasm conservation.

Despite the extensive global research on mango volatiles, few studies have systematically examined the aroma profiles of Vietnamese cultivars using standardised analytical techniques such as Gas Chromatography-Mass Spectrometry (GC-MS). Moreover, comparative analyses among local and introduced cultivars under shared environmental conditions are lacking. This study therefore, fills a critical gap by characterising the VOC composition of eight mango cultivars cultivated in An Giang Province, Vietnam, a representative region of the Mekong Delta known for its fertile alluvial soils and humid tropical monsoon climate. This study aimed to characterise the volatile organic compounds contributing to the aroma of eight mango cultivars using GC-MS, compare the qualitative and semi-quantitative VOC profiles among cultivars to identify chemotypic patterns, evaluate potential biochemical markers for cultivar identification and implications for breeding and germplasm conservation. We hypothesised that each cultivar possesses a distinct volatile composition reflecting its genetic background and local cultivars exhibit higher diversity and complexity in volatile profiles compared to introduced varieties due to long-term selection under regional environmental conditions.

## MATERIALS AND METHODS

**Study area:** The study was conducted from May, 2025 to October, 2025.

**Sample collection and preparation:** An Giang is one of the provinces that has a genetic diversity of mango. Therefore, this area was selected for the study. Eight mango cultivars (*Mangifera indica* L.) were selected for volatile analysis consisting of Xoai Keo, Xoai Thai Xanh, Xoai Thanh Ca, Xoai Dai Loan, Xoai Cat Hoa Loc, Xoai Cat Chu, Xoai Uc and Xoai Thom.

Fully ripe fruits (physiologically mature and ready for consumption) were harvested from local orchards with farm area over 3000 m<sup>2</sup> in An Giang Province. Three biological replicates per cultivar were collected, each consisting of three randomly selected fruits. Fruits were stored at 4°C and analysed within 48 hrs.

The mesocarp (edible pulp) was manually separated from the peel and seed, immediately diced and homogenised. Approximately 5 g of mango pulp was weighed into a 20 mL glass vial and sealed with a PTFE/silicone septum for Headspace Solid-Phase Microextraction (HS-SPME).

**HS-SPME and GC-MS analysis:** Volatile compounds were extracted using a 50/30 µm SPME fibre (Supelco, US). The fibre was preconditioned according to the manufacturer's instructions. The vial containing the mango pulp was incubated at 40°C for 15 min to equilibrate, followed by fibre exposure to the headspace for 30 min. The GC-MS analysis was performed using an Agilent 7890B gas chromatograph coupled with a 5977A mass selective detector (Agilent, California, US). Separation was achieved on an HP-5MS capillary column (30 m × 0.25 mm, 0.25 µm film thickness). The oven temperature was programmed as follows: Initial temperature 40°C (held for 3 min), ramped at 5°C/min to 230°C and held for 5 min. Helium was used as the carrier gas at a constant flow rate of 1.0 mL/min. The injector was operated in splitless mode at 250°C. Mass spectra were obtained in EI mode at 70 eV over the range of 30-500 m/z.

**Compound identification and data analysis:** Volatile compounds were identified by comparing mass spectra with entries in the NIST 2017 Mass Spectral Library. Only compounds with similarity index scores above 80% were retained for further analysis. Compounds were semi-quantified based on relative peak areas (%) without internal standards. Data were expressed as the average of three replicates. Volatile compounds were then categorised into chemical groups based on their functional class and biosynthetic origin. VOCs were semi-quantified without internal standards, a limitation that may affect the accuracy of the reported concentrations.

## RESULTS

A total of 95 volatile compounds were identified and classified into six major chemical groups based on their functional groups and structural characteristics: Alcohols, aldehydes and ketones, acids and esters, terpenes and terpenoids, hydrocarbons and miscellaneous compounds

including oxygenated heterocycles and halogenated compounds (Fig. 1). This classification facilitates the interpretation of aroma-related patterns and biochemical origins.

Alcohols constituted a significant portion of the dataset and included both primary and secondary alcohols such as 1-butanol, 1-hexanol and cis-3-hexen-1-ol, which are commonly associated with fresh, green and fruity odours. These alcohols are typically derived from lipid oxidation or amino acid degradation pathways.

Aldehydes and ketones were also prevalent, including compounds like hexanal, trans-2-hexenal and acetone. Many aldehydes are well known for their low odour thresholds and substantial impact on perceived aroma, especially those contributing green, fatty and grassy notes.

Acids and esters represented a diverse group known for their contribution to fruity and sweet notes. Ethyl esters such as ethyl butanoate and ethyl 2-methylpropanoate were abundant, alongside short-chain carboxylic acids including acetic acid and formic acid. These compounds are typically formed via enzymatic esterification or β-oxidation pathways.

Terpenes and terpenoids, mainly mono- and sesquiterpenes such as α-pinene, β-myrcene and D-limonene, were detected, reflecting their biosynthesis from the mevalonate (MVA) and methylerythritol phosphate (MEP) pathways. These volatiles are often associated with citrus, resinous, floral and herbal aromas.

Hydrocarbons comprised linear and cyclic alkanes, including hexane, cyclopentane and methylcyclopentane. Although generally perceived as neutral or less odour-active, their presence indicates potential matrix or carrier effects and possible background contributions from fruit cuticle or waxes.

The miscellaneous group included oxygenated heterocyclics (furfural, furaneol), halogenated solvents (trichloromethane) and sulphur- or nitrogen-containing compounds (methylthiirane, ethyl (methylthio)propionate). Notably, compounds such as 2,4-dihydroxy-2,5-dimethyl-3(2H)-furan-3-one and 3,5-dihydroxy-6-methyl-2,3-dihydro-4H-pyran-4-one are known Maillard reaction products that may contribute to caramel-like and roasted notes in ripe mango.

A total of 13 monoterpenoid compounds (hydrocarbon monoterpenes and oxygenated monoterpenoids) were detected across the eight mango cultivars (Xoai Keo, Xoai Thai Xanh, Xoai Thanh Ca, Xoai Dai Loan, Xoai Cat Hoa Loc, Xoai Cat Chu, Xoai Uc and Xoai Thom) (Table 1). These included alpha-pinene, β-myrcene, cis- and trans-β-ocimene, camphene, D-limonene, 2- and 3-carene, alpha- and β-terpinene/terpinolene isomers, β-phellandrene and

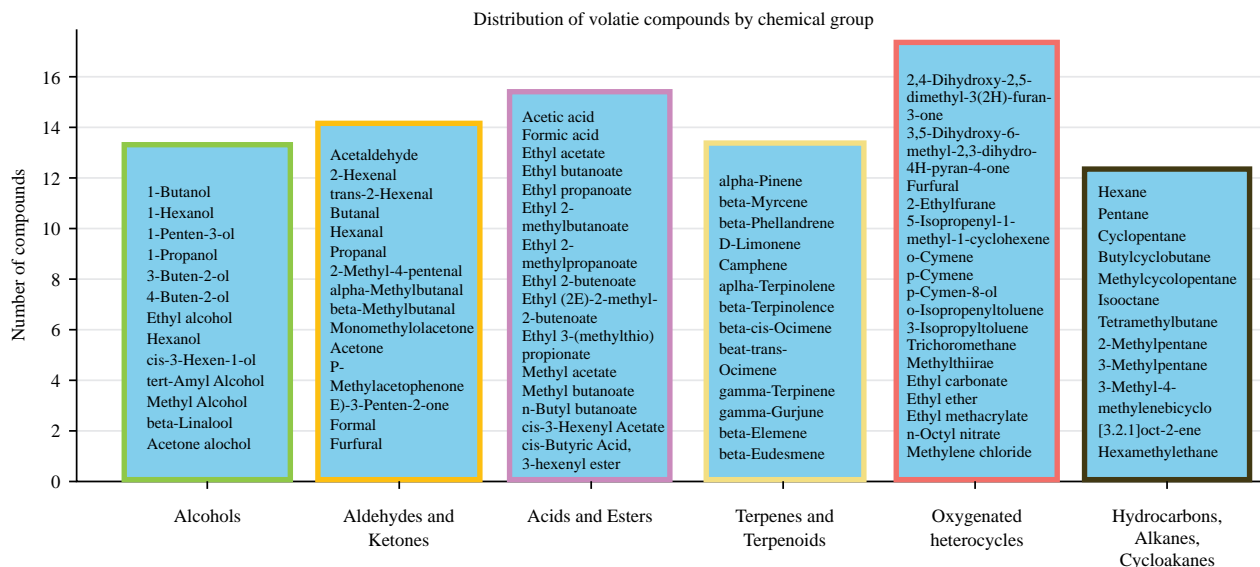


Fig. 1: Distribution of volatile compounds by chemical group

Table 1: Volatile compound profile of eight Vietnamese mango cultivars (the expressed numbers are area percentage)

No.	Compound name	Xoai	Xoai Thai	Xoai Thanh	Xoai Dai	Xoai Cat	Xoai Cat	Xoai Uc	Xoai Thom
		Keo	Xanh	Ca	Loan	Hoa Loc	Chu		
1	(Z)-Hex-3-en-1-ol	0.00	0.00	0.00	0.00	9.35	0.00	0.00	0.00
2	1,3,8-p-Menthatriene	0.20	0.00	0.28	0.00	0.00	0.28	0.00	0.32
3	1-Butanol	0.00	0.13	0.00	0.16	0.00	0.00	0.00	0.00
4	1-Hexanol	0.27	0.00	0.00	0.00	0.00	0.63	0.00	0.84
5	1-Penten-3-ol	0.00	0.49	0.00	0.00	0.49	0.00	0.00	0.00
6	1-Propanol	0.00	0.14	0.00	0.02	0.00	0.00	0.00	0.00
7	2,4-Dihydroxy-2,5-dimethyl-3(2H)-furan-3-one	0.00	0.00	0.39	0.00	0.00	0.00	0.00	0.00
8	2-Carene	0.23	0.00	1.24	0.00	0.00	2.46	1.33	0.58
9	2-Ethylfuran	0.00	0.19	0.00	0.00	0.30	0.00	0.00	0.00
10	2-Hexenal	0.95	5.71	4.79	0.00	0.00	9.56	0.00	0.00
11	2-Hexyl hydroperoxide	0.00	0.00	0.00	0.00	0.00	0.70	0.00	0.00
12	2-Methyl-4-pentenal	0.00	0.00	0.00	0.00	0.00	12.03	0.00	0.00
13	2-Methylpentane	0.00	0.00	0.00	0.00	0.00	0.57	0.00	0.00
14	3,5-Dihydroxy-6-methyl-2,3-dihydro-4H-pyran-4-one	0.00	0.00	0.72	0.00	0.00	0.00	0.00	0.00
15	3-Buten-2-ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.06
16	3-Carene	4.08	0.00	22.04	0.51	0.00	6.27	2.74	1.52
17	3-Isopropyltoluene	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93
18	3-Methyl-4-methylenebicyclo[3.2.1]oct-2-ene	0.19	0.00	0.26	0.00	0.00	0.00	0.00	0.00
19	3-Methylpentane	0.00	0.00	0.00	0.00	0.00	0.50	1.32	0.00
20	4-Buten-2-ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.38
21	4-Hydroxy-5-methyl-3-propyl-2-hexanone	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00
22	5-Isopropenyl-1-methyl-1-cyclohexene	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00
23	Acetaldehyde	6.52	29.40	4.55	3.77	17.54	4.94	17.30	33.37
24	Acetic acid	0.00	0.00	1.00	0.00	1.16	0.00	0.00	0.00
25	Acetone	0.21	0.47	0.39	0.00	2.88	0.15	0.45	2.47
26	Acetone alcohol	0.00	0.00	0.27	0.00	0.94	0.00	0.00	0.00
27	alpha-Methylbutanal	0.10	1.01	0.00	0.00	0.00	0.00	0.00	0.00
28	alpha-Methylbutyric aldehyde	0.00	1.88	0.00	0.00	0.00	0.00	0.00	0.00
29	alpha-Pinene	9.68	0.83	2.01	0.00	0.92	0.68	0.00	0.00
30	alpha-Terpinolene	1.74	1.54	8.42	0.04	1.72	0.00	0.00	0.00
31	β-cis-Ocimene	0.07	6.93	0.30	0.00	5.18	0.00	0.00	0.00
32	β-Elemene	0.00	2.97	0.00	0.00	0.00	0.00	0.00	0.00
33	β-Eudesmene	0.00	0.00	0.00	0.00	0.00	2.68	0.48	0.33
34	β-Linalool	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.00
35	β-Methylbutanal	0.14	0.31	0.12	0.00	0.00	0.00	0.00	0.00

Table 1: Continue

No.	Compound name	Xoai Keo	Xoai Thai Xanh	Xoai Thanh Ca	Xoai Dai Loan	Xoai Cat Hoa Loc	Xoai Cat Chu	Xoai Uc	Xoai Thom
36	$\beta$ -Myrcene	2.04	0.00	4.52	0.00	0.57	1.54	0.00	0.00
37	$\beta$ -Phellandrene	0.60	0.00	3.02	0.00	0.00	0.90	0.00	0.00
38	$\beta$ -Terpinolene	52.74	2.08	36.47	1.05	46.75	48.83	21.59	9.39
39	$\beta$ -trans-Ocimene	0.00	0.39	0.00	0.00	0.00	0.00	0.00	0.00
40	Butanal	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00
41	Butylcyclobutane	0.00	0.00	0.00	0.00	0.00	0.00	1.79	0.00
42	Camphene	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
43	cis-3-Hexen-1-ol	0.00	0.49	0.00	0.00	0.00	0.00	0.00	0.00
44	cis-3-Hexen-1-yl butyrate	0.00	0.00	0.00	0.00	0.00	0.00	0.53	0.00
45	cis-3-Hexenol	0.00	0.00	0.00	0.00	0.00	0.00	1.44	2.37
46	cis-3-Hexenyl Acetate	0.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47	cis-Butyric Acid, 3-hexenyl ester	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
48	Cyclopentane	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.12
49	D-Limonene	1.09	0.00	4.61	0.03	0.68	1.34	11.01	0.00
50	E)-3-Penten-2-one	0.00	1.96	0.00	0.00	0.00	0.00	0.00	0.00
51	Ethyl (2E)-2-methyl-2-butenolate	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
52	Ethyl 2-butenolate	0.00	0.00	0.00	1.09	0.00	0.00	0.00	0.00
53	Ethyl 2-methylbutanoate	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
54	Ethyl 2-methylpropanoate	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
55	Ethyl 3-(methylthio)propionate	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
56	Ethyl Acetate	0.35	0.16	0.00	7.18	0.91	0.00	1.76	1.32
57	Ethyl alcohol	10.40	38.36	1.53	71.07	6.58	2.00	12.99	32.40
58	Ethyl butanoate	0.00	0.00	0.00	10.45	0.00	0.00	0.00	0.00
59	Ethyl carbonate	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
60	Ethyl ether	0.00	0.00	0.00	0.00	0.00	0.00	15.54	0.87
61	Ethyl methacrylate	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.00
62	Ethyl octanoate	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
63	Ethyl propanoate	0.00	0.00	0.00	0.35	0.00	0.00	0.00	0.00
64	Ethyl pyruvate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.12
65	Formal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.58
66	Formic acid	0.00	0.00	0.78	0.00	0.56	0.00	0.00	0.00
67	Furfural	0.00	0.00	1.30	0.00	0.00	0.00	0.00	0.00
68	gamma-Gurjune	0.00	3.04	0.00	0.00	0.00	0.00	0.00	0.00
69	gamma-Terpinene	0.24	0.00	0.71	0.00	0.00	0.18	0.00	0.00
70	Hexamethylethane	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.00
71	Hexanal	0.43	0.26	0.43	0.00	0.00	0.00	0.98	0.00
72	Hexane	0.73	1.41	0.91	0.00	0.66	3.04	0.00	0.00
73	Hexanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34
74	Isooctane	0.96	2.85	0.00	0.00	0.00	0.00	0.00	0.00
75	Methyl acetate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31
76	Methyl Alcohol	0.27	2.58	0.25	0.05	0.00	1.06	4.40	15.35
77	Methyl butanoate	0.00	0.00	0.00	0.21	0.65	0.00	0.00	0.00
78	Methylcyclopentane	0.00	0.00	0.00	0.00	0.00	0.13	0.00	0.00
79	Methylene Chloride	0.00	0.00	0.00	0.00	0.00	0.46	1.08	1.25
80	Methylthiirane	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.00
81	Monomethylolacetone	0.00	0.00	0.00	2.41	0.00	0.00	0.00	0.00
82	n-Butyl butanoate	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
83	n-Octyl nitrate	0.00	0.00	0.00	0.00	0.00	1.12	0.00	0.00
84	o-Cymene	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.62
85	o-Isopropenyltoluene	0.00	0.00	0.00	0.00	0.00	0.00	1.22	0.00
86	p-Cymen-8-ol	0.21	0.00	0.16	0.00	0.00	0.44	0.00	0.22
87	p-Cymene	0.21	0.00	0.28	0.00	0.00	0.00	0.00	0.72
88	Pentane	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00
89	p-Isopropenyl toluene	0.31	0.00	0.50	0.00	1.40	0.99	0.00	0.00
90	p-Methylacetophenone	0.14	0.00	0.00	0.00	0.00	0.38	0.00	0.00
91	Propanal	0.14	0.57	0.06	0.00	0.45	0.00	0.80	0.51
92	tert-Amyl Alcohol	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00
93	Tetramethylbutane	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00
94	trans-2-Hexenal	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.12
95	Trichloromethane	0.00	0.15	0.00	0.00	0.00	0.00	0.00	0.00

$\beta$ -linalool. The relative abundances varied greatly by cultivar. In general,  $\beta$ -terpinolene was the most abundant monoterpene in six of the eight cultivars. In particular, Xoai Keo exhibited an extremely high  $\beta$ -terpinolene level (52.74% of total volatiles) and also the highest Alpha-pinene (9.68%). Xoai Cat Chu and Xoai Cat Hoa Loc similarly showed very high  $\beta$ -terpinolene (48.83% and 46.75%, respectively). By contrast, Xoai Thai Xanh and Xoai Dai Loan had only trace  $\beta$ -terpinolene (2.08% and 1.05%).

Other monoterpenes were enriched in specific cultivars. Xoai Thanh Ca had a distinctive profile with elevated 3-carene (22.04%) and Alpha-terpinolene (8.42%), whereas Xoai Uc stood out for D-limonene (11.01%) and moderate  $\beta$ -terpinolene (21.59%). Xoai Thai Xanh was notable for high  $\beta$ -cis-ocimene (6.93%) by far the highest o-cimene level of any cultivar, as well as minor  $\beta$ -trans-ocimene (0.39%). Several compounds were exclusive to single cultivars: For example,  $\beta$ -linalool was detected only in Xoai Cat Chu (0.27%) and camphene only in Xoai Keo (0.16%). Alpha-pinene appeared in five cultivars (highest in Xoai Keo, lower in others).  $\beta$ -myrcene was present in Xoai Keo (2.04%), Xoai Thanh Ca (4.52%) and Xoai Cat Chu (1.54%) but undetected in the other cultivars.  $\beta$ -phellandrene occurred only in Xoai Keo (0.60%), Xoai Thanh Ca (3.02%) and Xoai Cat Chu (0.90%). Other minor monoterpenes (Gamma-terpinene, Alpha-terpinene) were present at <1% in select cultivars. Overall, the profile of each cultivar was unique: for instance, Xoai Thai Xanh's aroma was dominated by o-cymene, Xoai Thanh Ca by carene/terpinolene, Xoai Keo by terpinolene/alpha-pinene, Xoai Cat Chu/Xoai Cat Hoa Loc by terpinolene and Xoai Uc by limonene.

## DISCUSSION

The volatile profiles of the Vietnamese mango cultivars are dominated by monoterpenes, consistent with other studies showing that monoterpenes typically comprise the bulk of mango fruit aroma<sup>8,9</sup>. In our data,  $\beta$ -terpinolene emerged as a principal compound, especially in Xoai Keo, Xoai Cat Hoa Loc and Xoai Cat Chu. High terpinolene content has been reported in several mango cultivars elsewhere, for example, Chinese and Brazilian varieties rich in terpinolene have been identified<sup>9,10</sup>. Xoai Keo, very high alpha-pinene is also paralleled by reports of alpha-pinene dominating in certain Indian and Chinese cultivars<sup>7,9</sup>. Conversely, Xoai Thai Xanh was characterized by marked cis-ocimene, echoing findings in some Indian varieties where ocimenes were major volatiles<sup>8</sup>. Other compounds followed expected

patterns: D-limonene was prominent in Xoai Uc and moderate in other cultivars, aligning with limonene as a common aroma terpene<sup>7,10</sup>. Notably,  $\beta$ -linalool and camphene occurred only as trace components in single varieties (Xoai Cat Chu and Xoai Keo respectively). Such minor terpenoids, though low in concentration, can contribute floral or green notes and are often used as varietal markers<sup>11,12</sup>. Differences in volatile profiles may reflect both genetic and environmental drivers. Genetic factors, such as variation in terpene synthase genes, influence  $\beta$ -ocimene and limonene synthesis<sup>2</sup>. Environmental influences including Mekong Delta's tropical monsoon climate, high humidity and soil salinity also modulate aroma metabolism<sup>6</sup>, affecting cultivar-specific volatile abundance.

The clear cultivar-to-cultivar differences support the idea that volatile profiles can serve as chemical "fingerprints" for mango varieties. Indeed, volatile profiling has been proposed as a chemotaxonomic tool: In mango, both leaf and fruit volatile patterns are variety-specific<sup>12</sup>. The distinct monoterpene patterns observed here would likely allow chemotaxonomic discrimination of the eight Vietnamese cultivars, much as prior work grouped mangoes by dominant terpenes<sup>7,10</sup>. For example, cultivars with high  $\beta$ -terpinolene form a clear group in our data, whereas Xoai Thai Xanh and Xoai Dai Loan (both low-terpinolene, with Xoai Thai Xanh high in ocimene) would cluster separately.

These findings have practical implications for breeding and cultivar identification. From a breeding perspective, the observed variation suggests avenues for enhancing aroma: Crosses involving high-terpinolene parents (like Xoai Keo or Xoai Cat Chu) could be used to introgress strong herbal/piney notes, while parents like Xoai Thai Xanh could confer citrusy ocimene character<sup>8,10</sup>. Conversely, breeders have traditionally focused on agronomic traits (disease resistance, size, sweetness) rather than aroma<sup>13</sup>, so our results emphasize untapped flavor variation in these local cultivars that could be harnessed. For cultivar identification and protection, the monoterpene fingerprint offers biochemical markers. Volatiles such as alpha-pinene, limonene or  $\beta$ -linalool which varied consistently by cultivar could aid authentication of clonal identity, complementing genetic markers. Indeed, prior work has shown that specific volatiles can act as biomarkers for mango fruit maturity and variety<sup>13</sup>. In summary, the unique monoterpene profiles of these An Giang cultivars underscore both the rich aroma diversity within *Mangifera indica* and the value of volatile profiling in breeding and taxonomy<sup>11,12</sup>.

## CONCLUSION

This study provides a detailed characterization of volatile organic compounds (VOCs) underlying the aroma profiles of eight Vietnamese mango cultivars. The analysis revealed distinct cultivar-specific aroma chemotypes: Xoai Keo and Xoai Cat Chu were rich in  $\beta$ -terpinolene and  $\alpha$ -pinene; Xoai Thanh Ca exhibited high levels of 3-carene and  $\alpha$ -terpinolene; Xoai Uc was enriched in D-limonene; and Xoai Thai Xanh was distinguished by an abundance of  $\beta$ -ocimene. These results enhance understanding of mango aroma diversity and demonstrate that VOC profiling can effectively differentiate cultivars.

## SIGNIFICANCE STATEMENT

The findings have practical implications for mango breeding, quality control and germplasm management. Identified volatile profiles can guide the selection of cultivars with desirable aroma traits, serve as biochemical markers for cultivar authentication and ensure consistent flavor quality in the mango industry. Overall, this study highlights untapped aroma diversity and supports the integration of VOC-based profiling into modern mango improvement programs.

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