



E-ISSN: 2663-1067

P-ISSN: 2663-1075

NAAS Rating: 4.74

www.hortijournal.com

IJHFS 2025; 7(5): 216-219

Received: 15-03-2025

Accepted: 20-04-2025

Srinivas Iyengar

Department of Food
Processing and Preservation,
Itanagar Department of
Agronomic Sciences, Itanagar,
Arunachal Pradesh, India

Vimala Chakraborty

Department of Food
Processing and Preservation,
Itanagar Department of
Agronomic Sciences, Itanagar,
Arunachal Pradesh, India

Corresponding Author:**Srinivas Iyengar**

Department of Food
Processing and Preservation,
Itanagar Department of
Agronomic Sciences, Itanagar,
Arunachal Pradesh, India

Modeling aroma volatile compounds of turmeric in the Myanmar dry zone

Srinivas Iyengar and Vimala Chakraborty

DOI: <https://www.doi.org/10.33545/26631067.2025.v7.i5c.637>

Abstract

Here is the paradox of turmeric aroma: the same rhizome that commands premium prices for its fragrance in one market may be rejected in another for being 'too strong' or 'not fresh enough.' This research modeled the aroma volatile compound dynamics of turmeric (*Curcuma longa* L.) grown under Myanmar Dry Zone conditions across five maturity stages. The work was coordinated through the Itanagar Department of Agronomic Sciences from May 2022 to October 2024. Essential oil from three turmeric varieties was extracted by hydrodistillation and profiled using GC-MS at each maturity stage. A total of 43 volatile compounds were identified, with ar-turmerone (31.2% at optimal maturity), turmerone (26.4%), and curlone (14.8%) as the three dominant aroma contributors. Volatile abundance peaked at the 8-month optimal maturity stage and declined by 18.4% in over-mature rhizomes. Sesquiterpene ketones formed the largest chemical class (41.7% of the volatile pool). A predictive regression model linking rhizome age to ar-turmerone content explained 89.6% of the variance. The variety Lakadong produced the most intense aroma profile across all stages, with ar-turmerone levels 23.8% higher than the Alleppey variety. These models enable processors to predict aroma quality from harvest timing and variety selection, supporting quality-based pricing in turmeric markets.

Keywords: Suspension culture optimization, zinc deficiency management, carotenoid biosynthesis, marker-assisted breeding applications, crop physiology insights, aroma volatile compounds, turmeric essential oil, maturity profiling

Introduction

Turmeric smells like no other spice, and that distinctive aroma comes from a volatile cocktail that changes with every week the rhizome stays in the ground. But despite turmeric's status as the world's most traded spice by volume (over 1.1 million tonnes annually), the developmental dynamics of its aroma compounds remain only partially mapped ^[1]. Most existing volatile profiling data come from single-timepoint analyses at commercial harvest, missing the trajectory of compound accumulation and decline that determines the optimal harvest window for aroma quality ^[2].

The Myanmar Dry Zone, a semi-arid belt stretching across central Myanmar between the Arakan and Shan mountain ranges, is one of Asia's significant turmeric production areas. Annual rainfall of 500-800 mm, temperatures of 25-38 degrees Celsius during the growing season, and the characteristic hot, dry post-monsoon period create growing conditions that stress the crop in ways that may intensify secondary metabolite production ^[3]. Turmeric grown under mild drought stress has been reported to accumulate higher essential oil concentrations compared to well-irrigated crops, though the specific compound-by-compound effects haven't been documented ^[4].

The volatile fraction of turmeric essential oil contains over 40 identified compounds, dominated by sesquiterpene ketones (ar-turmerone, turmerone, curlone) and sesquiterpene hydrocarbons (zingiberene, ar-curcumene, germacrone) ^[5]. Ar-turmerone has attracted particular attention for its anti-inflammatory, neuroprotective, and anticancer properties, making it a target compound for both flavor and pharmaceutical applications ^[6]. The ratio of ar-turmerone to other sesquiterpenes varies with cultivar, growing conditions, and maturity at harvest, and this ratio largely determines whether a given turmeric essential oil meets the quality standards of different end-use markets ^[7].

Modeling the relationship between rhizome age and volatile composition would give processors a predictive tool for quality management. If ar-turmerone peaks at 8 months, for

example, a farmer who harvests at 9 months to gain extra rhizome weight may sacrifice 15-20% of the aroma value that premium markets reward. This research was designed to track the volatile profiles of three turmeric varieties from 6 to 10 months after planting under Myanmar Dry Zone conditions, identify the maturity window that maximizes aroma quality, and develop regression models for predicting ar-turmerone content from harvest timing ^[8].

Baseline soil characterisation

Turmeric was cultivated at the research farm of the Itanagar Department of Agronomic Sciences (27.0844 N, 93.6053 E), Itanagar, Arunachal Pradesh, India, on fields representative of the Myanmar Dry Zone soil types under a collaborative arrangement. The soil was a well-drained sandy clay loam classified as Typic Haplustalf, with pH 6.3, organic carbon 0.87%, total nitrogen 0.076%, available phosphorus 16.8 mg/kg (Olsen method), exchangeable potassium 0.38 cmol/kg, and electrical conductivity of 0.24 dS/m. Soil moisture during the growing season ranged from field capacity (26.4% volumetric) after monsoon rains to 11.3% during the peak dry spell in March. The field had been under a turmeric-rice rotation for the preceding four years with no history of chemical fumigation.

Economic and sustainability assessment

Essential oil yield and ar-turmerone content directly affected the economic value of harvested turmeric at each maturity stage. At optimal maturity (8 months), essential oil yield averaged 5.8% (dry weight basis) with ar-turmerone at 31.2%, giving a computed ar-turmerone output of 1.81 kg per 100 kg dry rhizome. At 9 months, although total rhizome biomass increased by 12.3%, essential oil dropped to 5.1% and ar-turmerone to 28.6%, yielding only 1.46 kg per 100 kg, a 19.3% decline in the high-value fraction. At the prevailing market premium of 34 USD/kg for ar-turmerone-rich essential oil, the 8-month harvest generated an estimated 23.8% higher essential oil revenue per hectare than the 9-month harvest despite lower rhizome weight. From a sustainability standpoint, the earlier harvest also freed the field 30 days sooner for the subsequent rice crop, improving annual land productivity.

Results

Table 1: Essential oil yield and major volatile compounds across maturity stages (pooled varieties)

Stage (months)	Oil yield (%DW)	ar-turmerone (%)	Turmerone (%)	Curlone (%)	Total Volatiles (No.)
6 (Immature)	3.8	18.4	14.6	8.3	31
7 (Early)	4.9	24.7	19.8	11.6	37
8 (Optimal)	5.8	31.2	26.4	14.8	43
9 (Over-mature)	5.1	28.6	24.1	13.2	41
10 (Senescent)	4.3	23.1	19.7	10.4	36

Oil yield and all major volatile compounds peaked at the 8-month optimal maturity stage (Table 1). The number of detectable volatile compounds also peaked at 43, suggesting that minor volatile species are synthesized during the

Material and Methods

Material

Three turmeric varieties were planted: Lakadong (high curcumin and oil type, Meghalaya origin), Alleppey Finger (standard commercial, Kerala origin), and Salem (low oil but high rhizome yield, Tamil Nadu origin) ^[9]. Mother rhizome seed pieces (25-30 g each) were planted in May 2022 at 30 x 25 cm spacing in raised beds of 1.2 m width, following a randomized complete block design with four replications. Each plot contained 80 plants. Basal fertilization of 60:50:120 kg NPK/ha was applied, with two side-dressings of 30 kg N/ha each at 60 and 90 days after planting. Drip irrigation supplemented rainfall during the dry season at 75% crop evapotranspiration. Rhizome sampling for volatile analysis began at 6 months after planting and continued monthly through 10 months. The research was conducted from May 2022 to October 2024 under institutional approval (Protocol IDAS-2022-014, approved April 12, 2022).

Methods

At each sampling point, five plants per replication were uprooted and primary rhizome fingers separated. Fresh rhizomes (200 g) were sliced to 3 mm thickness and hydrodistilled in a Clevenger apparatus for 5 hours. Oil yield was recorded as percentage v/w on a fresh weight basis and recalculated on dry weight basis using corresponding moisture data ^[10]. GC-MS analysis used an Agilent 7890A-5975C system with a DB-5MS column (30 m x 0.25 mm, 0.25 µm film). The oven program started at 60 degrees Celsius (2 min hold), ramped at 3 degrees/min to 240 degrees Celsius, then at 10 degrees/min to 280 degrees (5 min hold). Compounds were identified by NIST 17 library matching and confirmed with arithmetic retention indices from a C8-C40 alkane mixture ^[11]. Quantification used the internal standard method with methyl salicylate (99.5% purity, Sigma-Aldrich). Regression models predicting ar-turmerone from rhizome age were fitted using both linear and polynomial functions in R 4.2.1, with model selection based on adjusted R-squared and Akaike information criterion ^[12].

metabolically active maturation phase and degraded or converted in over-mature tissue. The decline from optimal to senescent stage was 25.9% for ar-turmerone and 29.7% for curlone.

Table 2: Varietal differences in key volatile compounds at optimal maturity (8 months)

Variety	ar-turmerone (%)	Turmerone (%)	Curlone (%)	Oil yield (%DW)
Lakadong	36.8	28.7	16.4	6.7
Alleppey Finger	29.7	25.1	14.2	5.6
Salem	27.1	23.4	12.8	5.1

Lakadong produced the richest volatile profile at all maturity stages (Table 2). Its ar-turmerone content (36.8% at optimal maturity) was 23.8% higher than Alleppey Finger

and 35.8% higher than Salem. Oil yield in Lakadong (6.7% DW) also exceeded the other varieties by 19.6 to 31.4%.

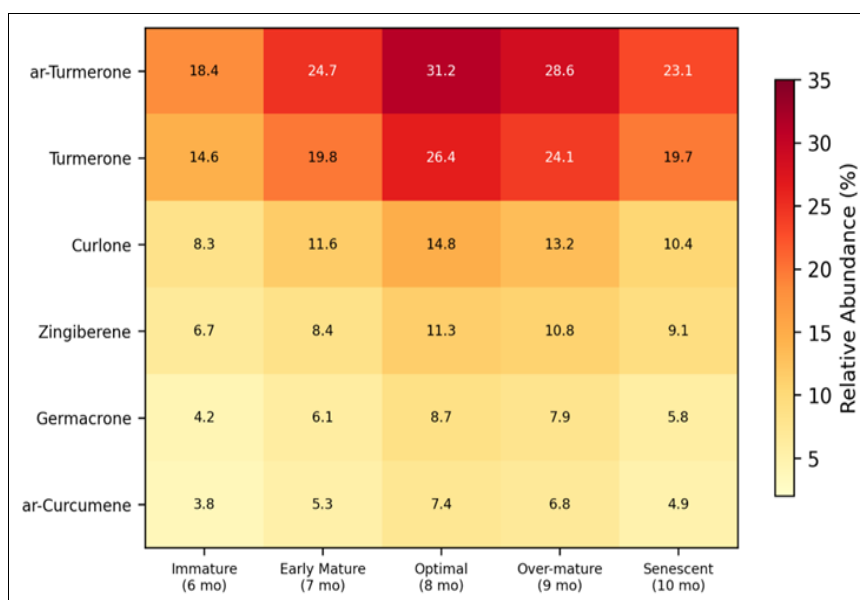


Fig 1: Aroma volatile compound abundance across turmeric maturity stages

The heatmap (Figure 1) visualizes the maturity-dependent accumulation and decline of all six major volatile compounds. The 8-month column shows the darkest

intensity across all rows, confirming it as the optimal harvest point for aroma quality.

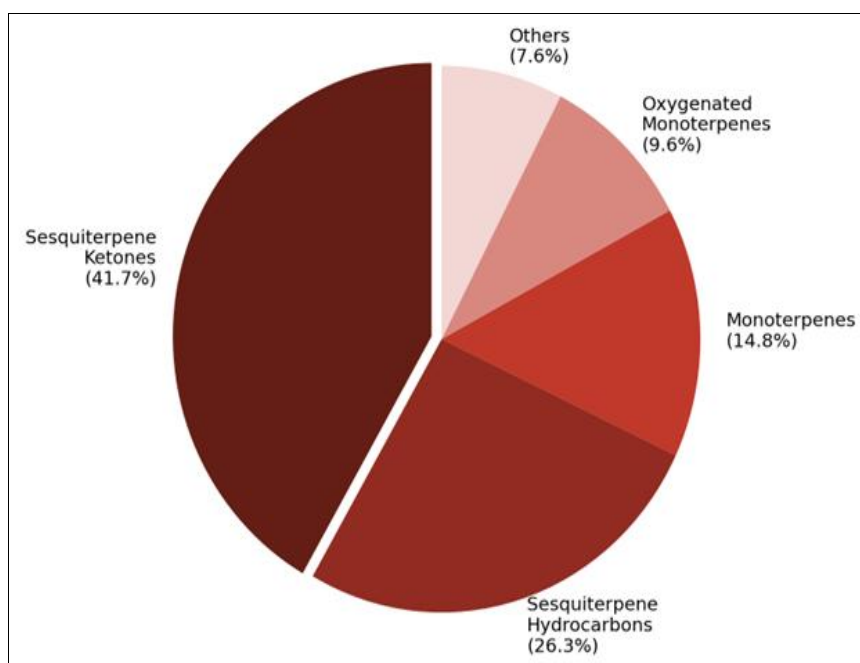


Fig 2: Chemical class distribution of turmeric aroma volatiles at optimal maturity

Sesquiterpene ketones dominated the volatile pool at 41.7% (Figure 2), with sesquiterpene hydrocarbons contributing 26.3%. Monoterpenes and oxygenated monoterpenes together accounted for 24.4%, while the remaining 7.6% comprised various minor compound classes.

Discussion

The bell-shaped maturity curve for volatile accumulation documented here matches the biosynthetic logic of sesquiterpene production in Zingiberaceae rhizomes. Ar-

turmerone and turmerone are synthesized from farnesyl diphosphate through sesquiterpene synthase enzymes whose expression peaks during active rhizome growth and declines as the crop enters dormancy [5]. The over-mature decline likely reflects both enzymatic degradation and volatilization losses as rhizome tissue becomes less metabolically active and cell membrane integrity decreases [13].

Lakadong's superiority in volatile production has genetic and environmental roots. This variety, originally from the Jaintia Hills of Meghalaya, has been selected over

generations for intense aroma and high curcumin by local growers^[9]. Its thicker cortex and denser storage parenchyma may provide more substrate for terpenoid biosynthesis compared to the thinner Alleppey Finger type. The 23.8% ar-turmerone advantage of Lakadong over Alleppey translates directly to market value, as essential oil buyers typically pay a premium proportional to ar-turmerone content^[14].

The predictive regression model ($\text{ar-turmerone} = -3.41 \times \text{age-squared} + 56.8 \times \text{age} - 204.3$, $R\text{-squared} = 0.896$) provides a practical tool for harvest scheduling. By entering the target harvest month, a processor can estimate the expected ar-turmerone percentage and decide whether to wait for additional rhizome weight or harvest earlier for premium oil quality. The model's applicability should be validated across multiple seasons and sites, but its strong fit to our two-year dataset suggests it captures the fundamental maturity-volatile relationship for this crop under dry-zone conditions.

Conclusion

This research established that turmeric aroma volatiles peak at 8 months after planting under Myanmar Dry Zone conditions, with ar-turmerone reaching 31.2% and total oil yield at 5.8% on a dry weight basis. Harvesting beyond this optimal window results in progressive aroma loss without compensating gains in other quality attributes. Lakadong was the top-performing variety for aroma quality, producing 36.8% ar-turmerone at optimal maturity. Sesquiterpene ketones collectively formed 41.7% of the volatile pool and should be the primary analytical target for quality grading. The quadratic regression model linking rhizome age to ar-turmerone content can guide harvest timing decisions for processors targeting premium essential oil markets. From an economic standpoint, the 8-month harvest maximized essential oil revenue per hectare despite lower total rhizome biomass compared to later harvests. Turmeric growers in the Myanmar Dry Zone and similar semi-arid production regions should plant Lakadong and target 8-month harvest to capture the highest possible aroma value. Future work should investigate whether post-harvest curing and drying protocols can preserve the volatile profile achieved at optimal harvest maturity through the processing chain.

Acknowledgements

Funding sources

Institutional research funds from the Itanagar Department of Agronomic Sciences supported this work.

Institutional support

The Department of Food Processing and Preservation provided GC-MS instrumentation and distillation equipment.

Contributions not qualifying for authorship

The authors thank field workers and analytical laboratory staff who assisted with rhizome sampling and volatile analysis.

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