



The effects of vapour heat treatment on key aroma volatiles of tropical fruits

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Abstract. This paper synthesises scholarly literature to explore the effects of vapour heat treatment (VHT) on aroma volatiles and flavour quality in tropical fruits. The effects of this phytosanitary treatment on volatile organic compound profiles and sensory qualities associated with three commercially important tropical fruits, namely mango, guava and papaya, were evaluated. Findings show that VHT had an effect on ripening dynamics and aroma emission patterns in mangoes, and the effect differs significantly based on the cultivar. With guava, the main sensory characteristics were mostly retained upon treatment, although long thermal processing can reduce the levels of important volatile compounds. Papaya requires VHT for export, and the effect of vapour heat treatment on its aroma volatiles is not well documented in the available literature. On the whole, the effects of VHT on fruit aroma are complex and dependent on cultivar type, which explains the need for additional research to optimize treatment protocols ensuring high level of phytosanitary safety and maintenance of the sensory attributes of tropical fruits.

Keywords and phrases: phytosanitary treatment, volatile organic compounds, fruit quality, sensory evaluation, postharvest technology

1. Introduction

National plant protection organizations (NPPOs) around the world utilize official pre-shipment and quarantine processes known as phytosanitary treatments to control biological threats associated with plants and their products from entering an importing country (Hennessey *et al.*, 2013). Pests and other organisms are prevented from contaminating plants or plant products by the exposure to various chemical and physical treatments (Hennessey *et al.*, 2013). Once these treatments have been applied, all unwanted organisms are inactivated, removed, or eliminated in the products as well as their packaging, rendering them safe to transport. Phytosanitary treatments ensure that exotic pests do not migrate to new areas or countries (Hennessey *et al.*, 2013). Many countries have approved the use of heat treatments as a quarantine disinfection method for a variety of tropical fruits due to their ease of application, effectiveness against fungi and insects, and the absence of chemical residues in products (Srimartpirom *et al.*, 2023). Hot water, steam, heat, and hot air treatments are the common methods employed for heating up agricultural products. Hot water treatment was initially used for controlling fungal growth, but it is now also applied for insect disinfestation, whereas vapour heat treatment was primarily designed for insect control. Hot air treatment is a technique utilized in controlling both insect and fungal infestation, as well as to determine the response of commodities to high temperatures (Chaurasia *et al.*, 2024; Jayasundara *et al.*, 2024; Ndlela *et al.*, 2022). Vapour heat treatment (VHT) aims at eradicating the possibility of the entry of insect pests that are related to the fruit into the territory of the importing countries. VHT entails the use of hot air that is fully saturated with water vapour to heat up the fruit interior to a predetermined temperature and maintain that temperature for a period of time to ensure that all target insects, insect eggs, and pests within the fruits are inactivated (Jacobi *et al.*, 2001).

VHT has become a mandatory phytosanitary treatment option for eradicating fruit fly (*Bactrocera dorsalis*) eggs in many host commodities, such as mangoes, papaya, and guava, in order to gain access to certain countries, such as Australia, Japan, and New Zealand, with strict sanitary and phytosanitary (SPS) requirements. Although there is much evidence of the effectiveness of VHT in pest control, particularly with regard to fruit flies, studies are currently being conducted on its indirect or invisible impact on the complex aroma volatiles and flavour quality of tropical fruits. The demand by consumers and the market value of fruits is greatly influenced by aroma and flavour, as it is widely accepted that volatile compounds are vital in the determination of fruit quality since flavour is influenced by volatile compounds (Granell & Rambla, 2013). Where appropriate, this review presents general studies on thermal processing such as hot water treatment, pasteurization, and heat treatment of purees to provide context for the potential mechanisms of

volatile degradation. However, it should be noted that these conditions are not similar to VHT due to differences in heating rate, medium (humid air versus liquid), and fruit tissue integrity. Mango, guava, and papaya were selected as the study fruits because of their importance in international trade, their possible susceptibility to fruit fly infestation, and VHT requirements for export to major markets such as Japan, Australia, and New Zealand. This review seeks to synthesise the existing understanding of VHT impact on the aroma volatile profiles and flavour characteristics of three commonly exported tropical fruits, namely mangoes, papaya, and guava, using more recent scientific literature.

2. The specific aroma signatures of tropical fruit

The aroma of fruits is mostly made up of volatile organic compounds (VOC). These compounds are generally small, low-polarity molecules with a weight of less than $M = 250\text{-}300\text{ Da}$. They have high vapour pressure, capable of crossing membranes easily and evaporating readily into the atmosphere, triggering the human senses through the olfactory receptors (Granell & Rambla, 2013). The nature of volatiles produced by fruits makes them chemically diverse. Some of the classes of volatile organic compounds found in fruits include aldehydes, ketones, alcohols, esters, organic acids, furanones, or terpenoids (El Hadi et al., 2013; Granell & Rambla, 2013). The aroma notes from this classification are distinct for each volatile compound, while terpenes generally produce fragrance notes of flowers and citrus, esters are known for their sweet fragrance notes, and aldehyde and alcohol-based volatile compounds are linked to green and fresh aromas. These compounds are biosynthesised through interconnected metabolic pathways, which include the fatty acid pathway, the terpenoid pathway, and the phenylpropanoid pathway (Lu et al., 2024; Granell & Rambla, 2013).

Table 1. VOC concentrations and variations in selected fruits

Fruit	VOC class	Key volatile compounds (VOCs)	Variation during ripening/storage	References
Banana	Esters	Isoamyl acetate, Butyl acetate, Isobutyl acetate	Esters increase rapidly, while C6 aldehydes (green notes) decrease.	(El Hadi et al., 2013; Taiti et al., 2015)
Mango	Terpenes	δ -3-carene, α -pinene, Limonene, Myrcene,	Terpenes are high in green fruit; esters increase as fruit matures, particularly in late storage.	(El Hadi et al., 2013; Xie et al., 2023; Taiti et al., 2015)

Fruit	VOC class	Key volatile compounds (VOCs)	Variation during ripening/storage	References
Pear	Esters/ Aldehydes	Hexyl acetate, Ethyl decadienoate, Hexyl 2-methylbutanoate	Aldehydes (e.g. Hexanal) decrease, while esters (pear-like) increase during ripening.	(El Hadi <i>et al.</i> , 2013; Xu <i>et al.</i> , 2023)
Tomato	Aldehydes	(E)-2-Nonenal, 2-Octenal, 2-Isobutylthiazole	High C6 aldehyde (green) content, decreases with maturity; refrigeration reduces aroma.	(El Hadi <i>et al.</i> , 2013; Guan <i>et al.</i> , 2025)
Apricot	Aldehydes	Hexanal, (E)-2-Hexenal, Linalool	Aldehydes (hexanal) dominate, decreasing during ripening, while terpene levels alter.	(El Hadi <i>et al.</i> , 2013)
Avocado	Aldehydes/ Terpenes	Hexanal, Myrcene, Acetaldehyde	Green notes (hexanal) decrease, while esters and acetaldehyde rise as maturity increases.	(El Hadi <i>et al.</i> , 2013; Taiti <i>et al.</i> , 2015)

2.1. Aroma of mango (*Mangifera indica*)

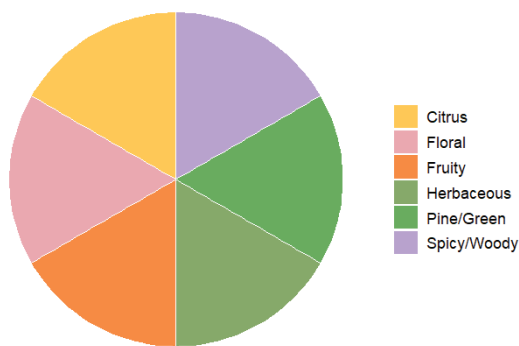
A mixture of volatile compounds such as terpenoids, alcohols, aldehydes, esters, carbonyl, and nitrogen-containing compounds gives mangoes their characteristic aroma. High levels of terpenes such as caryophyllene, α -pinene, and Δ^3 -carene, along with esters, which include ethyl butanoate and hexyl acetate, are the main aromatic volatile compounds in mangoes (Belgis *et al.*, 2023). These aroma compounds could differ based on the variety and ripeness of the mangoes; however, concentration level and aroma effects are influenced by storage conditions (Xie *et al.*, 2023).

Mango aroma volatile compound biosynthesis involves both fatty acid pathways and terpenoid biosynthetic pathways. For instance, linalool and α -terpineol organic compounds in mangoes are produced by the methylerythritol phosphate (MEP) pathway, while esters such as ethyl acetate and methyl butanoate result from the alcohol acyltransferase (AAT)-mediated esterification of alcohols with acyl-CoAs (Lu *et al.*, 2024; Granell & Rambla, 2013). The mass ratio of these aroma volatiles in mangoes will determine the aroma quality and intensity.

Table 2. VOC concentrations and variations in mangoes

Fruit	VOC class	Example compounds	Typical relative concentration (%)	Variations noted	References
Mango	Terpenoids	Δ^3 -carene, α -pinene	50–80 (dominant in many cultivars)	Higher in ‘Haden’, ‘Tommy Atkins’; lower at early maturity	(MacLeod & de Troconis, 1982; White et al., 2016; Narain & Galvão, 2004)
Mango	Esters	Ethyl dodecanoate, hexyl hexanoate	10–20	Increases postharvest; cultivar-specific (e.g. ‘Tommy Atkins’, ‘Nam Dok Mai Si Thong’)	(Narain & Galvão, 2004; Lin Aung et al., 2021)
Mango	Aldehydes	Hexanal	0–15	Varies with storage, ripening stage; declines after heat treatments	(Pandit et al., 2009; Lalel et al., 2003; Tandel et al., 2023; Zhang et al., 2019)

Citrus:(Limonene, γ -Terpinene)|Floral:(Linalool, α -Terpineol) | Fruity:(Ethyl butanoate, Hexyl acetate) | Pine/Green:(α -Pinene, β -Pinene, Δ^3 -Carene) | Spicy/Woody:(Caryophyllene, β -Myrcene) | Herbaceous:(β -Phellandrene, Terpinolene)



Source: data compiled from Belgis et al. (2023), Lu et al. (2024), Ounamornas et al., (2019), Wongkaew et al. (2021)

Figure 1. Aroma wheel of mango (*Mangifera indica* L.)

2.2. Aroma of papaya (*Carica papaya* L.)

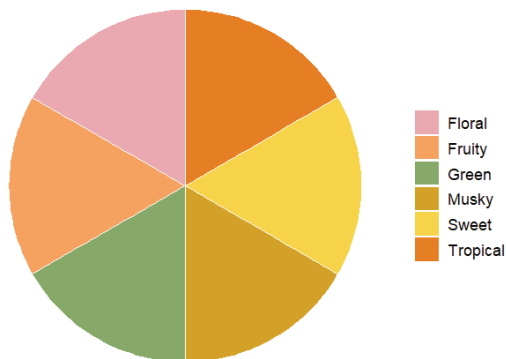
The aroma of papaya is typically soft and musky, and it is primarily comprised of esters and alcohols (Zhou *et al.*, 2021). Branched-chain amino acids such as leucine and isoleucine are used to produce aldehydes and esters through transamination and decarboxylation reactions. Amino acids would first undergo a transamination reaction to form the corresponding α -keto acids followed by decarboxylation to form aldehydes, which are then reduced to alcohols and esterified (Granell & Rambla, 2013; Lu *et al.*, 2024).

Table 3. VOC concentrations and variations in papaya

Fruit	VOC class	Example compounds	Typical relative concentration (%)	Variations noted	References
Papaya	Esters	Ethyl acetate, ethyl butanoate, methyl butanoate, and butyl acetate	20–90 (major aroma contributors)	Varies with fruits origin and cultivar type	(Pino <i>et al.</i> , 2003; Balbontín <i>et al.</i> , 2007)
Papaya	Alcohols	1-Hexanol, linalool	0–5	Higher in overripe fruit; varietal differences	(Jirovetz <i>et al.</i> , 2003)
Papaya	Organic acids	Citric, malic, and fumaric acid	11.67–379.49 mg/100 g	Increases with ripening; ascorbic acid	(Kelebek <i>et al.</i> , 2015; Ovando-Martínez <i>et al.</i> , 2018)

The primary enzymes involved are branched-chain aminotransferases (BCATs) and alcohol dehydrogenases (ADHs) as well as alcohol acyltransferase (AAT). These enzymes are regulated during ripening and respond to temperature and ethylene exposure (Lu *et al.*, 2024). Also, the aroma of papaya fruit tends to reduce in the postharvest period as the concentrations of the esters usually decrease during storage, which diminishes the sensory appeal (Shabina *et al.*, 2019).

Musky: (Isothiocyanatomethyl benzene, Benzyl nitrile) | Tropical: Exotic fruit notes (Linalool, Linalool oxide, β -Caryophyllene) |
Fruity:(Ethyl butanoate, δ -Decalactone, δ -Octalactone) | Floral:(Linalool, Verbenone, α -Terpineol) |
Green: Fresh, grassy (Hexanal, Nonanal, (Z)-2-Pentenol) | Sweet: Ripe, sugary notes (δ -Octalactone, Butanoic acid phenyl methyl ester)|



Sources: data compiled from Lu et al. (2024), Ulrich & Wijaya (2010), Zhou et al. (2021)

Figure 2. Aroma wheel of papaya (*Carica papaya* L.)

2.3. Aroma of guava (*Psidium guajava* L.)

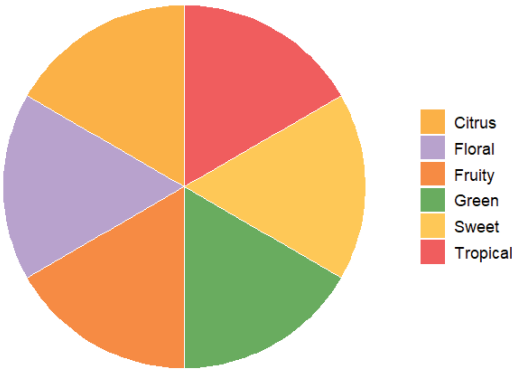
The aroma of guava is strong, sweet, and tropical. It is rich in esters, aldehydes, and terpenes. Methyl butanoate and ethyl butanoate are esters, adding fruity and sweet flavours, and hexanal and (E)-2-hexenal aldehydes add green and fresh flavours (Lu et al., 2024). Terpene compounds such as limonene and α -farnesene contribute citrus and floral notes to guava’s overall aroma profile (El Hadi et al., 2013). These aroma volatiles are produced as a result of the metabolism of fatty acids, directly through the lipoxygenase (LOX) pathway, which breaks down linoleic and linolenic acids into volatile aldehydes and alcohols that give fruits such as guava their fresh, green notes (Granell & Rambla, 2013).

Table 4. VOC concentrations and variations in guava

Fruit	VOC class	Example compounds	Typical relative concentration (%)	Variations noted	References
Guava	Esters	(E)-3-hexenyl acetate, 3-phenylpropyl acetate and ethyl esters	50–90	Dominant in sweet guava; off-flavours if excessive	(Pino & Trujillo, 2021; Porat et al., 2011)

Fruit	VOC class	Example compounds	Typical relative concentration (%)	Variations noted	References
Guava	Terpe-noids	-caryophyllene	20–42	Varies by type (apple vs sour guava); environment-dependent	(<i>Pino & Bent, 2013; Kamal et al., 2023</i>)
Guava	Organic acids	(E)-Cinnamic acid	95.4–374.00 mg/100 g	Higher in ripe pulp; sensitive to processing	(<i>Javed et al., 2016; Jawaheer et al., 2003</i>)

Sweet: Ripe, sugar(Methyl butanoate, Ethyl butanoate) | Fruity: Tropical fruit notes (Methyl butanoate, Ethyl butanoate)|
Tropical: Exotic fruit character (β-Caryophyllene, β-Caryophyllene oxide) | Green: Fresh, grassy (Hexanal, (E)-2-Hexenal) |
Citrus: Lemon-like (Limonene, α-Terpinene) | Floral:(α-Farnesene, Nerolidol) |



Sources: data compiled from Lu et al. (2024), Malik et al. (2021), Plaza et al. (2015), Steinhaus et al. (2008)

Figure 3. Aroma wheel of guava (Psidium guajava L.)

3. Vapour heat treatment of tropical fruits

The application of VHT has become a widely adopted quarantine method and safer alternative to the chemical fumigation for tropical fruits, especially mangoes exported to countries such as Japan from the Philippines, Taiwan, and India (Le et al., 2010). This process involves the immersion of fruit in heated, humid air until its core reaches a temperature that is fatal to fruit fly eggs and larvae development,

without affecting the market quality of the fruits. For instance, mango was subjected to VHT at a core temperature of 46.5 °C for 10–30 min in order to kill both oriental fruit fly and melon fruit fly of Nang Klangwan mangoes in Thailand and Irwin mangoes in Taiwan (*Hasbullah et al.*, 2001). VHT does not only control pests but also reduces postharvest diseases, including anthracnose and stem-end rot; therefore, this can be considered as a dual-purpose treatment for fruits intended for export (*Hasbullah et al.*, 2001).

Studies in Indonesia proving the effectiveness of VHT on local varieties of tropical fruits have been conducted. According to literature (*Lestari et al.*, 2017), VHT applied at 47 °C and with a processing time between 25 and 30 min was efficient in the disinfestation of the fruit flies in the Arumanis mangoes, and VHT followed by low-temperature storage at 13 ± 2 °C could preserve the quality of mangoes during storage. Notably, there was no physiological damage as a result of the treatment, as the fruit was still in a normal respiratory cycle. Storage temperature played a crucial role in prolonging mango shelf life: fruits stored at 13 ± 2 °C lasted for 18 days, whereas fruits stored at a temperature of 28 ± 2 °C had a short life span of only 9 days after VHT application (*Lestari et al.*, 2017).

Together these results show VHT as a useful and non-chemical solution to tropical fruit quarantine, as it does not affect weight loss, total soluble solids, and the firmness of tropical fruits. The empirical data obtained from both Okinawan Irwin mangoes and Indonesian Arumanis mangoes indicate that controlled exposure times (20–30 min) at a temperature of 47 °C can be used to achieve 100% fruit fly mortality, at the same time maintaining the acceptability of the fruits in foreign markets (*Hasbullah et al.*, 2001; *Lestari et al.*, 2017).

Table 5. Summary of documented effects of vapour heat treatment (VHT) on aroma volatiles and quality of tropical fruits

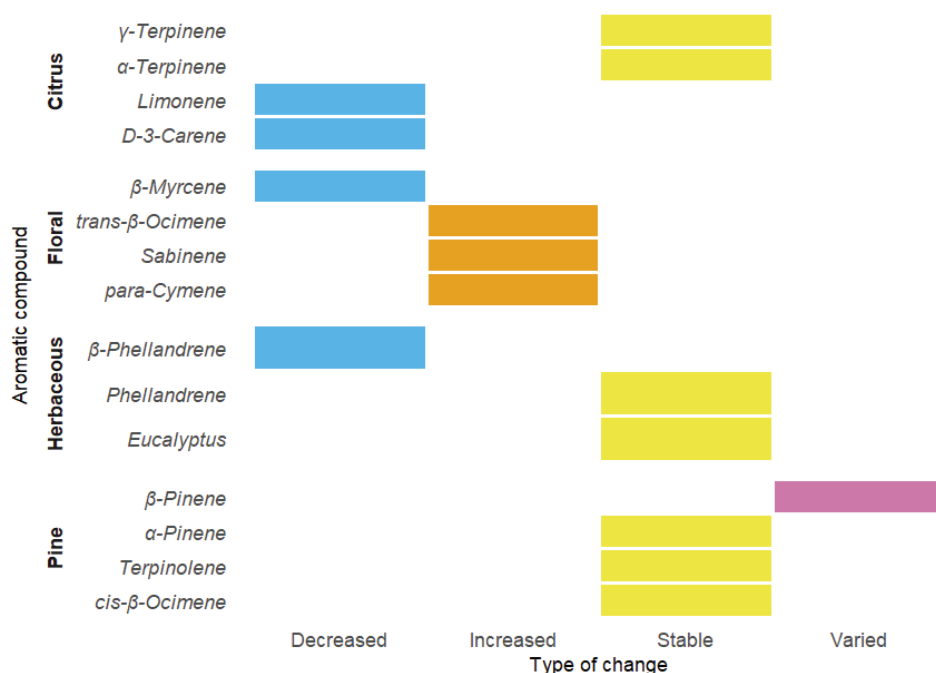
Fruit (cultivar)	VHT conditions	Key observed effects on aroma/volatiles
Mango (Chaunsa)	46.5 °C for 45 min, 47.5 °C for 30 min, 48 °C for 20 min	Accelerated ripening; delayed emission of aromatic volatiles (<i>Singh et al.</i> , 2014)
Mango (Samar Bahisht & Sufaid Chaunsa)	47 °C for 25 min	Improved eating quality (taste, flavour, aroma); increased phenolics, antioxidants, carotenoids (<i>Shah et al.</i> , 2021)
Mango (Keaw, Sam-pee)	General heat processing	Altered terpene hydrocarbons and oxygenated sesquiterpenoids (<i>Wongkaew et al.</i> , 2021)
Guava (Gola & Surahi)	47.5 °C for 25 min	Preserved aroma profile; maintained eating quality, colour, SSC, ascorbic acid (<i>Malik et al.</i> , 2021)

3.1. Vapour heat treatment of mangoes

Mangoes undergoing VHT as a quarantine disinfestation treatment exhibit minor but definite changes, as it does affect the mango ripening process and alters the balance of volatile aromatic compounds. Research conducted by *Singh et al.* (2014) found that the ripening process of a sample of mangoes was accelerated through the application of VHT (46.5 °C for 45 min or 47.5 °C for 30 min or 48 °C for 20 min), and the fruits reached an edible soft stage faster than untreated or control samples whilst potentially delaying the emission of aromatic volatiles to a significant degree. This implies that the volatile aroma compounds found in mangoes can be delayed or altered, as the ripening process in mangoes proceeds after VHT application.

However, VHT effects on mango fruits are not entirely negative. In another study, VHT was shown to enhance the organoleptic properties (taste, flavour, texture, and aroma) of mangoes. A study exploring two varieties of mango fruit, namely Samar Bahisht Chaunsa and Sufaid Chaunsa, has shown that VHT applied at 47 °C for 25 min in accordance with Japanese quarantine treatment improved the eating quality of the mangoes. The mango varieties treated using the VHT method showed better eating quality in terms of their taste, flavour, texture, and aroma. The mangoes also recorded higher values for total phenolic content, total antioxidant capacity, and carotenoids as compared to untreated mango fruits (*Shah et al.*, 2021). This indicates that the cultivar type and VHT parameters used play a key role in influencing the outcome.

Apart from VHT, the general thermal processing of mangoes has been reported to cause volatile profile changes in the fruit. Studies involving over-ripe Thai mango puree revealed that heat treatment could change the aromatic properties of mangoes, and the effects are highly dependent on the mango variety. In particular, the amount of both terpene hydrocarbons and oxygenated sesquiterpenoid molecules were found to be altered after exposure to heat treatment. The Maha-Chanok mango variety recorded a relatively unchanged volatile profile, while other varieties such as the Keaw and Sam-Pee demonstrated significant chemical composition changes as a result of heating (*Wongkaew et al.*, 2021). Consistent with previous studies, an analysis of the use of heat treatment at 85 °C for 15 min in mango flesh has identified changes in primary aromatic components, including pine (i.e. α -pinene, -pinene, terpinolene cis--ocimene), herbaceous (i.e. -phellandrene, phellandrene, eucalyptus), floral (i.e. sabinene, -myrcene, para cymene, trans--ocimene), and citrus (i.e. Δ^3 -carene, α -terpinene, limonene, -terpinene) aromatic volatiles in a range of Thai mango varieties (*Ounamornas et al.*, 2019). The results obtained are an indication that the aromatic response in mango is dependent on the type of mango variety undergoing thermal stress.



Source: based on findings from Ounamornas et al. (2019) in Thai mango cultivars

Figure 4. Effect of heat treatment (85 °C, 15 min) on aromatic compounds

3.2. Vapour heat treatment of guava

VHT has also been used as a phytosanitary method on guava fruits, and promising results were obtained in terms of preserving the quality of fruits. Studies showed that VHT applied at 47.5 °C for 25 min was effective for guava cultivars as an environmentally friendly and safe quarantine treatment that maintained the physical, biochemical, and overall eating quality of guava. The Gola and Surahi varieties of guava maintained a higher fruit marketability index and eating quality in relation to taste, flavour, and aroma, along with better colour, as well as higher soluble solid content, sugar acid ratio, and ascorbic acid content (Malik et al., 2021). This implies that VHT can be used on guava without any major adverse effects on the sensory characteristics valued by consumers.

However, the effects of thermal processing on the volatile compounds of guava require further investigation from a broader perspective. A comparison of thermal treatment with other processes, such as dense phase carbon dioxide (DPCD) treatment of guava purée, has confirmed that thermal processing can significantly

reduce total sulphur peak areas and alter volatile profiles. The thermal treatment led to the decrease of total sulphur peak area by 47.9%, thus affecting the overall volatile composition (Plaza *et al.*, 2015).

Even though this analysis was conducted on puree and not on whole guava fruits using VHT, it highlights the fact that the guava's volatile profile is vulnerable to heat. Aldehydes and terpenoids are the main flavour compounds that are usually found in guava juices, and they confer the aromatic characteristics on the fruit. Various treatments, including pectinase pre-treatment, can significantly change the absolute and relative concentrations of such volatile compounds, leading to lower scores in sensory evaluation due to a decrease in the relative concentration of important aroma constituents (Chen *et al.*, 2023). These results indicate the need to carefully optimize the conditions of thermal processing to prevent unwanted changes in the aroma of fruits. The complex profile of the guava aroma contains many volatile organic compounds, including 4-methoxy-2,5-dimethyl-3(2H)-furanone and 3-sulfanylethyl acetate among others, which produce its original guava aroma (Steinhaus *et al.*, 2008). Any treatment that affects these volatile compounds will probably have an adverse effect on the sensory properties of the guava fruit.

Table 6. Effects of pectinase on guava juice

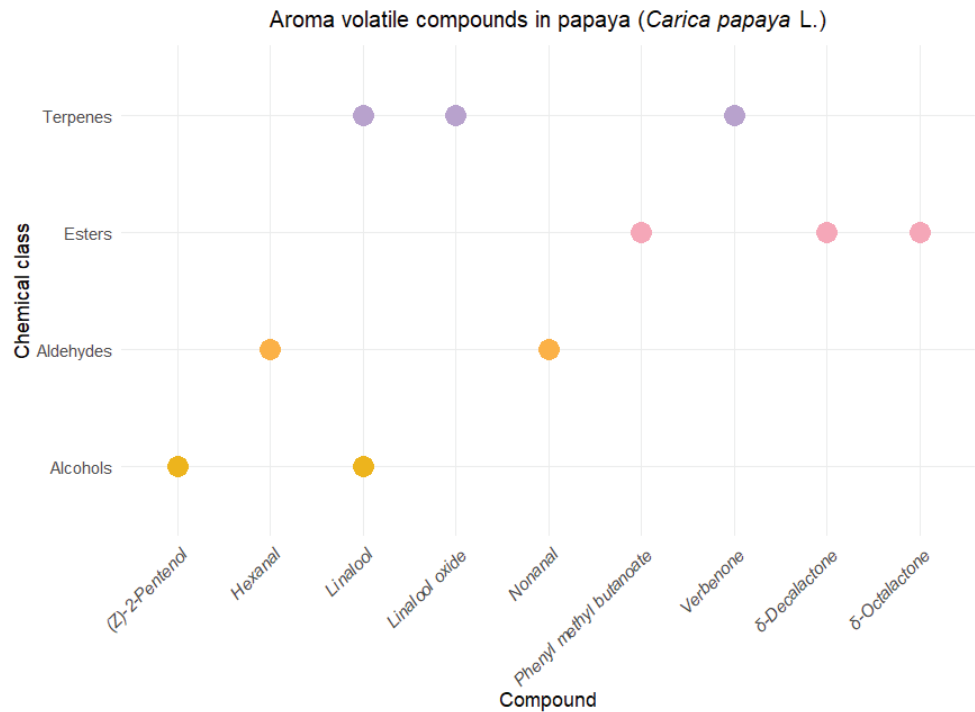
Parameter	Control (without pectinase)	Pectinase-treated	Change
Juice yield	Baseline	Improved	Positive
Total phenolics	Baseline	Increased ↑	Positive
Total flavonoids	Baseline	Increased ↑	Positive
Key volatiles	Aldehydes, terpenoids dominant	Main aroma constituents decreased	Negative
Sensory score	Higher	Lower ↓	Negative
Key guava odourants	4-methoxy-2,5-dimethyl-3(2H)-furanone 3-sulfanylethyl acetate	Likely affected	Vulnerable

Sources: Chen *et al.* (2023), Steinhaus *et al.* (2008)

3.3. Vapour heat treatment of papaya

Papaya (*Carica papaya* L.) plays a significant role in global fruit trade, and it is highly susceptible to fruit fly infestations, therefore often subjected to phytosanitary measures such as VHT when exported to EU markets (Srimartpirom *et al.*, 2023). Despite this commercial relevance, research work specifically targeting the impact

of vapour heat treatment on the aroma volatiles and flavour quality of papaya remains limited in the existing literature. Papaya is known to have a unique aromatic profile due to the complex interaction of volatile organic compounds. General reviews of tropical fruit aroma often cite papaya as a fruit containing a distinctive volatile aroma profile that includes aldehydes, alcohols, esters, and terpenes (Ulrich & Wijaya, 2010).



Source: based on findings from Ulrich & Wijaya (2010)

Figure 5. Key aroma volatile compounds in papaya by chemical class

In particular, esters such as methyl and ethyl butanoate contribute fruity and sweet notes to papaya, while terpenes such as limonene and linalool confer citrusy and floral notes (Zhou *et al.*, 2021; Lu *et al.*, 2024). These volatile compounds are biosynthesized through temperature-sensitive pathways, including the fatty acid and amino acid metabolism, and are therefore potentially sensitive to heat during the VHT process (Granell & Rambla, 2013). However, the effects of VHT, specifically on papaya, in regard to enhancing, delaying, or degrading the biosynthesis and the emission of these volatiles' compounds remain unexplored. Recent developments in metabolomic modelling are beginning to associate volatile compounds with consumer preferences for papaya. According to Lomax *et al.*

(2026), aroma characteristics explained 31% of the variance in acceptance, while volatile organic compounds explained 63%, together accounting for 94% of the variance in consumer liking of papaya, highlighting the commercial importance of understanding the VHT effects on papaya aroma volatiles. Available studies on the thermal processing of papaya have focused on disease control and general quality parameters of the fruit (*Shabina et al.*, 2019), with limited attention to changes in volatile components. This knowledge gap is relevant, as esters that constitute a significant portion of the aroma profile of papaya are formed through temperature-sensitive enzymatic reactions that can be affected by VHT protocols that target core temperatures of 46.5–47.5 °C (*Srimartpirom et al.*, 2023). Further studies are required to systematically characterize post-VHT papaya volatile profiles using gas chromatography–mass spectrometry (GC–MS) and sensory analysis, ensuring that phytosanitary interventions do not impair the sensory properties of papaya fruit.

4. Challenges and future directions

The existing literature is insightful, and presents numerous challenges and opportunities for future research. What is consistently noted is that VHT affects different fruit species (even cultivars within the same species) in different ways, with varying results. This renders a generalized strategy for enhancing the potential of VHT ineffective. Therefore, broader studies are needed to outline the biochemical pathways that are influenced by VHT, with special attention to the processes that control the synthesis and degradation of key aroma volatiles. Specifically, further studies are required to determine the effects of VHT on key enzymes such as alcohol acyltransferase (AAT), lipoxygenase (LOX), and terpene synthases (TPS), which govern the production of the major aroma compounds, including esters, aldehydes, and terpenoids in tropical fruits. Transcriptomic and proteomic analyses using RNA sequencing and LC-MS/MS, respectively, could be used to track these molecular changes during and after VHT application.

Also, the significant research gap regarding the effect of VHT on papaya aroma and flavour is of great importance for future research. Due to the economic importance of papaya, the determination of how VHT affects its sensory properties is necessary to maintain market competitiveness and increase consumer satisfaction. Controlled VHT experiments under standard quarantine conditions (core temperature of 20–30 minutes at 46.5–47.5 °C) should be prioritized in commercially important varieties, including Solo, Eksotika, and Red Lady, with time course sampling in order to identify volatile changes following treatment and during the entire ripening process. Future studies should use advanced analytical methods such

as gas chromatography–mass spectrometry (GC–MS) and gas chromatography–olfactometry (GC–O) together with sensory assessment panels to carefully map changes in volatile constituents and their correlation with perceptive flavour quality. For the real-time monitoring of volatile emissions during the VHT process itself, techniques such as proton-transfer-reaction mass spectrometry (PTR-TOF-MS) and electronic nose technology are some complementary methods that can also be applied. The main objective must be to improve the VHT protocol so that it is not only phytosanitary but also conserves or even enhances desirable aroma compounds. Important parameters to test are the heating rate, the cooling method, and the possibility of combining VHT with controlled atmosphere storage in an attempt to reducing the negative effects on aroma.



Figure 6. Commercial-scale vapour heat treatment (VHT) machine in Indonesia (PT Buah Angkasa)

VHT is considered one of the most important technologies that allows shipments of tropical fruits such as mangoes, guava, and papaya to comply with quarantine regulations in order to enter premium markets, e.g. Japan. According to Horti Indonesia, the establishment of VHT facilities in Indonesia will help alleviate the ban on mango exports to Japan, as it will allow exporters to keep mangoes free from fruit fly and also maintain the quality of the fruit when applying the treatment process. To ensure that research findings can translate to commercial applications, future studies need to confirm optimized protocols under realistic conditions in facilities like PT Buah Angkasa in Indonesia.

5. Conclusions

While phytosanitary use is the main purpose of VHT, it has a complex and oftentimes unseen or undetectable effect on the volatile substances (aroma compounds) of tropical fruits. Studies have demonstrated that the intensity of VHT correlates positively with the degree of volatile changes, higher treatment intensity being associated with higher volatile degradation; however, this is dependent on the cultivar and the processing characteristics. Data-driven analysis has shown that in the case of mangoes, VHT affects ripening dynamics and changes volatile emission patterns. On the other hand, in some combinations of cultivar and process parameters, the process shows a positive correlation with an increase in the overall sensorial quality. In guava, phenolic and biochemical properties were maintained after the application of VHT, and the fruits were able to retain their quality attributes, indicating a positive correlation; however, general thermal processing conditions may significantly change its volatile structure (negative correlation). The gap in knowledge with regard to the exact effects of VHT on the aroma and flavour properties of papaya calls for further investigations. Therefore, there is an urgent need for cultivar-specific studies adopting advanced analytical procedures to develop VHT strategies that would guarantee the safety of fruits and maintain their sensory-related characteristics to provide value for consumers and producers.

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