horticulturae

Review

Volatile Organic Compounds from Basil Essential Oils: Plant Taxonomy, Biological Activities, and Their Applications in Tropical Fruit Productions

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Citation: Tangpao, T.; Charoimek, N.; Teerakitchotikan, P.; Leksawasdi, N.; Jantanasakulwong, K.; Rachtanapun, P.; Seesuriyachan, P.; Phimolsiripol, Y.; Chaiyaso, T.; Ruksiriwanich, W.; et al. Volatile Organic Compounds from Basil Essential Oils: Plant Taxonomy, Biological Activities, and Their Applications in Tropical Fruit Productions. *Horticulturae* **2022**, *8*, 144. https://doi.org/10.3390/horticulturae8020144

Academic Editors: Dasha Mihaylova, Aneta Popova and Isabel Lara

Received: 28 December 2021
Accepted: 5 February 2022
Published: 8 February 2022

Abstract: Basils of the genus *Ocimum* are aromatic plants grown widely throughout the tropical and temperate regions. The essential oils obtained from their aerial parts are enriched with volatile organic compounds with high market demand for food and pharmaceutical industries. The volatile organic compounds have been shown to exhibit biological activities. Therefore, their novel applications have been extensively explored in the last few decades. The most widely available basils in the tropical areas include white holy basil (*O. sanctum* var. Shyama), red holy basil (*O. sanctum* var. Rama), Thai basil (*O. basilicum* var. thyrsiflorum), lemon basil (*O. citriodorum*), and tree basil (*O. gratissimum*). Over 60 volatiles of different classes have been exclusively described, and some of them could be useful as biomarkers for genotype specification. The major volatile ingredient is the phenylpropanoids, such as methyl eugenol, which has the potential as a natural product for mitigating Oriental fruit fly (*Bactrocera dorsalis*) during tropical fruit production. Moreover, basil essential oils are also used to control diseases of the fruits during post-harvest storage. As a result, the application of basil essential oils as a sustainable defect control strategy for tropical fruit value chains seems intriguing. This review provides comprehensive information on plant taxonomy and volatile compositions of the essential oil fractions from different basil species. Their biological activities and applications are also discussed, mainly during the pre- and post-production of tropical fruits. Additionally, the available techniques to enhance the efficacy of the volatile active compounds are also described.

Keywords: essential oil; integrated pest management; Oriental fruit fly; pomology; post-harvest disease control

1. Introduction

Ocimum is one of the important genera within the wealthiest essential oil-bearing plant family, the Lamiaceae. It is represented by more than 150 species cultivated and distributed throughout the tropical and temperate regions [1]. They are collectively known as the "basils" that retain the commercial demand for their nutritional, aromatic, ornamental, culinary, religious, and medicinal importance [2]. Different basil types are commonly used, including holy basil (*O. sanctum*), sweet or Thai basil (*O. basilicum*), lemon basil (*O. citriodorum*), and tree basil (*O. gratissimum)* [3,4]. It is well established that different basil cultivars have the genetic potential to create and maintain distinct sets of volatile components, resulting in a wide variety of chemotypes within the same basil species [5]. The essential oils of these basils are predominantly constituted of phenylpropanoids such as estragole, eugenol, and methyl eugenol; however, they also contain common monoterpenes such as geranial, neral, and α-ocimene, as well as sesquiterpenes such as β-caryophyllene, α-cubebene, and γ-muurolene [6]. Most of which are biologically active on living organisms, especially the antimicrobial and antioxidant properties for food and medicinal uses [7,8]. It was discovered that eugenol has antimicrobial and analgesic effects on humans [9]. Additionally, the essential oils also possess a wide range of biological functions that theoretically minimise post-harvest deteriorations. Volatile organic compounds have been shown to inhibit the growth of microorganisms, especially those responsible for post-harvest diseases such as *Aspergillus* spp. [10–12], *Colletotrichum acutatum* [13], *Botrytis cinerea* [14], and *Penicillium italicum* [15]. They have also been extensively used in insect pest management to control rice weevil (*Sitophilus oryzae*) [16], bean weevil (*Acanthoscelides obtectus*) [17], and cotton bollworm (*Helicoverpa armigera*) [18]. Prominently, methyl eugenol has been claimed for its ability to attract Oriental fruit flies (*Bactrocera dorsalis*) [19], the most important tropical fruit pest [20,21]. The estimated annual loss from this pest alone is roughly over US$ 100 million, and mangoes have been the most susceptible crops [20,21]. Aside from the infestation of the Oriental fruit flies that cause physiological damage to fresh fruits, biological stress could encourage post-harvest biochemical mechanisms such as browning and physiological decay [22]. A study of fresh apple has also proven that spraying the sweet basil essential oil on the fruit skin illustrated the preservative effect, thereby extending its shelf life [23]. With all these advantages, it is interesting to use basil essential oils as biological controls during the production of tropical fruits. However, the instability of essential oils at ambient conditions, as well as harsh environmental exposure, are the limitations. Moreover, volatile organic compounds decompose quickly with the presence of light, heat, humidity, and oxygen [24].

This review aims to serve as a guide to using the volatile components obtained from commercially available *Ocimum* species in the development of functional products for the sustainable production of tropical fruits. It attempts to provide the relevant data, both taxonomical and chemotypes, with particular attention to the biological activities and applications. The typical constraints of these applied uses are discussed, along with the recent approaches to improve efficiency.

2. Taxonomy

The genus *Ocimum* is known as one of the most prominent genera in the Lamiaceae family and currently comprises more than 150 species [1,25]. The distribution is mainly in the tropical and template regions and is likely to have originated (mainly the holy basil) in India [26]. Recently, they have been cultivated worldwide as culinary herbs and for essential oil extraction [27]. Taxonomical identification within the genus and between the varieties can be made by the morphological characteristics such as leaf shape and its colour, flower, and seed morphology [4,28]. Numerous polymorphisms resulting from extended cultivation and inter- and intra-specific cross hybridisation result in a vast range of subspecies, each with its own chemical makeup and biological activity [25,29,30].

The commonly available *Ocimum* plants were studied in the previous work for their distinct morphological characteristics [6]. The leaf is generally simple, petiolate and the leaf blade is ovate with a rounded base, oblique, and the apex is acute. *O. gratissimum* has a large leaf size (~45 cm^2), whereas *O. citriodorum* has a leaf size of around 3.5 cm^2 (Figure 1c,d). The *O. sanctum* of var. Rama and Shyama can be distinguished by having the aerials of red and white (Figure 1a). Similarly, different leaf and stem colours were noticed, ranging from red, purple-green, and green among the different varieties of the *O. basilicum* L. used in Iran [31]. Singh [32] used the number of leaf veins to show that *O. americanum* was described to have seven distinct veins, and the mid-vein reached the apex, while *O. tenuiflorum* has nine distinct veins, and the mid-vein does not reach the apex. The typical inflorescence of *Ocimum* spp. is a thyrse composed of opposite 1–3-flowered cymes (Figure 1b) [33]. The calyx is generally a short tube or funnel-shaped; it is straight or slightly curved. The corolla is formed forward (sometimes bent downwards), larger upper lip and a smaller lower one and declinate stamens [34]. The posterior lip of the corolla comprises four lobes. There are always four stamens, an anterior pair that attaches near the corolla mouth and a posterior pair that connects close to the corolla base. The size of basil seeds varies depending on the phenotype, cultivating location, and moisture content [35]. Its colour can occasionally be used to differentiate between varieties [36]. The complex polysaccharide structure gives the seed a unique mucilaginous characteristic after soaking in water, which is prominent in *O. citriodorum* and *O. basilicum* var. thyrsiflorum. Table 1 illustrates the taxonomical characteristics of different basil species.

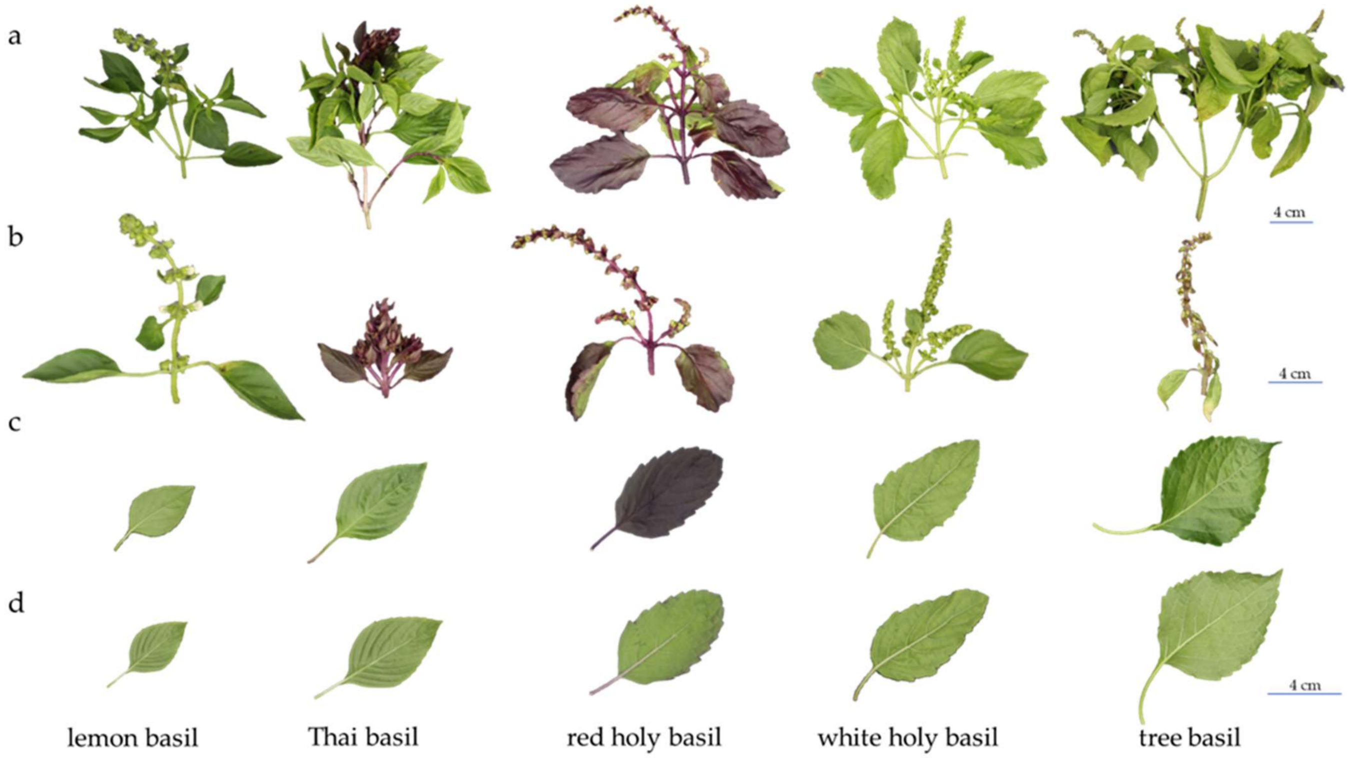


Figure 1. Morphological characteristics of some *Ocimum* species; aerial part (**a**) inflorescence (**b**) upper (**c**) and lower (**d**) leaf surface of lemon basil (*O. citriodorum*), Thai basil (*O. basilicum* var. thyrsiflorum), red holy basil (*O. sanctum* var. Rama), white holy basil (*O. sanctum* var. Shyama) and tree basil (*O. gratissimum*).

Table 1. Comparison of morphological characteristics of studied *Ocimum* species.

Scientific Name	Common Name	Overall Characteristic	Leaf		Fluorescence		Seed Characteristics	Location	References
			General Characteristic	Leaf Colour	General Characteristic	Flower Colour			
O. americanum L.	bon tulsi	annual, herb, 20–60 cm tall	leaf elliptic-lanceolate, leaf surface glabrous except hairy midrib, veinlets, and margin	grey green	inflorescence greenish, calyx green with sometimes purplish stripe, long hairy	white	seed black, narrowly ellipsoid, mucilaginous	India	[25]
O. × *africanum Lour.* or *O. citriodorum*	lebu tulsi, lemon basil	annual, herb, 45–105 cm tall	leaf size ~3.5 × 1 cm, leaf elliptic—broadly obovate, glabrous except hairy midrib, veinlets, and margin	n/d	inflorescence greenish, calyx green, long hairy	white	seed brownish-black, ellipsoid, mucilaginous	India, Thailand	[6,25]
O. basilicum var. thyrsiflorum	Thai basil, marua tulsi	annual, herb, 45–100 cm tall	leaf size ~5.5 × 2 cm, leaf ovate-lanceolate to oblong-lanceolate, glabrous except hairy midrib, veinlets, and margin	n/d	inflorescence greenish, calyx green, long hairy	pinkish white	seed brownish-black, ellipsoid, mucilaginous	Thailand, India	[6,25]
O. gratissimum var. *macro-phyllum*	tree basil, clove basil, African basil, ram tulsi	perennial, undershrub, or shrub, 140–200 cm tall	leaf size ~9 × 5 cm, leaf lanceolate, ovate or ovate-lanceolate, glabrous except hairy midrib	n/d	inflorescence greenish-purple, calyx greenish-purple, hairy	purple, yellowish-white	seed brown, sub-globose, non-mucilaginous	Thailand, India	[6,25,37,38]
O. kilimand-scharicum Guerke	karpur tulsi	perennial, herb, 60–120 cm tall	leaf ovate-oblong, leaf surface pubescent with white hairs on both sides, much denser and longer on veins beneath	n/d	inflorescence, greenish-greyish, calyx greenish-greyish, densely hairy	white	seed black, narrowly ellipsoid, mucilaginous	India	[25]
O. sanctum or *O. tenuiflorum* var. Shyama	red holy basil, krishna tulsi	annual to biannual, branched sub-shrub 30–150 cm tall	simple opposite leaves, leaf size ~4 × 1.5 cm, ovate-obovate, elliptic-oblong, surface patently hairy to clothed with soft spreading hair, purple leaf	purple	inflorescence purple, calyx purple, patently hairy to densely pubescent	purplish	seed brown, globose, non-mucilaginous	Thailand, India	[6,25,39]
O. sanctum or *O. tenuiflorum* var. Rama	white holy basil, radha tulsi	annual to biannual, branched sub-shrub 30–160 cm tall	simple opposite leaves, leaf size ~4 × 1.5 cm, leaf ovate-obovate, elliptic-oblong, surface patently hairy to clothed with soft spreading hair, green leaf	green	inflorescence green-greenish-purple, calyx green, patently hairy to densely pubescent	purplish	seed brown, globose, non-mucilaginous	Thailand, India	[6,25,39]
O. suave or *O. gratissimum* var. *suave*	holy basil, wild basil	92.75 cm tall, 84.42 cm width	leaf blade ovate-oblong to oblong ~5–12 × 1.5–6 cm, gradually reduced toward apex, slightly scabrid	grey green	inflorescence with persistent bracts, calyces flattened dorsoventrally tinged with brown, corolla small white	white	brownish, black-globose, subglobose, non-mucilaginous	India	[38,40–42]
O. viride	African basil, nunum	158.58 cm. tall, 114.71 cm width	leaf size ~4.73 × 9.46 cm	n/d	less conspicuous, autogamous, fruiting calyx large amount of terpene	brownish green	brownish, black-globose, subglobose, non-mucilaginous when wetted	India	[38,40,43,44]

n/d = no data.

3. Volatile Chemical Compositions of Basil Essential Oils

A number of unique epidermal structures known as trichomes are developed on the surface of the aerial part, which may or may not be secretory [45]. These include the glandular trichomes where the essential oil is localised and the non-glandular trichomes for pest defence [46]. Essential oils are refined lipophilic mixes derived as liquids that possess aromatic properties due to the volatile aroma-active components (i.e., molecules that elicit a distinctive taste and smell) [47]. According to the French Agency for Normalization (AFNOR), the essential oil is defined as follows (NF T 75-006): "The essential oil is the product obtained from a vegetable raw material, either by steam distillation or mechanical processes, from the epicarp of citrus, or dry." [48]. The conventional essential oil extractions are steam distillation [49,50] and hydro-distillation [51,52]. However, a few techniques have been used to enhance the efficiency of the extraction process, including microwave-assisted extraction [52,53] and ultrasonication [51]. The extraction techniques and processes used to influence the quality and quantity of the extract result in a range of bioactive levels, for example, biopesticide activity against stored-grain pests [51]. Basil plants contain up to 1% of the essential oil, depending on genotypes, cultivation, growing location, and post-harvest management [54–57]. The essential oils are more concentrated in leaves and flowers and much less in the stems [58]. In the study of different basils used as culinary herbs, the essential oil yield of white holy basil (*O. sanctum* var. Rama) and Thai basil (*O. basilicum* var. thyrsiflorum) was ~0.4%, followed by lemon basil (*O. citriodorum*) and red holy basil (*O. sanctum* var. Shyama) ~0.3%, and tree basil *O. gratissimum*) was the least (<~0.2%) [6]. Variation of essential oil colours also depends on the genotypes, harvesting stages as well as different extraction techniques [58,59]. Under the visible light, the essential oil of *O. gratissimum*, *O. citriodorum*, *O. sanctum*, and *O. basilicum* var. thyrsiflorum colour are orange, yellow, and colourless, respectively. However, the colour difference is not noticed within the same species, such as those of white and red holy basils (*O. sanctum* var. Rama and Shyama) [6,58,60]. According to this, the volatile chemical compositions of essential oils may play a crucial role in the colour characteristic of the essential oils [61]. Other factors include thermal degradation, oxidation, isomerisation, dehydrogenation, and polymerisation [62–64].

Essential oils are a complex mixture of various classes of volatile organic components such as alcohols, aldehydes, esters, ketones, phenylpropanoids, and terpenoids [65]. Table 2 illustrates the different volatile classes in the essential oils with the representative descriptors of the *Ocimum* plants. The essential oil profiles are displayed by the heat map of mass spectrums of the different volatile components from Thai basil plants (Figure 2). It is apparent that there is the closest relationship between the volatile organic compounds of plants within the same species (white and red holy basils). The phenylpropanoids (estragole, eugenol, and methyl eugenol) are dominant with a proportion of up to 30–50% of analysed compounds, followed by the sesquiterpenes (i.e., trans-caryophyllene, trans-α-bergamotene, τ-cadinol, cis-α-bisabolene, β-elemene, and germacrene) and monoterpenes (i.e., trans-ocimene, linalool, 1,8-cineole, and camphor) [57,65,66]. The principal constituents of *O. citriodorum* essential oil are estragole, citral, and neral, which serve as crucial fingerprints representing its distinctive citrus scent [6]. Holy basil oil comprises a mixture of 17 volatile compounds with methyl eugenol, trans-caryophyllene, eugenol representing clove-like aroma being dominant [6,66,67]. In the essential oil of *O. basilicum*, estragole is the key volatile element. At the same time, others, such as those of alcohols (i.e., linalool), ketones (i.e., camphor), and esters, are variable among different varieties [68]. It also illustrates that *O. gratissimum* essential oil is enriched with eugenol, trans-ocimene, trans-α-bergamotene, and linalool as the significant components [6,66] projected away from the other basil species. In another study, thymol, eugenol, and geraniol were used as volatile markers to distinguish sub-varieties grown in the USA [69].

Table 2. Chemical classes of the volatile organic compounds in the essential oils of the *Ocimum* spp.

No.	Volatile Organic COMPOUNDS	Odour Type	Odour Description	Chemical Class	*Ocimum* Species [7,8]
1	3-hexen-1-ol	green [1]	fresh, green, cut grass, foliage, vegetable, herbal, oily [1]	alcohol	TrB
2	1-octen-3-ol	earthy [1]	mushroom, earthy, green, oily, fungal, raw, chicken [1]	alcohol	LB, TrB
3	3-octanol	earthy [1]	earthy, mushroom, herbal, melon, citrus, woody, spicy, minty [1]	alcohol	Trb
4	linalool	floral [1]	citrus, floral, sweet, woody, green, blueberry [1]	alcohol	LB, RB, TB, TrB, WB

Table 2. *Cont.*

No.	Volatile Organic COMPOUNDS	Odour Type	Odour Description	Chemical Class	*Ocimum* Species [7,8]
5	borneol	balsamic [1]	pine, woody, camphor [1]	alcohol	RB, WB
6	terpinen-4-ol	spicy [1]	peppery, woody, earthy, musty, sweet [1]	alcohol	LB, TB
7	l-borneol	balsamic [1]	pine, woody, camphoreous, peppery [1]	alcohol	RB, WB
8	p-mentha-1,5-dien-8-ol	n/d	n/d	alcohol	TrB
9	fenchol	camphoreous [1]	camphoreous, pine, woody, dry, rooty, sweet, lemon [1]	alcohol	LB, TB, WB
10	(e,e)-2,6-dimethyl-3,5,7-octatrien-2-ol	n/d	n/d	alcohol	TrB
11	nerol	floral [1]	sweet, natural, neroli, citrus, magnolia [1]	alcohol	LB
12	geraniol	floral [1]	sweet, floral, fruity, rose, waxy, citrus [1]	alcohol	LB
13	elemol	spicy [1]	spicy, citrus, woody, resinous [1]	alcohol	RB, WB
14	spathulenol	earthy [1]	earthy, herbal, fruity [1]	alcohol	TB, TrB
15	(z)-4-decen-1-ol	waxy [1]	waxy, fatty, fruity [1]	alcohol	RB
16	lanceol	n/d	n/d	alcohol	TrB
17	cubenol	spicy [1]	spicy, herbal, green tea [1]	alcohol	TB
18	τ-cadinol	balsamic [1]	balsamic, earthy [1]	alcohol	LB, TB, WB
19	β-eudesmol	woody [1]	woody, green [1]	alcohol	LB
20	α-cadinol	herbal [1]	herbal, woody [1]	alcohol	TrB
21	juniper camphor	n/d	n/d	alcohol	RB, WB
22	α-bisabolol	floral [1]	floral, peppery, balsamic, clean [1]	alcohol	LB
23	(e)-hex-2-enal	green [1]	green, banana, aldehydic, fatty, cheesy [1]	aldehyde	TrB
24	trans-chrysanthemal	n/d	n/d	aldehyde	TB
25	neral	citrus [1]	sweet, citrus, lemon, lemon peel [1]	aldehyde	LB
26	geranial	n/d	pleasant citrus [6]	aldehyde	LB
27	citral	citrus [1]	sharp lemon, sweet [1]	aldehyde	LB
28	estragole	anisic [1]	sweet, sassafras, anise, spicy, green, herbal, fennel [1]	benzene derivative, ether	LB, RB, TB, WB
29	methyl eugenol	spicy [1]	sweet fresh, warm spicy, clove, carnation, cinnamon [1]	benzene derivative, ether	LB, RB, TB, TrB, WB
30	eugenol	spicy [1]	sweet, spicy, clove, woody [1]	benzene derivative, ether, alcohol	LB, RB, TrB, WB
31	1-bromo-8-heptadecyne	n/d	n/d	bromoalkene	LB
32	methyl 2-methylbutanoate	fruity [1]	etherial, iifting, fruity, tutti-frutti and ripe with a fatty, green nuance [1]	ester	TrB
33	bornyl acetate	balsamic [1]	woody, pine, herbal, cedar, spicy [1]	ester	LB
34	1,8-cineole	herbal [1]	eucalyptus, herbal, camphoreous, medicinal [1]	ether	LB, TB
35	trans-epoxyocimene	n/d	n/d	ether	TrB
36	nerol oxide	green [1]	green, weedy, cortex, herbal, narcissus, celery [1]	ether	LB

Table 2. *Cont.*

No.	Volatile Organic COMPOUNDS	Odour Type	Odour Description	Chemical Class	*Ocimum* Species [7,8]
37	caryophyllene oxide	spicy [1]	sweet, fresh, dry, woody, spicy [1]	ether	LB, RB, TrB, WB
38	humulene epoxide ii	n/d	n/d	ether	LB, TB
39	ledene oxide-(ii)	n/d	n/d	ether	TrB
40	6-methyl-5-hepten-2-one	citrus [1]	citrus, green, musty, lemongrass, apple [1]	ketone	LB, TrB
41	fenchone	n/d	eucalyptus-like, mouldy [2]	ketone	LB
42	camphor	camphoreous [1]	camphoraceous [3]	ketone	LB, TB, WB
43	6-methyl-hepta-3,5-dien-2-one	spicy [1]	cinnamon, coconut, spicy, woody, sweet, weedy [1]	ketone	TrB
44	salvial-4(14)-en-1-one	n/d	n/d	ketone	TrB
45	α-pinene	herbal [1]	fresh, camphoreous, sweet, pine, earthy, woody [1]	monoterpene	WB
46	β-pinene	herbal [1]	dry, woody, resinous, pine, hay, green, eucalyptus, camphoreous [1]	monoterpene	LB, TB, WB
47	camphene	woody [1]	woody, herbal, fir, needle [1]	monoterpene	WB
48	myrcene	spicy [1]	peppery, terpenic, spicy, balsamic, plastic [1]	monoterpene	TB, TrB
49	α-ocimene	fruity [1]	fruity, floral, cloth, laundered cloth [1]	monoterpene	TB, TrB
50	l-limonene	terpenic [1]	terpenic, pine, herbal, peppery [1]	monoterpene	TB
51	γ-terpinene	terpenic [1]	oily, woody, terpenic, lemon/lime, tropical herbal [1]	monoterpene	LB, TB
52	β-ocimene	floral [1]	citrus, tropical green, terpenic, woody, green [1]	monoterpene	LB, TrB
53	3-carene	citrus [1]	citrus, terpenic, herbal, pine, solvent, resinous, phenolic, cypress, medicinal, woody [1]	monoterpene	RB, TB, TrB
54	(e)-3,7-dimethylocta-1,3,6-triene	herbal [1]	sweet, herbal [1]	monoterpene	TB
55	(3e,5e)-2,6-dimethyl-1,3,5,7-octatetraene	n/d	n/d	monoterpene	TrB
56	3-methyl-1,4-heptadiene	n/d	n/d	monoterpene	TB
57	2,6-dimethyl-2,4,6-octatriene	floral [1]	sweet, floral, nut, skin, peppery, herbal, tropical [1]	monoterpene	TrB
58	(r)-α-pinene	n/d	n/d	monoterpene	TB
59	(+) -(−)-3-carene	citrus [1]	sweet, turpentine-like [1]	monoterpene	TB
60	α-copaene	woody [1]	woody, spicy, honey [1]	sesquiterpene	LB, RB, TB, WB
61	β-bourbonene	herbal [1]	herbal, woody, floral balsamic [1]	sesquiterpene	TrB
62	β-cubebene	citrus [1]	citrus, fruity, radish [1]	sesquiterpene	RB, TrB
63	β-elemene	herbal [1]	herbal, waxy, fresh [1]	sesquiterpene	LB, RB, TB, WB
64	caryophyllene	spicy [1]	sweet, woody, spicy, clove, dry [1]	sesquiterpene	LB, RB, TrB, WB
65	α-bergamotene	woody [1]	woody, warm, tea [1]	sesquiterpene	LB, TB, TrB
66	(z,e)-α-farnesene	n/d	n/d	sesquiterpene	TrB
67	rotundene	n/d	n/d	sesquiterpene	RB
68	α-guaiene	woody [1]	sweet, woody, balsamic, peppery [1]	sesquiterpene	LB

Table 2. *Cont.*

No.	Volatile Organic COMPOUNDS	Odour Type	Odour Description	Chemical Class	*Ocimum* Species [7,8]
69	β-sesquiphellandrene	herbal [1]	herbal, fruity, woody [1]	sesquiterpene	TrB
70	trans-α-bergamotene	woody [1]	woody, warm, tea [1]	sesquiterpene	LB, TB, TrB, WB
71	α-humulene	woody [1]	woody [1]	sesquiterpene	LB, RB, TrB, WB
72	bicyclo sesquiphellandrene	n/d	n/d	sesquiterpene	LB, TB, TrB
73	germacrene	n/d	spicy, woody [5]	sesquiterpene	LB, RB, TB, TrB, WB
74	trans-β-farnesene	floral [1]	floral, grass [4]	sesquiterpene	LB, TrB
75	γ-muurolene	woody [1]	herbal, woody, spicy [1]	sesquiterpene	TrB
76	β-selinene	herbal [1]	herbal [1]	sesquiterpene	LB, RB, WB
77	α-cubebene	herbal [1]	herbal, waxy [1]	sesquiterpene	RB, WB
78	α-selinene	herbal [1]	amber [1]	sesquiterpene	LB, RB, WB
79	bicyclogermacrene	greem [1]	green, woody, weedy [1]	sesquiterpene	LB, TB, TrB
80	α-bulnesene	n/d	n/d	sesquiterpene	TB, WB
81	β-gurjunene	n/d	n/d	sesquiterpene	RB
82	trans-α-bisabolene	n/d	n/d	sesquiterpene	LB, TrB
83	β-copaene	n/d	n/d	sesquiterpene	LB, TB, WB
84	δ-cadinene	herbal [1]	thyme, herbal, woody, dry [1]	sesquiterpene	LB, RB, TrB, WB
85	α-farnesene	woody [1]	citrus, herbal, lavender, bergamot, myrrh, neroli, green [1]	sesquiterpene	TrB
86	α-amorphene	n/d	n/d	sesquiterpene	ThB
87	α-amorphene	n/d	n/d	sesquiterpene	LB, WB
88	(z)-α-bisabolene	n/d	n/d	sesquiterpene	TB
89	eremophilene	n/d	n/d	sesquiterpene	RB
90	1,3-diisopropyl-1,3-cyclopentadiene	n/d	n/d	sesquiterpene	TrB
91	α-muurolene	woody [1]	woody [1]	sesquiterpene	RB
92	β-bisabolene	balsamic [1]	balsamic, woody [1]	sesquiterpene	LB

[1] The Good Scents Company Information System [70]; [2] Zeller and Rychlik [71]; [3] Pripdeevech et al. [72]; [4] Genovese et al. [73]; [5] Miyazawa et al. [74]; [6] Jiang and Kubota [75]; [7] Tangpao et al. [6]; [8] Tangpao et al. [66], LB = lemon basil (*O. citriodorum*); RB = red holy basil (*O. sanctum* var. Rama); TB = Thai basil (*O. basilicum* var. thyrsiflorum); TrB = tree basil (*O. gratissimum*); WB = white holy basil (*O. sanctum* var. Shyama), n/d = no data.

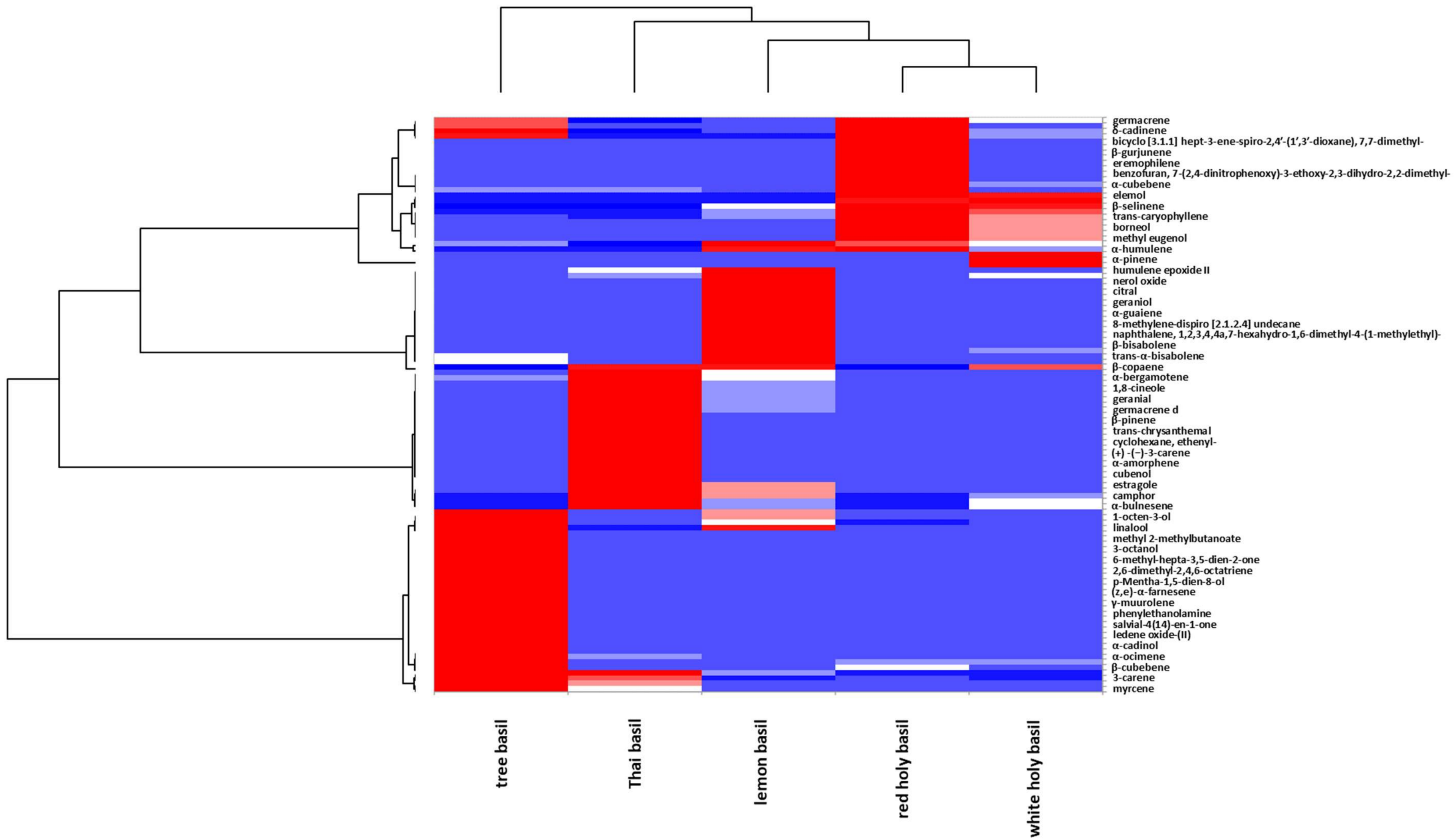


Figure 2. Heat map on volatile organic components in the essential oil of different basil species. The volatile components of different basil species as from the previous studies [6,66]. The heat map was generated using XLSTAT version 2020 (Addinsoft Inc., New York, NY, USA).

4. The Applications of the Basil Essential Oils in the Production of the Tropical Fruits

Plants synthesise various volatile organic compounds in the essential oils to defend themselves from environmental stresses, both biotic and abiotic [76]. These compounds' beneficial or adverse effects on the living matter are known as "biological activity". Consequently, essential oils have been used in many industrial applications and mainly replace synthetic chemicals [77–79]. During the pre- and post-harvest productions of the horticultural crops, essential oils were tested for their antipathogenic and pest control properties, such as insecticidal agents [80], repellents, attractants [81], and microbial disease controlling agents. In the production of most tropical fruits, the Oriental fruit flies attack the soft-skin fruits by laying eggs and feeding the larvae inside the fruits [66]. At post-harvest, *Colletotrichum* spp. is a major fungus causing anthracnose disease, accelerating the fruit deterioration process [82].

4.1. Pre-Harvest Applications

Several studies have investigated the control potential of essential oils from basil plants against pests during pre-harvesting (Table 3). The volatile organic constituents in the essential oils of some *Ocimum* species influence the behaviour of insects; for example, the ability to attract the Oriental fruit flies [66] and *Ceraeochrysa cubana* (herbivore predator) [83] as well as the repellent effect on *Allacophora foveicollis*, a serious pest that causes severe damage to pumpkin [84]. In addition, essential oils from *O. basilicum* and *O. gratissimum* were shown to have the ability to prevent egg hatching and adult emergence in *Callosobruchus maculatus*, the cowpea seed beetle [85]. Therefore, basil plants have been used as an intercrop in integrated pest management that has proven to reduce the total pest infestation in the cotton field [86] and greenhouse tomato production [87]. Methyl eugenol has been found in almost all types of basil essential oils, and it is the most active attractant for the Oriental fruit flies [66], while essential oil of the sweet basil is attractive to green lacewings *Ceraeochrysa cubana* Hagen (Neuroptera: Chrysopidae) [83]. The toxicity of methyl eugenol against larvae of the tobacco armyworms, *Spodoptera litura* has also been well defined [88]. Furthermore, the toxicity of *Ocimum* essential oils to fruit flies have been investigated [89]. Chang et al. [89] tested the toxicity of the three main components detected in the essential oil of *O. basilicum* L. viz., trans-anethole, estragole, and linalool. It successfully eliminated the flies, especially the estragole was the most effective.

The essential oil of sweet basil also illustrated the promising effect in controlling symptoms of wilt or root rot disease of cumin caused by *Fusarium* spp. [90]. It was also found that the mycelial growth of *Botrytis fabae* was significantly reduced by the basil oil types that were rich in methyl chavicol (or estragole) and linalool, while methyl chavicol, linalool, eugenol, and eucalyptol significantly reduced the overall growth of the fungus [10].

4.2. Post-Harvest Applications

In addition to their potential to control pre-harvest insect pests, the influence of extracts from *Omimum* spp. plants on the control of post-harvest insect pests was also investigated (Table 4). It was discovered that the essential oils of basils (*O. basilicum* and *O. tenuiflorum*) had volatile toxicity against stored-grain pests such as *Sitophilus oryzae*, *Rhyzopertha dominica*, *Cryptolestes* pusillus, *Sitophilus zeamais*, *Tribolium castaneum*, and *Acanthoscelides obtectus* [16,17,91–93] as well as the stored dates pests (*Ectomyelois ceratoniae* and *Ephestia kuehniella*) [94]. The powder form of the dried sweet basil plant has been used to repel *Sitophilus zeamais* Motschulsky, a post-harvest pest causing considerable damage to maise grain in most stores in Africa [95]. In addition to its ability to control insects, the role of essential oils as a natural post-harvest fungicide was also well recognised. From previous studies, the vapour of essential oils has the potential to inhibit post-harvest microorganisms [96,97], such as the harvested avocado fruit disease fungus (*Cercospora purpurea*) [98] and the peach and nectarine disease fungus (*Monilinia laxa*) [99]. The substances with low molecular weight and low polarity of essential oil play a role in the loss of cell membrane integrity of the pathogen by altering the pH in the cell, thereby inhibiting the growth as well as inducing programmed cell death [100]. The essential oils from *Ocimum* spp. were able to inhibit the fungi causing the post-harvest diseases of the tropical fruits [10,13,14,101]. This also includes *Colletotrichum* spp., the fungus that causes anthracnose disease in common tropical fruits. Linalool is the most active substance in the *O. basilicum* essential oil that could inhibit the diseases of the stored seeds of lettuce and tomatoes caused by *F. oxysporum*, *Penicillium* spp., and *C. gloeosporioides* [102]. The crown rot pathogens that infected cut bananas during farm-level handling and packhouses were positively controlled by the combination of aluminium sulphate and basil oil in the modified atmosphere packaging during cold storage (12–14 °C) [103].

Table 3. Uses of volatile organic compounds from the studied *Ocimum* species against pests of horticulture crops.

Pests	*Ocimum* Species (Volatile Active Compounds)	Forms of Biological Activity	References
Bactrocera dorsalis (tropical fruit pest)	*O. sanctum* (methyl eugenol)	male fly attractant	[66]
Bactrocera dorsalis (tropical fruit pest)	*O. basilicum* (trans-anethole, estragole and linalool)	insecticide (100% mortality at 2 h after applying 10% oil)	[89]
Ceratitis capitata (fruit pest)	*O. basilicum* (trans-anethole, estragole and linalool)	insecticide (95% mortality at 2 h after applying 2.5% oil)	[89]
Bactrocera cucurbitae (tropical fruit pest)	*O. basilicum* (trans-anethole, estragole and linalool)	insecticide (100% mortality at 2 h after applying 7.5% oil)	[89]
Callosobruchus maculatus (cowpeas, green gram, and lentils pests)	*O. basilicum* and *O. gratissimum*	reducing egg hatch rate and the emergence of adults	[85]
Allacophora foveicollis (pumpkin pest)	*O. basilicum*	repellent	[84]
Botrytis fabae (cause of faba bean's chocolate spot disease)	*O. basilicum* (methyl chavicol, linalol, eugenol, and eucalyptol)	antifungal agent and fungicide	[10]
Uromyces fabae (cause of faba-bean rust)	*O. basilicum* (methyl chavicol, linalol, eugenol, and eucalyptol)	antifungal agent and fungicide	[10]
Fusarium spp. (cause of cumin root rot disease)	*O. basilicum* var. *basilicum* and var. *minimum)*	antifungal agent (antagonistic effect and reduction in mean disease rating of root rot in the in vivo test)	[90]

Table 4. Uses of volatile organic compounds from the studied *Ocimum* species during post-harvest management of horticultural produce.

Pests	*Ocimum* Species (Volatile Active Compound)	Forms of Biological Activity	References
Sitophilus oryzae (stored rice pest)	*O. basilicum* (methyl eugenol, estragole, linalool)	insecticide (30%–77% mortality at 24 h after fumigation of *O. basilicum* essential oil)	[93]
Rhyzopertha dominica (stored rice pest)	*O. basilicum* (methyl eugenol, estragole, linalool)	insecticide (37%–80% mortality at 24 h after fumigation of *O. basilicum* essential oil)	[93]

Table 4. *Cont.*

Pests	*Ocimum* Species (Volatile Active Compound)	Forms of Biological Activity	References
Cryptolestes pusillus (stored rice pest)	*O. basillicum* (methyl eugenol, estragole, linalool)	insecticide (90%–100% mortality at 24 h after fumigation of *O. basilicum* essential oil)	[93]
Ectomyelois ceratoniae (major insect pest of dates both in field and in storage)	*O. basilicum* (linalool, methyl cinnamate, and eugenol)	insecticide (LC_{50} = 1.23 µL/L air after fumigation of *O. basilicum* essential oil)	[94]
Ephestia kuehniella (major insect pest of dates both in field and in storage)	*O. basilicum* (linalool, methyl cinnamate, and eugenol)	insecticide (LC_{50} = 0.96 µL/L air after fumigation of *O. basilicum* essential oil)	[94]
Sitophilus zeamais (stored-grain pest)	*O basilicum* (linalool, estragole, α-humulene)	insecticide (LC_{50} = 0.014 mg/cm^3 air at 24 h after fumigation of *O. basilicum* essential oil)	[92]
Tribolium castaneum (stored-grain pest)	*O. basilicum* (linalool, estragole, α-humulene)	insecticide (LC_{50} = 0.02 mg/cm^3 air at 24 h after fumigation of *O. basilicum* essential oil)	[92]
Sitophilus oryzae (stored-grain pest)	*O. basilicum*	insecticide (30.7% mortality at 48 h after fumigation of *O. basilicum* essential oil) and repellent	[91]
Sitophilus orzyae (stored-grain pest)	*O. tenuiflorum* (eugenol and caryophyllene)	insecticide (LC_{50} = 963.3 µL/L air at 6 hours after essential oil exposure; inhibiting acetylcholinester)	[16]
Acanthoscelides obtectus (pest of beans)	*O. basilicum*	insecticide (74.94% mortality at 120 µL on day 15 after the oil application)	[17]
Aspergillus flavus (produce aflatoxins toxic)	*O. basilicum* (linalool, 1,8-cineol, eugenol)	antifungal agent (100% growth inhibition at 1000 µL/L essential oil)	[10]
Colletotrichum acutatum (anthracnose disease)	*Ocimum* sp. (methyl chavicol and linalool)	antifungal agent (MIC = 4 µL/mL)	[13]
Monilinia laxa (brown rot and grey mould rot of stone fruits)	*O. basilicum* (linalool, eugenol, estragole)	antifungal agent (control the growth of fungus on inoculated fruits)	[14]
Botrytis cinerea (brown rot and grey mould rot of stone fruits)	*O. basilicum* (linalool, eugenol, estragole)	antifungal agent (control the growth of fungus on inoculated fruits)	[14]
Penicillium italicum (rotting of citrus fruits)	*O. canum*	antifungal agent (enhance the shelf life of fungus inoculated oranges)	[15]
Cercospora purpurea (post-harvest pathogen of avocado)	*O. gratissimum*	antifungal agent (100% growth inhibited using ethanolic extract)	[98]
Aspergillus flavus (produce mycotoxins, aflatoxins toxic)	*O. basilicum*	antifungal agent (inhibits the production of aflatoxin B1)	[12]
Monilinia laxa (brown rot diseases of peach and nectarine)	*O. basilicum* var. purpurascens (estragole)	antifungal agent (inhibit the mycelium growth)	[99]

Table 4. *Cont.*

Pests	*Ocimum* Species (Volatile Active Compound)	Forms of Biological Activity	References
Monilinia laxa (brown rot diseases of peach and nectarine)	*O. tenuiflorum* (β-bisabolene and 1,8-cineole)	antifungal agent (inhibit the mycelium growth)	[99]
Aspergillus niger (associated with post-harvest rot of avocado pear)	*O. gratissimum*	antifungal agent (23.70% growth inhibition at 100% essential oil)	[11]
Aspergillus flavus (associated with post-harvest rot of avocado pear)	*O. gratissimum*	antifungal agent (51.93% growth inhibition at 100% essential oil)	[11]
Galactomyces candidum (associated with post-harvest rot of avocado pear)	*O. gratissimum*	antifungal agent (44.37% growth inhibition at 100% essential oil)	[11]
Trichoderma viride (associated with post-harvest rot of avocado pear)	*O. gratissimum*	antifungal agent (51.00% growth inhibition at 100% essential oil)	[11]
Lasiodiplodia pseudotheobromae (associated with post-harvest rot of avocado pear)	*O. gratissimum*	antifungal agent (66.74% growth inhibition at 100% essential oil)	[11]

5. Techniques for Enhancing the Essential Oil Efficiency

Encapsulation is a widely used process for generating an external membrane or coating material that protects or preserves sensitive bioactive, volatile, and quickly degradable substances from biochemical and thermal degradation [104]. Encapsulation is a technique that is commonly used in the flavour and fragrance industries to enhance both taste and scent. This technology also increases the efficacy of pesticides, fertilisers, and other toxic agrochemicals in agriculture, thereby improving productivity and food security. The active substances are encapsulated to regulate the release under accurate conditions (e.g., humidity, temperature, pH, and time) and to be active for a specific object (e.g., organisms or parts of the organisms). Moreover, encapsulation in agriculture can minimise harmful chemicals [105,106] and increase the efficiency of the natural extracts' action [66]. The encapsulation can be performed by coating with the material, creating core materials, filing in the internal phase or payload, and the substance's characteristics can be pure or mixed.

The coating materials are packing material, capsule, wall material, film, membrane, carrier, or outer shell [107]. They are usually made of natural or modified polysaccharides, gums, proteins, lipids, and synthetic polymers [108]. The organic flavour and the aroma of interest are low molecular weight compounds that are relatively volatile and very sensitive to open conditions (air, heat, light, and moisture). Depending on the applied encapsulation technique, the encapsulated essential oil products can be in powder, paste, or liquid forms [109,110]. Numerous techniques are available for encapsulating essential oils for agricultural uses, depending on the nature of the environment in which the products are applied.

5.1. Emulsification

To encapsulate the essential oil by the emulsion technique, the oil, including those of low polar molecules, has to be dissolved with emulsifiers such as gum Arabic and converted to droplets in water before further processes [111]. The droplets of basil oil are highly needed in food, perfumery, oral, and dental products. Emulsifiers such as proteins, phospholipids, and polysaccharides are used to maintain the stability of the essential oil emulsion. In addition, surfactants such as sugar esters and polyoxyethylene are also used to reduce the interfacial tension of the emulsion solution by electrostatic/steric stabilisation [112]. This technique has been successfully proven to maintain the efficacy of the essential oil over harsh environmental conditions such as high temperature and provide the slow-release rate of the essential oil [113–115].

5.2. Complex Coacervation

Complex coacervation is an encapsulation method that links and forms two differently charged biopolymers in a solution with the appropriate pH value. The most commonly used biopolymers are gum Arabic, gelatine, carrageenan, chitosan, carboxymethyl cellulose, and pectin [116]. This technique is claimed to be suitable for application at high temperatures and humidity exposure [117,118].

5.3. Spray Drying

Spray drying is a method of forming a liquid essential oil into a powdery form. First, the essential oils are mixed in a solution containing wall materials such as maltodextrin, modified starch, gum, and the combination. Adding emulsifiers and homogenising agents is required to obtain smaller oil globules. Subsequently, the well-mixed solution is sprayed into hot air under high pressure, creating a mist that spreads in the drying chamber [119]. This results in a physical guard of the core matrix that protects the viability of essential oil during processing, storage, and transport [120].

5.4. Complexation

Encapsulation by complexation usually refers to the applied use of oligosaccharides such as cyclodextrins, specifically β-cyclodextrin, which are often used to encapsulate low polar substances such as essential oils. β-cyclodextrin, a cone-shaped molecule, comprises a network of compounds with 7 D-glucose α-1,4 glycosidic bonds. This structure allows essential oils to dissolve well in water and aids in fixing low-polarity substances and controlling evaporation [121]. The inclusion complex is said to increase the stability of the essential oils, particularly when exposed to sunlight [122].

5.5. Ionic Gelation

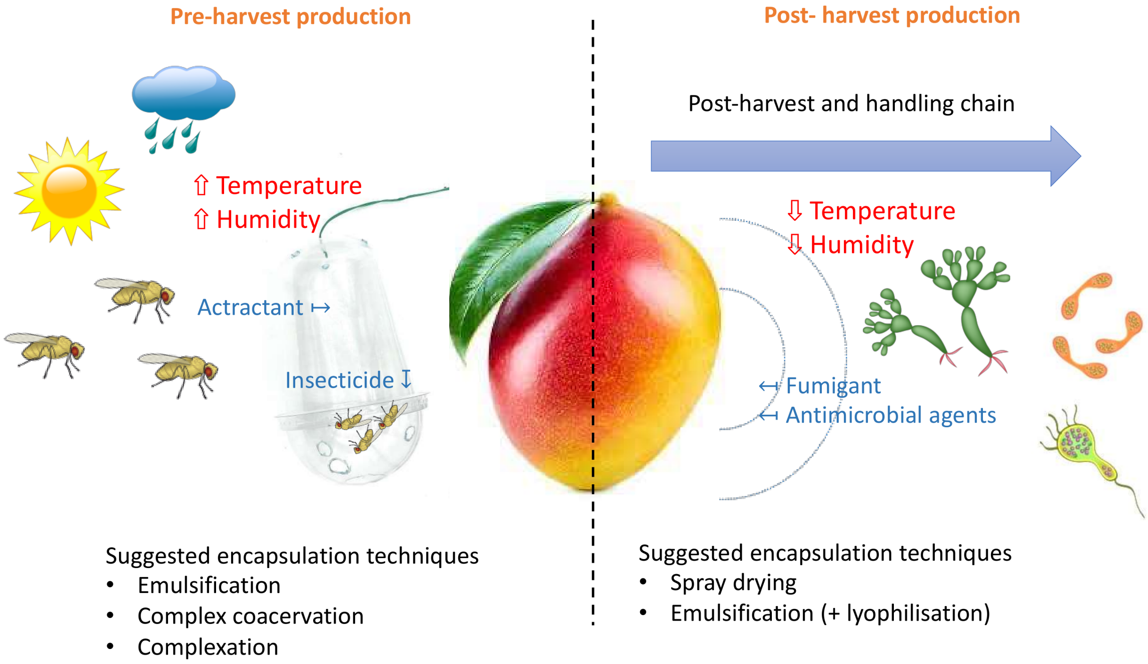
Essential oil encapsulation using the ionic gelation technique uses charged polymers with essential oils to form the solution. It is then moulded by dripping it into a crosslinking solution. Sodium alginate is a low-cost polymer often used to encapsulate essential oils due to its biocompatibility and biodegradability [123]. This alginate microsphere provides a protective structure from environmental factors such as volatilisation or oxidation. As for food, it facilitates the mobility of the essential oil into the animal digestive system [124].

5.6. Nanoprecipitation

The process of hydrophobic component encapsulation using the nanoprecipitation (solvent displacement or interfacial deposition) technique involves first dissolving the essential oil in an organic solvent together with the polymers. The solution is then added to the water that is being stirred at the proper speed. The solution is then supersaturated, nucleated, and then it expands and coagulates [125]. This technique is suitable during post-harvest to increase the insecticidal efficiency against stored-grain insect pests [126]. There is, however, limited study on insect pest control during post-harvest and handling of tropical fruits.

Tangpao et al. [66] studied the Oriental fruit fly-attracting ability of methyl eugenol plant-based essential oils and encapsulated the oil using an adapted complexation with the paste method of different wall materials. The holy basil essential oil was found to have the ability to attract the Oriental fruit flies, and encapsulation with maltodextrin and gum Arabic at a ratio of 75:25 could enhance its effectiveness in attracting the flies in mango orchard. For this purpose, the paste method is the economical and straightforward technique to encapsulate the essential oil using the chemical and mechanical reaction between the core and wall materials [127]. In addition, the encapsulation of basil essential oil by freeze-drying technique is encouraged to prevent the loss of such heat-sensitive active volatiles that are unstable in aqueous solution [128].

The antimicrobial properties of essential oils have led to research interest in their applications during the post-harvest and storage of fruits. However, the downside is that the strong scents from essential oils could interfere with the true aroma of the produce. This is generally mitigated by the nanoemulsion technique with sodium alginate or pectin-based edible coating and the high-pressure homogenisation technique [112]. All in all, several considerations should be taken into account when applying the essential oil in agricultural productions, such as its volatilisation nature [129] and the activity losses due to the exposure to ultraviolet light, temperature, humidity, and oxygen [130]. More importantly, the release-control rate of the products needs to be investigated [131,132]. Scheme 1 illustrates the possible encapsulation approaches to increase the efficiency of the essential oil during tropical fruit production.



Scheme 1. Enhancing the efficiency of basil volatile organic compounds during pre- and post-production of the tropical fruits.

6. Conclusions

This review provides essential information for understanding the usefulness of volatile organic compounds from diverse types of basil essential oils and their biological activities. Moreover, as far as sustainable food production in the tropical region is concerned, it is interesting to value-add the natural products from the commonly available resources. Several studies validated the bioassays of these beneficial components during the pre- and post-harvest stages of food crop development. However, the limitation is that essential oils generally decompose fast when exposed to the environment. Consequently, encapsulation techniques are recommended to improve its stability and control its release rate. The option of choice depends on the targeted applications and better-controlled release performance of the essential oils.

Author Contributions: Conceptualization, S.R.S. and T.T.; software, T.T.; validation, S.R.S. and T.T.; formal analysis, T.T., N.C. and P.T.; resources, T.T., N.C. and P.T.; data curation, T.T.; writing—original draft preparation, T.T.; writing—review and editing, S.R.S.; visualisation, T.T.; supervision, S.R.S., R.C.; project administration, T.T.; funding acquisition, N.L., K.J., P.R., P.S., Y.P., T.C., W.R., P.J. and H.V.D. All authors have read and agreed to the published version of the manuscript.

Funding: The research project is funded by the National Research Council of Thailand (NRCT): (contact no: N41A640354). This research project was partially supported by Chiang Mai University.

Acknowledgments: We would like to acknowledge the Teaching Assistant and Research Assistant (TA/RA) scholarship from the Graduate School, Chiang Mai University.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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