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Potential of volatile organic compounds in the management of insect pests and diseases of food legumes: a comprehensive review

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Cool season legumes (Faba bean, chickpea, lentil, pea, and grass pea) are important protein harvests for food and nutrition security in many countries. They play key roles in sustainable cereal production through their ecological benefits. However, diseases and pests attack continue to have a substantial impact on crop yield and quality. Although growers used different control options to manage these biotic stresses such as pesticide application, cultural practices, and resistant varieties, there is a pressing need for the development of new, more cost-effective and environmentally friendly solution to help farmers in facing the existing environmental issues. Recently, there is a growing interest among researchers in exploiting Volatile Organic Compounds (VOCs) for the elaboration of disease and pest control strategies in food legumes and other crops. These compounds have important functions in ecological relationships occurring between plants and their surrounding environment, as well as plants and others species, such as pests and pathogens. Due to their unique properties, VOCs can be employed in improving management alternatives for food legume diseases and pests. In this assessment, we investigated the role of VOCs in plant-pest and plant-pathogen interactions and their present applications in pest and diseases control strategies. We emphasized the ecological importance of employing plant VOCs in legume farming and crop breeding. Additionally, we highlighted the potential of microbial VOCs in facilitating microbe-microbe, microbe-plant and microbe-plant-pest interactions, along with their role in food legume protection.

KEYWORDS

food legumes, volatile organic compounds, microbial VOCs, pest and disease management, cropping systems, crop breeding, pest and disease resistance

1 Introduction

Cool-season food legumes such as faba bean, chickpea, lentil, field pea, and grass pea, play a vital role in food production, animal feed, and revenue generation in many regions (Semba et al., 2021). Globally, they occupy huge cultivated areas and are mainly grown for their edible protein-rich seed, and thus are named grain legumes (Calles, 2016).

In cropping systems that mostly rely on cereals, food legume crops are essential for enhancing soil fertility by fixing nitrogen. In Morocco, farmers practice wheat rotation with faba bean and benefit 48% over wheat monocropping (Yigezu et al., 2019).

However, in many regions of the world, their production exhibits significant yield fluctuations over the years due to abiotic and biotic factors. Pathogen invasions and insect pest infestations have damaging impact on both crop production and ecosystem worldwide. The surveillance and management of these biotic stresses are critical to increase crop yields and maintain food security for the expanding global population.

Farmers employ diverse strategies to cope with diseases and pests in food legume crops, involving agricultural approaches such as diverse crop rotation and adapting sowing schedules. Additionally, the planting of resistant varieties is a common approach (Sharma et al., 2016); however, its effectiveness is sometimes compromised by the emergence of new pathogen races and insect biotypes that can overcome the resistance in cultivated varieties.

Moreover, the application of fungicides and insecticides allow to reduce the pathogen and pest infestation, but their excessive use can induce resistance in target organisms, disrupt the soil's microbial community, result in environment pollution with harmful chemicals (Li et al., 2012). Consequently, there is a need to develop new eco-friendly options to enhance pest management effectiveness (Haware and Nene, 1982; Brilli et al., 2019).

Over the recent decades, Volatile Organic Compounds produced by living beings have received growing attention in agricultural, environmental and ecological researches due to their various properties, and their potential applications in the biocontrol of plant pests and pathogens, as well as plant growth promotion (Choudhary et al., 2008; Pickett and Khan, 2016; Gualtieri et al., 2022; Devrnja et al., 2022; Russo et al., 2022; Patel et al., 2023).

Plants and microorganisms produce a wide range of Volatile Organic Compounds appertain to various chemical families with distinct biochemical origins like alcohols, aldehydes, aromatic compounds, esters, furans, monoterpenes, sesquiterpenes, hydrocarbons, and ketones (Kramer and Abraham, 2012). These secondary metabolic products typically possess low molecular weight (averaging below 300 Da), reduced boiling temperatures, and elevated vapor pressure (evaporating at 0.01 kPa around 20°C) (Morath et al., 2012). Consequently, they can diffuse into the air, ground, and fluids, exerting their effects over both short and long distances to ensure interactions between the organism and its environment, including connections among plants themselves (Delory et al., 2016; Sakurai et al., 2023), as well as exchanges between plant and pests or pathogens (Baldwin, 2010; Piechulla et al., 2017; Pérez-Hedo et al., 2024).

Due to their significant attributes and role as signaling compounds, VOCs provide several ecological and agricultural roles, and contribute to plant defense against pests and diseases (Piesik, 2011; Bezerra et al., 2021; Annaz et al., 2023).

This review outlines the various applications of VOCs as natural and eco-friendly solution in food legume protection, highlighting their specific properties that make them effective as traps for managing different insect pest species. It indicates also the role of plant VOCs in inhibiting disease development, controlling insect pests and attracting natural enemies with a specific focus on their use in cropping systems. Furthermore, it demonstrates the exploitation of VOCs potential in plant breeding as non-invasive and rapid phenotypic tool for pest and disease resistance. Additionally, it details the different interactions mediated by microbial VOCs and their function in disease and pest management.

This review utilized a bibliometric analysis to gather data from Scopus, Google Scholar, and Web of Science databases. The search was guided using the keywords “Volatile Organic Compounds AND food legume AND insect and disease management” resulting in a total of 224 documents. These documents comprised articles (80.4%), reviews (16.1%), book chapters (2.2%), conference papers (0.9%), and short surveys (0.4%) (Figure 1C).

Several bibliometric indices, including frequently used keywords were used to perform the Network analysis. This network was conducted using the VOS viewer processing software, revealing relationships among the identified keywords and offering a comprehensive overview of current use of Volatile Organic Compounds in legume crop protection (Figure 1D).

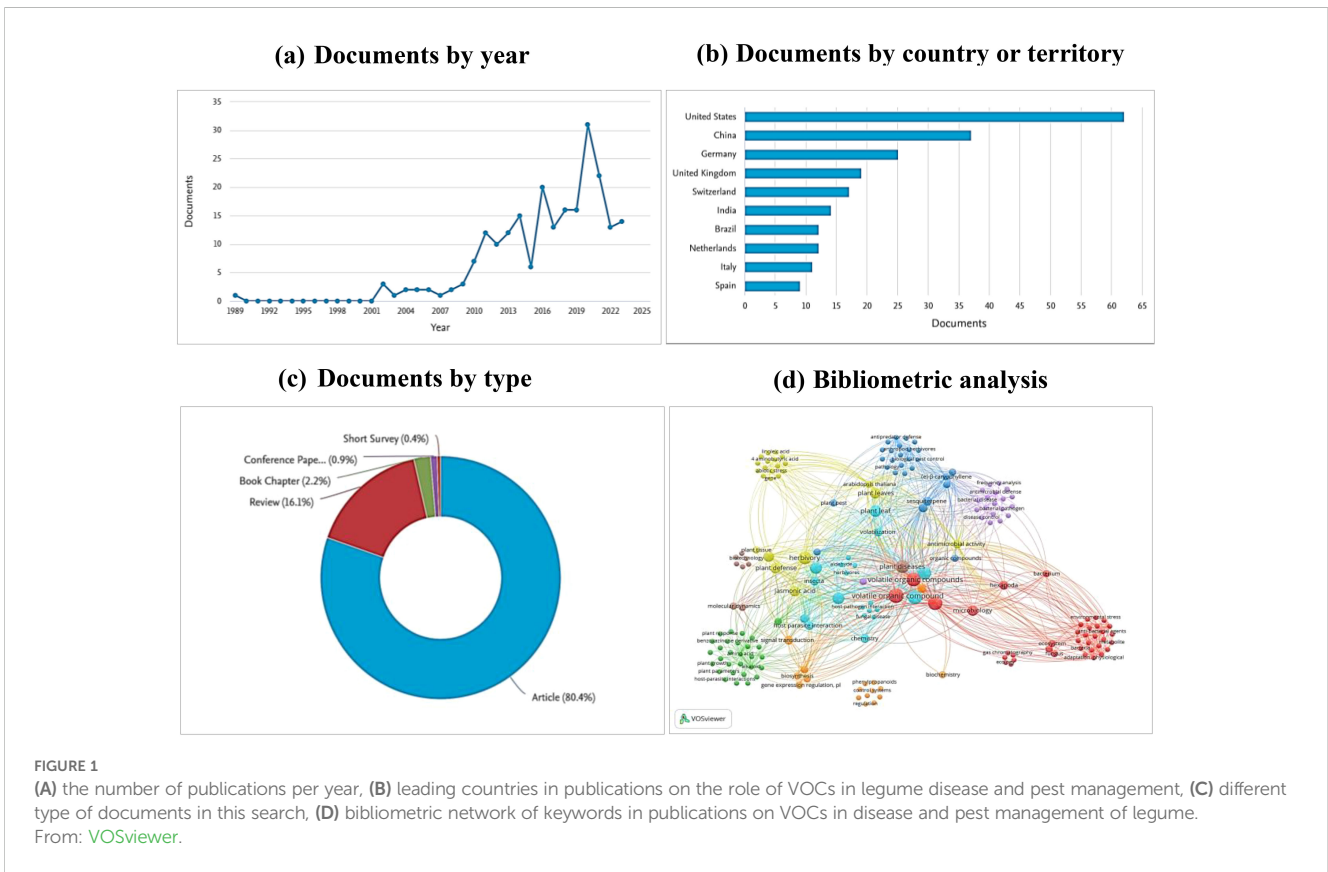
Furthermore, these findings facilitated an assessment of the significance of the published research. The classification of leading countries in article publications on the subject revealed that United States had the highest number of documents (62), followed by China with 37 documents and Germany with 25 documents (Figure 1B).

The publication trend indicated a substantial increase in the number of articles from 2015 to 2020, a slight decrease between 2020 and 2021, and a subsequent rise between 2021 and 2023, indicating a growing interest in the topic (Figure 1A).

2 Current progress in using plant VOCs for pest and disease management in food legume crops

Plants release a diverse set of volatile organic compounds (VOC), either naturally or as reaction to both biotic and abiotic stressors, to cope with pest attack or pathogen invasion (Maffei et al., 2007; Dicke and Loreto, 2010; Mutyambai et al., 2016; Castro et al., 2017; Karolkowski et al., 2021).

These chemical signals serve multiple purposes for plants, including defense against pests and diseases, attraction of pollinators and other beneficial organisms, and communication with neighbouring plants (Figure 2) (Annaz et al., 2023; Ficke et al., 2021). An increasing attention is emerged for reducing reliance on chemical pesticides by adopting new sustainable, natural, and eco-friendly solution for effective pest and disease control like

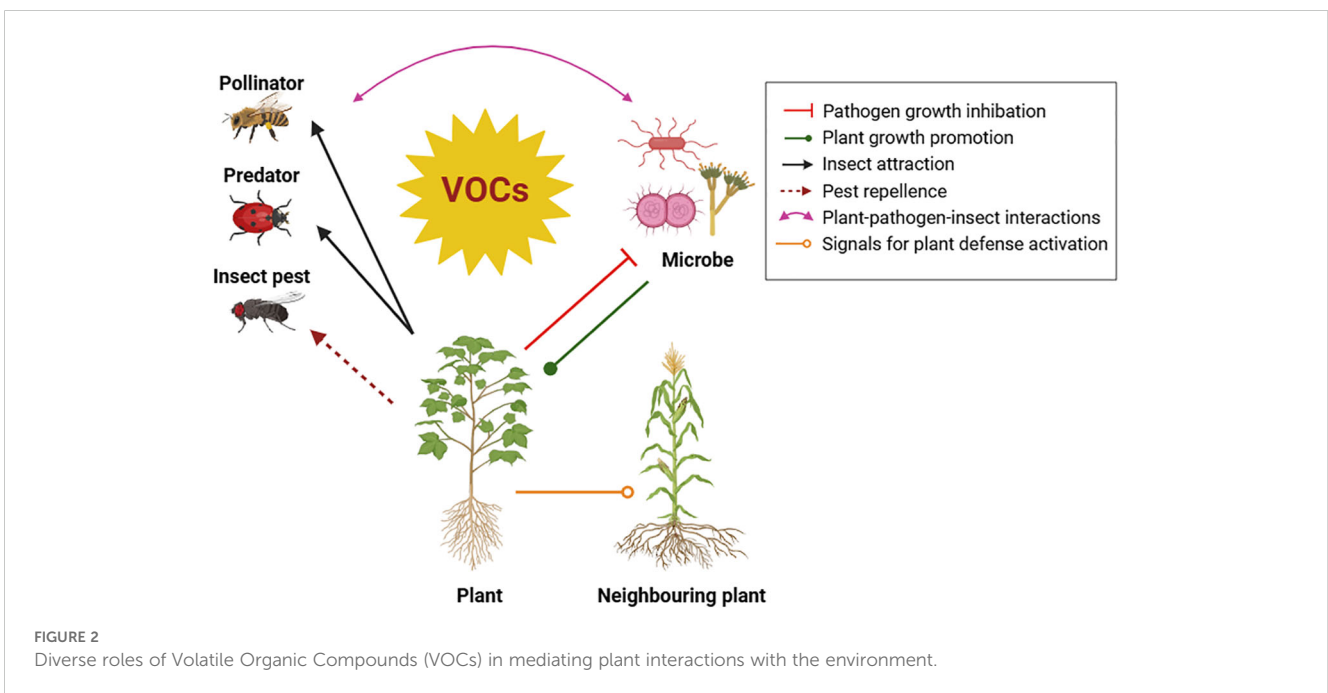


exploiting the ecological and agronomic potential of VOCs to protect plants (Brilli et al., 2019).

The following briefly outlines the functions of VOCs in pest and disease management and other ecological services.

2.1 VOCs and pest management

Due to their attractive or repellent action, VOCs can influence the feeding behavior of insect pests, their reproduction, their



olfactory perception, and the selection of their hosts (Hegde et al., 2011; Santos et al., 2015; Bruno et al., 2018; Singh et al., 2021). Therefore, they can be used as pest traps to control insect population dynamics.

Understanding and deciphering the chemical ecology of insects may offer opportunities for enhancing eco-friendly methods to fight against bio-aggressors. This involves the exploitation of repellent or disruptive volatile organic compounds (VOCs) to annoy harmful insects, as well as the use of attractive compounds for pest trapping (Reisenman et al., 2016; Fountain et al., 2017; Wyatt, 2018) (Table 1).

2.1.1 Legume leaf miner

The leaf miner, *Liriomyza spp* (Diptera: Agromyzidae), is among the most threatening insect pests to chickpea crop (*Cicer*

arietinum L.) and other legumes in the Mediterranean region (Chrigui et al., 2020; Sabraoui et al., 2019). Adult leaf miners do not possess pheromone specific to their species; they utilize herbivore-induced plant volatiles HIPVs triggered by female punctures, which include green leaf volatile (GLVs), terpenoids and oximes, as cues for the host plant location. Also, natural enemies can exploit these HIPVs to locate their hosts.

For example, in pea plant, HIPVs such as (Z)-3-hexenyl-acetate and (Z)-3-hexenol promote the attraction of male and female flies of the pea leafminer *Liriomyza huidobrensis* (Figure 3A) and mating occurs on host leaves (Ge et al., 2019).

Moreover, bean plant odors such as cis-3-hexen-1-ol and 4-hydroxy-4-methyl-2-pentanone, produced by healthy and damaged bean plants, are reported in attracting leafminer (*L.*

TABLE 1 Diverse roles of Volatile Organic Compounds in plant-pest interactions.

	Insect pest	Plant emitting VOCs	Role of VOCs in plant-pest interaction
Leafminers	Serpentine leafminer, <i>Liriomyza huidobrensis</i>	Pea	Influence reproduction (attraction of male and female flies) (Ge et al., 2019)
	Vegetable leafminer, <i>Liriomyza sativae</i>	Faba bean	Attraction of parasitoid <i>Diglyphus isaea</i> (Zhao and Kang, 2002)
	Chickpea leafminer, <i>Liriomyza cicerina</i>	Chickpea	Deterrent and toxic potential (a means of resistance against insects) (Soltani et al., 2020)
Aphid	Black bean aphid, <i>Aphis fabae</i>	Faba bean	Influence feeding behaviour by reducing the time spent by the aphid on its host (Webster et al., 2008)
Beetle	Bean seed beetle, <i>Bruchus rufimanus</i>	Faba bean	Influence the olfactometry perception of female <i>B. rufimanus</i> (Bruce et al., 2011)
Weevils	Sitona weevil (PLW), <i>Sitona lineatus</i>	Pea and Faba bean	Attraction of weevil in combination with an aggregation pheromone (Onge et al., 2018)
	The pea weevil (<i>Bruchus pisorum</i> L.)	Pea	Serve as inherent cues guiding <i>B. pisorum</i> male and female in locating suitable hosts (Ceballos et al., 2015)
Bean bug	Bean bug, <i>Riptortus pedestris</i>	Soybean	Interact synergistically with the aggregation pheromone to attract the bean bugs (Song et al., 2022)
Stink bug	Southern green stink bug, <i>Nezara viridula</i>	Faba bean	Affect the egg parasitoid <i>Trissolcus basalidis</i> attraction (influence their host selection) (Tariq et al., 2013)
Pod borers	Legume pod borer, <i>Maruca vitrata</i>	Cowpea	Influence olfactory behavior response of female moths and the selection of oviposition site (Zhou et al., 2015)
	The gram pod borer, <i>Helicoverpa armigera</i>	Chickpea	Enhance the foraging activity of <i>Trichogramma spp</i> (Pawar et al., 2023)
	Faba bean stem borer, <i>Lixus algirus</i>	Faba bean	Attract both male and female <i>L. algirus</i> (Ait Taadaouit et al., 2021a)
Storage insect pest	The adzuki bean weevil, <i>Callosobruchus chinensis</i>	Clove, holy basil, lemongrass, turmeric	Oviposition deterrence, antifeedant activity, F1 progeny inhibition, and adult repellent activity (Mario et al., 2023)
	Cowpea weevil, <i>Callosobruchus maculatus</i>	Grass pea	Host locating (Adhikary et al., 2015)

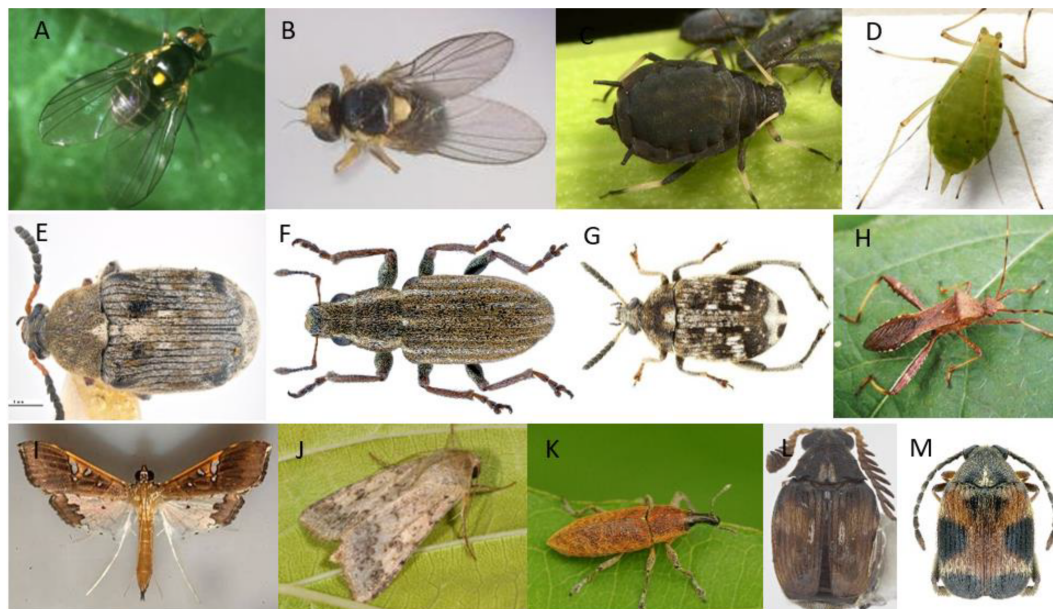


FIGURE 3

(A) *Liriomyza huidobrensis*; (B) *Liriomyza sativae*; (C) *Aphis fabae*; (D) *Acyrthosiphon pisum*; (E) *Bruchus rufimanus*; (F) *Sitona lineatus* L.; (G) *Bruchus pisorum* L.; (H) *Riptortus pedestris*; (I) *Maruca vitrata* (J) *Helicoverpa armigera*; (K) *Lixus algerius*; (L) *Callosobruchus chinensis*; (M) *Callosobruchus maculatus*.

sativae) (Figure 3B) and its parasitoids *Diglyphus isaea* (Zhao and Kang, 2002). So these herbivores induced volatiles (HIVs) can be utilized to trap the pest or to attract its natural enemy.

2.1.2 Aphids and virus on legumes

Legumes such as faba beans, chickpeas, lentils and peas are susceptible to many viruses of which 42 are identified as transmitted by vectors, mainly by insects (Makkouk, 2020; Jones and Roger, 2021; Adane and Vetten, 2022; Tatineni and Hein, 2023). The major vectors for legume viruses are aphids, leafhoppers, thrips, and beetles (Guerrieri and Digilio, 2008; Congdon et al., 2017).

For example, the black bean aphid, *Aphis fabae* (Hemiptera: Aphididae) (Figure 3C) poses a significant threat to faba beans (*Vicia faba*), inflicting harm by feeding and also by transmitting plant viruses.

The aphids is attracted to its host through a mixture of volatile compounds released by *V.faba* plant, which consists of (Z)-3-hexen-1-yl acetate, 1-hexanol, (Z)-3-hexen-1-ol, benzaldehyde, (E)-2-hexenal, 6-methyl-5-hepten-2-one, octanal, (R)-(-)- linalool, methyl salicylate, decanal, undecanal, (E)- β -farnesene, (E)- β -caryophyllene, (S)-(-)-germacrene D and (E,E)-4,8,12-trimethyl-1,3,7,11-tridecatetraene (TMTT).

Among this blend, the molecules octanal, (R)-(-)-linalool and (S)-(-)-germacrene D can reduce the duration that aphid remains on its host. However, the presence of these compounds in VOCs blend has no effect on the aphids' behavior which underlining the importance of the blend effect on aphid behavior over individual compounds' effect (Webster et al., 2008).

The pea aphid, *Acyrthosiphon pisum* (Hemiptera: Aphididae) (Harris), (Figure 3D) can consume its host plant, *Vicia faba*, without

causing alterations in plant VOCs release. The volatile organic compound amount emitted by affected bored beans stayed consistent or reduced compared to undamaged plants. For example, aphid feeding decreased the emission of sesquiterpene (E)- β -ocimene and GLV (Z)-3-hexenyl acetate in comparison with intact plants. Contrarily, the GLV (E)-2-hexenal emission is not impacted by aphid attack.

Also, Pea aphid can prevent the emission of some VOCs during feeding, such as β -caryophyllene, (E)- β -ocimene and (E, E)-4,8,12-trimethyl-1,3,7,11-tridecatetraene (TMTT), which can attract its parasitoid, *Aphidius ervi*. So the suppression of some VOCs production by aphid feeding make the plant incapable to attract natural enemies and protect itself (Schwartzberg et al., 2011).

2.1.3 Legume beetle and weevil

The bean seed beetle, *Bruchus rufimanus* (Coleoptera: Chrysomelidae) (Figure 3E) presents a significant economic threat to beans, mainly field beans (*Vicia faba*) sown during the spring and winter seasons (Carrillo-Perdomo et al., 2018).

Bruce et al. (2011) showcased the significance of plant host-emitted volatile organic compounds in monitoring *B. rufimanus*. Nine active compounds were identified from *V. faba* cv. 'Sutton dwarf' flowers, including cinnamyl alcohol, cinnamaldehyde, myrcene, (R)-limonene, (E)-ocimene, (R)-linalool, 4-allylanisole, (E)-caryophyllene, and α -humulene.

The semiochemicals derived from host plant flowers and male bruchids induced electrophysiological and behavioral reactions in female *B. rufimanus*, which may be utilized to attract and trap the pests in the field (Dell'Aglio and Tayeh, 2023).

Although host plant odors are attractive as a blend, their individual exposure to insects may be less effective and even

repellent. The proportion of each compound in the VOCs blend that the host plant naturally released is critical for communicating with insects. Therefore, to create an effective attractant, it's crucial to mimic these natural ratios accurately.

In olfactometer bioassays, the chosen headspace collections and synthesized molecules were evaluated, and then incorporated into semiochemical lures for traps. During field trials, cone baits loaded with a combination of three floral volatile compounds, including (R)-linalool, cinnamyl alcohol, and cinnamaldehyde, trapped significantly more male and female of *B. rufimanus* compared to unbaited control traps.

Sitona weevil (PLW), *Sitona lineatus* L., (Coleoptera: Curculionidae) (Figure 3F) is a pest of pea (*Pisum sativum* L.), faba bean (*Vicia faba* L.) and other legume crops. Larvae that feed on root nodules reduce nitrogen fixation and cause the most damage. This pest could be managed by using an aggregation pheromone 4-methyl-3,5-heptanedione, in combination with host plant volatiles such as linalool, (Z)-3-hexenol, and (Z)-3-hexenyl acetate. The addition of plant volatiles to the aggregation pheromone can increase weevil attraction, however plant volatiles solely didn't attract *S. lineatus* adults (Onge et al., 2018).

The pea weevil (*Bruchus pisorum* L.) (Coleoptera: Bruchidae) (Figure 3G) stands among the most damaging pests of peas (*Pisum sativum* L.) (Mendesil et al., 2016; Reddy et al., 2018; Aznar-Fernández and Rubiales, 2019). Ceballos et al. (2015) explored how the volatiles emitted by pea plants can affect the electrophysiological and behavioral reactions of *B. pisorum*, employing electroantennography (EAG) and olfactometry tests.

Volatiles produced at various developmental phases were extracted in headspace by Porapak Q tubes and identified using gas chromatography coupled to mass spectrometry (GC-MS) (Makhlouf et al., 2024). The Analysis using GC-MS showed variations, both qualitative and quantitative, in plant-emitted volatiles across different phenological stages. Terpenes were the most frequent compounds in every stage, with terpinene and 1-S-verbenone exclusively detected during the flower stage. Flowers released large amounts of all compounds, excluding myrcene and n-dodecane. Pea pods released low amount of (Z)-2-hexen-1-ol, 2,4-hexadienal, α -pinene, β -pinene, myrcene, and limonene, except for n-dodecane that was prevalent at this phase.

The highest concentration of compounds coincided with the vegetative and flower stages, consistent with Dudareva et al.'s (2004) findings, indicating that volatiles emission intensified when leaves are young and flowers are ready for pollination.

In olfactometer bioassays, volatiles produced in all growth phases prompted an attractant behavioral reaction from both male and female *B. pisorum*. Significantly, the female *B. pisorum* displayed a grater attraction to pod volatiles than other phenological stages. These volatiles released by the flowers and pods of pea plants act as natural signals directing *B. pisorum* to find appropriate hosts.

2.1.4 The bean bug and stink bug

The bean bug *Riptortus pedestris* (Fabricius) (Heteroptera: Alydidae) (Figure 3H), is a generalist pest that mainly attack

legumes particularly soybean, can recognize its host through the plant's volatile organic compounds (VOCs).

Research carried out by Song et al. (2022) revealed that both sexes of *R. pedestris* are able to perceive volatiles emitted from soybeans such as (Z)-3-hexen-1-ol, (Z)-3-hexenyl acetate, 4-ethylbenzaldehyde, α -farnesene, and methyl salicylate. When assessed in controlled laboratory settings, bean bugs adult showed no specific behavioral responses to single molecule; however, they did demonstrate strong preference towards a specific combination of synthetic volatile compounds of soybean.

In natural conditions, the mixture of soybean volatiles didn't considerably lure *R. pedestris*. However, it showed a synergistic interaction with the aggregation pheromone, effectively attracting the bean bugs. These findings emphasize the importance of host plant volatiles in the perceptive behavior of the bean bug, shedding light on the colonization dynamics of *R. pedestris* in soybean plantations.

2.1.5 Legume pod borer

Zhou et al. (2015) have investigated how the female *Maruca vitrata* (Lepidoptera: Crambidae) (Figure 3I), a major pest in cowpea cultivation, responds to the volatiles emitted from *Vigna unguiculata* flowers and their role in the selection of host plants.

By employing gas chromatography coupled to electroantennography (GC-EAD) and gas chromatography-mass spectrometry (GC-MS) analysis, 17 major volatile compounds produced by *V. unguiculata* have been determine, involving butyl ester, butanoic acid, limonene, butanoic acid octyl ester, 4-ethylpropiofenone, 1H-indol-4-ol, and 2-methyl-3-phenylpropan.

During the field trials, six compounds from these floral volatiles successfully lured female moths and revealed notable distinctions in comparison with the control bait. These findings indicated that cowpea VOCs likely influence the scent-driven behavioral reaction of female moths, which in turn affecting their choice of egg-laying locations. This insight offers valuable understanding for investigating monitoring effectiveness and combined pest control approaches against the legume pod borer in agricultural settings.

The chickpea pod borer, *Helicoverpa armigera* (Lepidoptera: Noctuidae) (Figure 3J) presents a significant threat to chickpea crops. It can tunnel into the pods during the reproductive stage which resulting in major decreases in productivity (El Fakhouri et al., 2022; Boulamtat et al., 2019). *Trichogramma* spp., egg parasitoid, is used as biological control agents against Lepidoptera pests. Plant volatiles such as n-octadecanoic acid, n-hexadecanoic acid, and octadecane have been proven to improve the foraging function of *Trichogramma* spp, mainly octadecane which has been detected in several plant volatile profiles and is known to be attractive to *Trichogramma* spp. Pawar et al. (2023) demonstrated that applying a kairomone gel formulation of octadecane (Saturated hydrocarbon) after 24h of the *Trichogramma chilonis* release in chickpeas have improved the biological control capability of *T. chilonis* towards *H. armigera* larvae, leading to decreased pod damage and an increased chickpea grain yield.

Faba bean stem borer, *Lixus algirus* L. (Coleoptera: Curculionidae) (Figure 3K), is regarded as one of the main insect pests affecting faba beans in the Mediterranean area

(Ait Taadaouit et al., 2021a, b). Their extensive damage is primarily attributed to larval feeding within the plant stems. El Fakhouri et al. (2021) conducted experiments using both small wind tunnels and olfactometer bioassays, revealing that the volatiles emitted by healthy host plants during the flowering stage attract both male and female *L. algerus* significantly. The study also demonstrated that faba bean plants exhibit distinct volatile profiles based on the degree of infection, and the growth stage (VOCs of vegetative stage plants are different from those of the blooming stage). During the flowering stage of the infested plants, sixty-six compounds with notable GLV amounts such as 3-Hexen-1-ol, acetate, (Z)-, 1-Hexanol, 2-ethyl-, 3-Hexen-1-ol, 1 acetate, (E)- were released.

2.1.6 Storage pests

Storage losses caused by insect pests in food legumes contribute significantly to food and nutrition insecurity, leading to reduced incomes for growers. Smallholder farmers, relying on traditional storage methods, often experience substantial losses, surpassing 70%. Reports indicate storage damages reaching up to 50% in certain essential legume crops including chickpea, faba bean, lentil, and pea (Keneni et al., 2011). Smallholder farmers employ various pest management strategies, including insecticide seed treatment, the use of botanicals, the adoption of improved storage structures and bags, and fumigation, which is the most common method for grain protection against insect pests. However, the two primary fumigants methyl bromide and phosphine, have encountered challenges due to environmental concerns such as decreasing ozone levels and biological factors like insect resistance, which highlight the need for urgent development of eco-friendly alternatives (Rajendran and Sriranjini, 2007). Volatile organic compounds emitted from different plants serve as an efficient tool for the control of many storage pests (Singh et al., 2021).

The adzuki bean weevil, *Callosobruchus chinensis* (L.) (Coleoptera: Chrysomelidae) (Figure 3L) is a highly harmful insect of stored legumes due to its highly destructive nature. In a study conducted by Mario et al. (2023), the application of plant powder fumigants emerged as a sustainable and economical strategy for managing pests of stored product. The effectiveness of powder fumigants of four plants including clove, holy basil, lemongrass, and turmeric was assessed. These plants exhibited substantial efficacy, causing mortality rates of up to 100% in *C. chinensis*. Additionally, they demonstrated oviposition deterrence, antifeedant activity, suppression of F1 offspring, and repellent efficacy for adults. Consequently, this multifaceted impact resulted in a reduced percentage of bean damage and weight loss.

Examining of the volatile organic compounds found in the four plant powder fumigants revealed key constituents responsible for their anti-pest properties. Clove was characterized by eugenol and caryophyllene, holy basil by estragole, lemongrass by α -Citral and β -Citral, and turmeric by α -zingiberene and β -sesquiphellandrene. Notably, the powder fumigant from clove plant has proved outstanding effectiveness across all observed variables, displaying remarkable bioefficacy despite the minimal quantity applied.

Callosobruchus maculatus (F.) (Coleoptera: Bruchidae) (Figure 3M) is a threatening stored grain pest affecting *Lathyrus*

sativus L. (Leguminosae), widely referred to as khesari, in India, Bangladesh, and Ethiopia. This pest has the ability to locate its host by detecting the volatile organic compounds released from the host seeds (Hamdi et al., 2017).

A total of 23 volatiles were identified and quantified in different types of healthy khesari seeds including Bio L 212 Ratan, Nirmal B-1, WBK-13-1, and WBK-14-7, using gas chromatography coupled to mass spectrometry and gas chromatography-flame ionization detector analyses. Nonanal emerged as the predominant compound in the seeds of the two varieties Bio L 212 Ratan and WBK-13-1, then we found farnesyl acetone. Conversely, Nirmal B-1 and WBK-14-7 khesari seeds were characterized by farnesyl acetone as the predominant volatile, followed by nonanal.

The Y-shaped glass tube olfactometer bioassays were used to study the olfactory reactions of female *C. maculatus* towards volatile blend released by different varieties of khesari seed, as well as distinct synthetic compounds, and their mixture. The results indicated that this pest preferred the entire volatile mixture emitted by Bio L 212 Ratan seeds compared to those from the other three types. *C. maculatus* was attracted to five different synthetic compounds including 3-octanone, linalool oxide, 3-octanol, 1-octanol, and nonanal.

Notably, a synthesized mixture consisting of linalool oxide, 3-octanone, 3-octanol, 1-octanol, and nonanal at concentrations of 448, 390, 1182, 659, and 8114 ng/20 μ l methylene chloride, respectively, proved to be the greater appealing to *C. maculatus*. This mix holds promise for potential use in *C. maculatus* pest control programs, like lured traps (Adhikary et al., 2015).

Furthermore, Ajayi et al. (2015) have investigated the host selectivity of *C. maculatus* female regarding seeds from three legume cultivars, Ife-brown and black-eyed cowpeas (*Vigna unguiculata* L.) and soybean (*Glycine max* L.). Results revealed that *C. maculatus* selects its host based on the odor and 2-ethyl hexanol has been identified as a possible attractant for this pest, which is more produced in Ife-brown cowpea.

2.2 VOCs and disease management

Plant overcomes pathogen attack by producing a set of volatile organic compounds (VOC) from different organs including seeds, leaves, roots, and nodules (Singh et al., 2022).

These VOCs serve as chemical signals that mediate interactions between plant and pathogen by reducing disease development, as well as, plant and their neighbouring plants by inducing resistance against pathogen attack (Kasote et al., 2023; Kong et al., 2024).

2.2.1 VOCs in plant-pathogen interaction

Fusarium species that are associated with chickpea plants are considered one of the most serious biotic stresses that affect chickpeas in the main growing regions (Lokesh et al., 2020; Sampaio et al., 2020). Chickpea plants can defend themselves against *Fusarium* attacks (Figure 4) by producing different volatile organic compounds (Table 2). Research conducted by Cruz et al. (2012) showed that chickpea VOCs, such as 1-hexanol, trans-2-hexenal,



FIGURE 4
Fusarium symptoms (A) Fusarium head blight (FHB), caused by *Fusarium graminearum*, (B) Fusarium wilt on chickpea caused by *Fusarium oxysporum* (f) sp. *Ciceris* (InsectImages, 2018).

1-penten-3-ol, cis-3-hexen-1-ol, and trans-2-hexen-1-ol, have negatively impacted both *Fusarium avenaceum* and *F. graminearum* development, however the intensity of their impact differed. For instance, trans-2-hexenal and trans-2-hexen-1-ol were highly effective, fully inhibiting *F. avenaceum* development even at the minimum dosage (2 μ l). Every VOCs have totally suppressed the pathogen growth at the highest dosage (50 μ L), except for 1-penten-3-ol that decreased development by about 50% in comparison with the control without VOCs.

Bioassays performed in Petri plates revealed that volatile organic compounds (VOCs) produced by chickpeas, when tested individually, exhibited greater efficacy toward *F. graminearum* and *F. avenaceum* compared to VOCs produced by wheat (Cruz et al., 2012).

However, VOCs released from plants can exhibit harmful effects if they are found in high concentrations. For example, 2-ethyl-1-hexanol produced by chickpea may have an adverse effect on plant growth and also can prevent *Fusarium* development (Horiuchi et al., 2007; Barney et al., 2009).

Additionally, Ascochyta blight, caused by *Ascochyta rabiei* (Class: Coelomycetes, order: Sphaeropsidales) (Telomorph: *Didymella rabiei*; class: Dothideomycetes, order: Pleosporales) (Krimi et al., 2022)

(Figure 5), stands as the major devastating foliar disease that affects chickpea plant (Gaur et al., 2012). It represents a serious obstacle to winter chickpea production (Houasli et al., 2021). To protect themselves from *A. rabiei* invasion, chickpea plants release a set of VOCs that can affect the pathogen's development. According to Cruz et al. (2012), the release of the two volatile compounds 1-penten-3-ol and cis-3-hexen-1-ol, was triggered by the *A. rabiei* fungus. Besides, chickpea VOCs production was related to Ascochyta blight severity. However, research carried out by Oliva et al. (1999) has shown that the application of fungicides can reduce the production of volatile organic compounds in chickpea. Furthermore, volatile organic compounds (VOCs) can be employed for the evaluation of Ascochyta blight disease severity in chickpea crops (Kashyap and Kumar, 2021).

2.2.2 VOCs in plant-plant interaction

Plants exhibiting resistance to herbivores and pathogens release volatile organic compounds (VOCs) that can prompt resistance reactions in nearby healthy plants. Latest investigations suggests that these VOCs may also induce resistance to pathogens through various mechanisms: either by priming the stimulated expression of resistance genes in the receiver plant or by inhibiting directly microbial pathogens, leading to a passive resistance in the plant subjected to VOCs (Sakurai et al., 2023). Research of Quintana-Rodriguez et al. (2015) revealed that VOCs released by infected resistant bean plants (*Phaseolus vulgaris*) offered resistance to bean anthracnose caused by *Colletotrichum lindemuthianum* in a susceptible cultivar after being exposed over 6 hours to volatile compounds collected from the headspace of resistant plants. Furthermore, individual VOCs like limonene, linalool, nonanal, methyl salicylate, and methyl jasmonate, at normal levels, could directly inhibit conidia development and can also suppress the conidia production using an active mycelium *in vitro*. VOCs from infected plants displayed a more potent inhibitory effect on conidial germination compared to VOCs from uninfected plants. This inhibitory effect was found to be correlated with the abundance of b-linalool, limonene, or methyl jasmonate. In conclusion, VOCs are pivotal in enhancing bean resistance to fungal pathogens, both by directly reinforcing the emitting plant's resistance, and indirectly by influencing the resistance traits of nearby receiver plants through induced and associational resistance.

TABLE 2 Major volatile organic compounds of chickpea leaves.

Chemical family	Name of compound
Aliphatic Alcohols	Ethanol
	1-penten-3-ol
	1-hexanol
	Cis-3-hexen-1-ol
	Trans-2-hexen-1-ol
	3-methyl-1-butanol
Aliphatic Aldehydes	Trans-2-hexenal
Aliphatic Ketones	3-hydroxy-2-butanone
Aromatic compounds	3-methylbenzaldehyde
	Naphthalene



FIGURE 5
Ascochyta blight symptoms on chickpea plant (A) Brown lesions on leaves and pods, (B) Breakage of the stem (InsectImages, 2018).

Several VOCs like, linalool, limonene, nonanal, methyl salicylate, and methyl jasmonate, exhibit antimicrobial activity (Fernando et al., 2005; Arroyo et al., 2007; Neri et al., 2007). For instance, nonanal has been found to suppress fungal germination in leaves through direct fungistatic actions (Zeringue et al., 1996) and also conferred resistance in lima bean to *Pseudomonas syringae* (Yi et al., 2009). Notably, the dominant volatile component cis-hexenyl acetate in the volatile blend of the susceptible cultivar, is more probable to be linked to herbivory than pathogen resistance mechanism.

3 VOCs application on food legume crops

3.1 Exploring the role of VOCs in cropping systems

Smallholder farmers adopt diverse cropping systems to promote sustainable crop production (Brilli et al., 2019; Murphy-Bokern, 2022). Legume crops are integrated into crop rotation and multiple cropping strategies to reduce fertilizer consumption, minimize

pesticide use, and enhance various ecosystem services (Agegnehu et al., 2008; Gaba et al., 2015; Wahbi et al., 2016; Ajal and Weih, 2022). Some major multiple cropping systems (Figure 6), focusing on volatile organic compounds (VOCs) role in pest management and other ecological services are briefly described (Figure 7).

3.1.1 Crop rotation

Crop rotation is an agricultural strategy that involves the sequential planting of various crops in one parcel for a set period of time to enhance soil fertility and control pests and diseases.

The rotation of wheat with chickpea has proven beneficial in reducing *Fusarium* head blight, through volatile organic compounds (VOCs) released from legumes. Cruz et al. (2012) showed that VOCs produced from both wheat and rotation crops, particularly chickpea, appear to have a negative impact on pathogenic *Fusarium* which cause significant financial deficits in crop rotations based on wheat.

The findings further indicate that in chickpea-wheat rotation systems, *Fusarium* inoculum rates could be minimized by cultivating chickpea genotypes with elevated concentrations of 1-hexanol and trans-2-hexen-1-ol in both roots and shoots (Cruz et al., 2012).

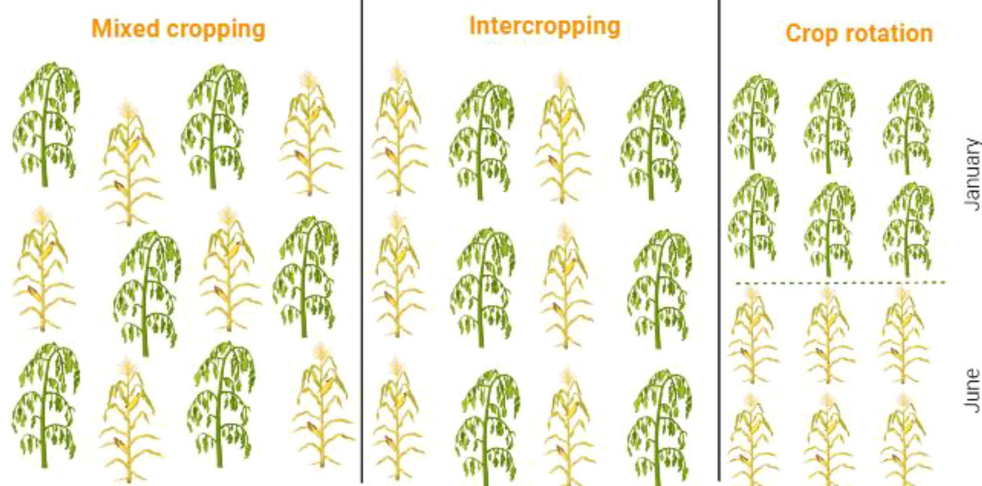
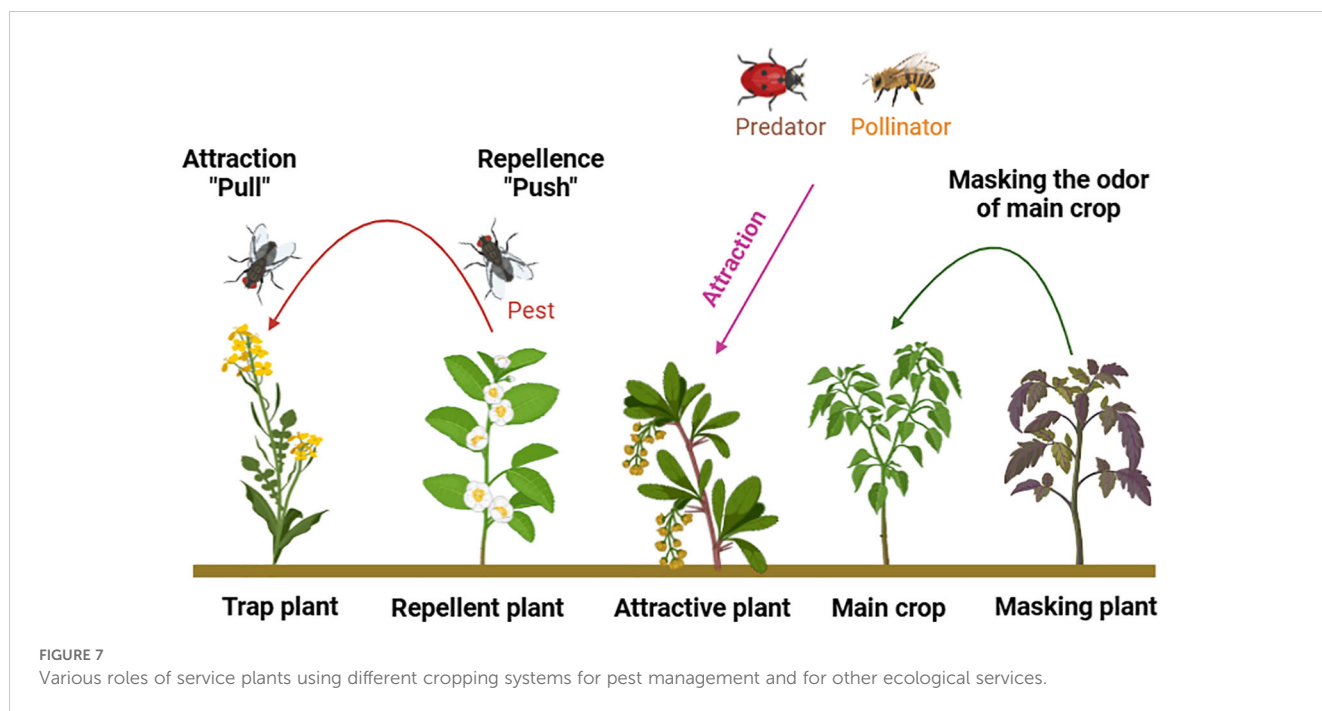


FIGURE 6
Different cropping systems adapted in legume crops as cultural practices to manage pest attack.



3.1.2 Polyculture

Farmers grow different crops in the same area to exploit resources and avoid risks due to pest outbreaks or weather variability. As opposed to monocropping, polyculture increases crop diversity that influences insect populations and diseases by reducing the population density of herbivores and promoting beneficial insects like pollinators and natural enemies, especially parasitoids. Growing diverse plant species in close proximity can contribute to insect control through various mechanisms, which differ according to the particular volatile proprieties of each plant (Shrivastava et al., 2010).

3.1.2.1 Inter - and mixed cropping

These cropping practices are a type of polyculture in which crop varieties or different plant species are planted, in the same space at same time, as mixed or arranged in rows or strips (Ghaley et al., 2005; Pelzer et al., 2012). Cereal-legume inter/mixed cropping practices contribute positively to insect pests' control (Mweke et al., 2020; Emery et al., 2021).

In maize-legume intercropping, the overall system dynamics can influence the presence of legume pests (Bukovinszky et al., 2004). For instance, intercropping bean plants with older and taller maize plants can significantly reduced black aphids (*Aphis fabae*) infestations (Ogenza-Latigo et al., 1992). Similarly, cowpea crops experienced a lower population of pod-sucking bugs when grown alongside with maize at particular percentages, in contrast to being cultivated alone (Olufemi et al., 2001). The intercropping of cereals and legumes has the potential to impact the insect diversity and population by changing foliage nitrogen concentration and modifying the plant taste for herbivores (Pierre et al., 2023).

3.1.2.2 Companion crops

The cultivation of both non-commercial and main crops is a common practice that supports nutrient uptake, pollination, and

various other benefits. Push-pull is the most popularized innovation in managing insect pests through companion cropping (Murage et al., 2015; Eigenbrode et al., 2016; Isgren et al., 2023).

Trap cropping is a sort of companion planting where specific plants are strategically grown around the field to protect the main crop by reducing pest pressure. Typically, trap crops exhibit higher attractiveness to insects compared to the main crops, and the allocated area for trap crops should be relatively small (Sarkar et al., 2018).

These companion plants (CP) are recognized to emit compounds that may impact the aphid behavior through various ways, including mobility, feeding, and reproductivity (Moreno and Racelis, 2015).

Firstly, volatile organic compounds (VOCs) released by CPs can entice aphids far from their primary host plants. Additionally, they have the ability to modify the perception of the host plant by masking its aroma which renders it undesirable host for aphids, or by emitting repellent volatiles. Thirdly, CP can attract natural enemies by releasing VOCs to enhance and maintain biological pest management (Ben-Issa et al., 2017).

In a research investigation on the black bean aphid (*A. fabae*) conducted by Nottingham et al., showed that combining host plant volatiles with α -pinene identified in rosemary oil (*Rosmarinus officinalis*) obscured the host plant odors and make them unattractive in olfactory tests, which disrupted the aphid's behavioral response. Additionally, the individual volatile compound from CP, when tested alone, was repellent to the aphids.

The 3-butenyl or 4-pentenyl isothiocyanate released by savory (*Satureja hortensis*) and thyme (*Thymus vulgaris*) exhibited a similar obscuring impact on enticing host odors for the black bean aphid, but when tested independently, they proved to be repellent.

Repulsive plants, which are non-host plants nearby that disrupt the insect activity and deter feeding on host plants, have been

identified in laboratory tests. The compounds myrtenal and isothiocyanates released from the *Brassicaceae* family, demonstrated repulsing effects on the black bean aphid (*A. fabae*). Moreover, many terpenoids present in CP-emitted VOCs (e.g., rosemary), like 1,8 cineole, α -pinene, or camphor were found to have a repellent impact on aphids.

Basedow et al. (2006) noticed that the intercropping arrangement of bean plants (*V. faba*) alongside basilic (*Ocimum basilicum*) and summer savory (*Satureja hortensis*) plants (*Lamiaceae* family) significantly reduced the *A. fabae* population in wind tunnels, greenhouses, and fields. Tests conducted by Nottingham et al. (1991), employing a straight-line pathway olfactometer and a flight cage to exhibit the deterrent impact of *Satureja hortensis* and *Tanacetum vulgare* on *A. fabae*. *Ocimum basilicum* also exhibited repellent activity against the black bean aphid.

3.2 The use of VOCs in crop breeding

In most cases, plant VOCs are genetically regulated and highly species specific (Splivallo et al., 2012; Niederbacher et al., 2015). Improved crop varieties, landraces and their wild relatives release various VOCs as a defense mechanism against biotic and abiotic stressors (Moayeri et al., 2007; Thomas et al., 2023). The variability in VOCs content can be an important trait to be exploited in developing germplasm for effective deployment in insect pest and disease management (Keneni et al., 2011; War et al., 2012; Arous and Cairns, 2014; Valencia-Ortiz et al., 2022).

Limited research showed that cultivated crops have less complex inducible volatiles due to modern breeding that make them less ecologically competitive comparing to their wild relatives (Palmgren et al., 2015; Rowen and Kaplan, 2016).

3.2.1 VOCs and breeding for pest resistance

Differences in volatile organic compounds (VOCs) among genotypes offer insights into insect preferences and the degree of damage caused by insects. These findings help breeders to select genotypes that demonstrate higher tolerance or resistance to pest attacks, based on their VOCs profile. They can target crop germplasm that emits fewer herbivore-attractant volatile organic compounds (VOCs) or that increases the release of VOCs known to repel pests.

In cowpea, females of *C. maculatus* preferred some genotypes over the others in oviposition due to variation in volatile compounds. Ahuchaogu and Ojiako (2021) demonstrated how the mated female *C. maculatus* responded to odor signals released by multiple bean cultivars (Pinto beans, boro-brown beans and adzuki beans) employing both two-arm and four-arm olfactometers. The study of volatile organic compounds by gas chromatography coupled to mass spectrometry (GCMS) revealed variations in the abundance profile of these compounds. This implies that the nature and amounts of volatile compounds detected in beans impact the female *C. maculatus* behaviors related to host finding and preference. The volatile compounds like benzyl alcohol, nonanal, and limonene were identified as

potential compounds capable to influence the behavioral attractiveness of beetles to specific bean types.

Moreover, the attractiveness of phytophagous alate *Aphis craccivora* (Hemiptera: Aphididae) in cowpea varies among cultivars of the same species depending on VOCs profile of each genotype. Diabate et al. (2019) identified 23 volatile compounds from four cowpea cultivars with just 4 volatiles (hexanal, 1-octen-3-ol, (E)-2-hexenal, and p-xylene) showing significant differences in emission quantities across the cultivars.

In the olfactometer assays, the aphids exhibited a notable preference for odors from cultivar Ex-Luanda and significant non-preference to Katumani 80. Machakos and Ken Kunde generated unbiased reactions.

The Ex-Luanda cowpea cultivar appeared more attractive than Katumani 80 based on plant odor. The unattractant cultivar Katumani released significant amount of Hexanal and (E)-2-hexenal, while the attractant cultivar Ex-Luanda emitted large quantities of 1-octen-3-ol and p-xylene.

The composition and proportions of volatile organic compounds in cowpea varied among varieties. The attractant cowpea cultivar releases the adequate combination and particular proportion of compounds recognized by *A. craccivora* to identify the host plant, whereas the unattractive cultivar is distinguished via the unsuitable mixture and proportions of compounds.

In tests using standard compounds, *A. craccivora* responded neutrally once the attractant cowpea cultivar (Ex-Luanda) was mixed with hexanal and (E)-2-hexenal compared to purified air. These two compounds may mask the volatile profile of Ex-Luanda, making it less attractive.

In contrast, the repellent cultivar Ex-Luanda was characterized by the presence of 1-octen-3-ol compound. Although the existence of the two compounds 1-octen-3-ol and p-xylene with the less favored cultivar Katumani, *A. craccivora* didn't display attraction.

In grass peas (*Lathyrus sativus* L.), Mitra et al. (2020) characterized the volatile organic compounds (VOCs) profile of two grass pea genotypes, namely BIO L 212 Ratan and Nirmal B-1, in response to infestation by the viviparous aphid *A. craccivora*.

The aphids attack led to an elevation in the VOCs emission in comparison to undamaged plants of each cultivar. Nevertheless, the overall quantity of VOCs was greater in the NIR cultivar in comparison with the BIO cultivar, for both undamaged or damaged plants. The overall quantity of VOCs released reflects the extent of insect damage (a greater number of aphids resulting in increased VOCs emission). The GC-MS analysis of the VOCs profile in damaged plants of the NIR cultivar revealed the presence of 4 compounds including thymol, benzyl alcohol, 1,3-diethylbenzene, and 1-hexadecene. In contrast, BIO grass peas cultivar plants exhibited 11 compounds such as benzyl alcohol, diacetone alcohol, p-cymene, linalool oxide, 1,3-diethylbenzene, acetophenone, 1-nonanol, ethylacetophenone, p-cymen-7-ol, thymol, and 1-hexadecene, in their volatile extracts. This blend of VOCs functioned as a lure for *A. craccivora*. In olfactometer bioassays, female aphids displayed a preference for an artificial mixture comprising 1,3-diethylbenzene, benzyl alcohol, 1-hexadecene, and thymol. This finding suggests the potential use of these compounds in developing lures for an effective control of this insect pest.

In chickpea, trichomes provide a potential resistance mechanism against the pod borer *Helicoverpa armigera* (Hübner), as highlighted by Brar and Singh, (2017). Glandular trichomes, specialized hairs on plant surfaces, serve as physical barriers against herbivores and act as essential chemical defenses. These trichomes produce various secondary chemicals, including terpenoids, phenylpropenes, flavonoids, methyl ketones, acyl sugars, and defensive proteins. Terpenoids, a major component of volatile mixtures triggered by herbivore activity, serve a crucial function in attracting predators and parasitoids to plants infested by herbivore. Additionally, terpenoids contribute to direct defenses by acting as deterrents or repellents, with higher concentrations often proving toxic. For instance, the sesquiterpene (E)- β -farnesene released by glandular trichomes was found to drive away aphids (*Myzus persicae*), whereas their parasitoids, such as the hymenopteran *Diaeretiella rapae*, were drawn to (E)- β -farnesene.

Phenylpropenes play double functions, acting as defense mechanism against herbivores, and also serving as attractants for pollinators. Notably, eugenol and methylchavicol are mainly produced and retained in glandular trichomes. The use of synthesized eugenol resulted in mortality and deterrence in Coleoptera species. Methyl ketones, a form of volatile compounds derived from fatty-acid, are particularly effective in defending plants against pests. Plants typically contain Methyl ketones with 7 to 15 carbons consist of 2-heptanone, 2-nonanone, 2-undecanone, 2-tridecanone and 2-pentadecanone (Glas et al., 2012; Xing et al., 2017; Kaur and Kariyat, 2020).

3.2.2 VOCs and crop breeding for disease resistance

Evaluation of disease severity is a crucial phase in developing disease-resistant cultivars. Visual evaluation and classical plant phenotyping techniques is a common practice in plant breeding; nevertheless, these methods requires intensive training, destructive harvesting during precise phenological periods, and are both time consuming and expensive.

Due to their particular properties, plant VOCs are a promising tool that could be used as a rapid and non-destructive assessment of plant phenotypic traits (Jud et al., 2018).

Research carried out by Zhang et al. (2023) showed that sensing methods utilizing volatile organic compounds (VOCs) such as a field asymmetric ion mobility spectrometry (FAIMS) system could be an alternative solution for disease monitoring. This method was evaluated as a non-invasive and fast VOC-based phenotyping approach for the surveillance of Ascochyta blight disease intensity in chickpeas.

In addition, the high variability of VOC emissions between plant genotypes and species makes them great phenotypic markers to distinguish between different levels of disease resistance and resilience, which in consequence will contribute to enhance the effectiveness and productivity of crops (Niederbacher et al., 2015).

To evaluate resistance for Aphanomyces root rot disease, caused by *Aphanomyces euteiches* Drechs., which is a serious soil-borne disease affecting various crops, such as pea plant (*Pisum sativum* L.). Marzougui et al. (2022) investigated the reaction of two cultivars, Ariel (susceptible) and Hampton (elevated degrees of partial

resistance). Disease progression was assessed non-intrusively at three distinct intervals (15, 20, and 30 days post-inoculation). VOCs emitted by both infested and healthy plants were gathered employing dynamic headspace sampling. Analysis via GC-FID and GC-MS revealed a profile of sixteen volatile compounds including 2-Propanone, 2-Butanone, 3-Pentanone, 3-Hexanone, Hexanal, (E)-2-Hexanal, (Z)-3-Hexen-1-ol, (E)-2-Hexen-1-ol, 1-Hexanol, 3-Heptanone, 2-Heptanone, 2-Octanone, (Z)-3-Hexenyl acetate, (E)-2-Hexenyl acetate, Nonanal, and Decanal. At 20 DPI, the Ariel cultivar exhibited a significant increase in hexanal emissions compared to the Hampton cultivar. Concurrently, the standardized proportional peak strength of the Ariel cultivar showed elevated emissions of (Z)-3-hexen-1-ol and (Z)-3-hexenyl acetate (Marzougui et al., 2022).

Several VOCs detected through non-destructive sampling presented significant correlations with visual disease ratings and relative chlorophyll level.

This study indicated that pea varieties with varied level of resistance and susceptibility to Aphanomyces root rot displayed differences in VOC blends across several time intervals and development phases. The observed differences in VOC emissions between cultivars underscore the potential of VOCs as biomarker-based phenotyping tools for distinguishing resistance levels in evaluated pea cultivars. Integrating VOC profiles with high-throughput VOC detection methods presents a promising unique approach for characterizing disease reactions in plants.

Plants exhibiting resistance to herbivores and pathogens release volatile organic compounds (VOCs) that can prompt resistance reactions in nearby healthy plants. Latest investigations suggests that these VOCs may also induce resistance to pathogens through various mechanisms: either by priming the stimulated expression of resistance genes in the receiver plant or by inhibiting directly microbial pathogens, leading to a passive resistance in the plant subjected to VOCs.

Research of Quintana-Rodriguez et al. (2015) revealed that VOCs released by infected resistant bean plants (*Phaseolus vulgaris*) offered resistance to bean anthracnose caused by *Colletotrichum lindemuthianum* in a susceptible cultivar after being exposed over 6 hours to volatile compounds collected from the headspace of resistant plants. Furthermore, individual VOCs like limonene, linalool, nonanal, methyl salicylate, and methyl jasmonate, at normal levels, could directly inhibit conidia development and can also suppress the conidia production using an active mycelium *in vitro*. VOCs from infected plants displayed a more potent inhibitory effect on conidial germination compared to VOCs from uninfected plants. This inhibitory effect was found to be correlated with the abundance of b-linalool, limonene, or methyl jasmonate (Quintana-Rodriguez et al., 2015).

In conclusion, VOCs are pivotal in enhancing bean resistance to fungal pathogens, both by directly reinforcing the emitting plant's resistance, and indirectly by influencing the resistance traits of nearby receiver plants through induced and associational resistance. Several VOCs like, linalool, limonene, nonanal, methyl salicylate, and methyl jasmonate, exhibit antimicrobial activity (Fernando et al., 2005; Arroyo et al., 2007; Neri et al., 2007). For instance, nonanal has been found to suppress fungal germination in leaves through direct

fungistatic actions (Zeringue et al., 1996) and also conferred resistance in lima bean to *Pseudomonas syringae* (Yi et al., 2009). Notably, the dominant volatile component cis-hexenyl acetate in the volatile blend of the susceptible cultivar, is more probable to be linked to herbivory than pathogen resistance mechanism.

4 Microbial VOCs in food legume crops

During plant-pathogen or plant-pest interactions, microbial antagonists can interrupt the developmental process of pest or pathogen. This may take place via parasitic activity, conflict for area and food, the secretion of hydrolytic enzymes (Punja and Utkhede, 2003), and the release of antimicrobial compounds, including volatiles (Vinale et al., 2006). These microbial VOCs emitted from microorganisms like bacteria and fungi (Korpi et al., 2009; Francis et al., 2010; Thorn and Greenman, 2012) have the ability to travel via both air and ground (Aochi and Farmer, 2005). Therefore, they present an ideal “infochemicals” that mediate interactions of microorganisms with their natural environment (Weisskopf et al., 2021; Morath et al., 2012), including regulation of symbiotic associations, phytotoxicity, enhancement of plant development, activation of plant defense responses against pathogen attack, and insect attractant or repellent activities (Morath et al., 2012; Lee et al., 2016). These characteristics could be utilized to create eco-friendly solutions such as biofertilizers and biopesticides to enhance plant productivity and protection (Kaddes et al., 2020; Soto et al., 2021).

Over a 100 bacteria and fungi emit microbial VOCs in the ground (Effmert et al., 2012), with around 250 fungal VOCs were reported to date (Duc et al., 2022).

Five classes of microbial volatiles (alcohols, ketones, aromatic compounds, terpenes, and organic acids) each comprised at least 10% of the volatiles, reaching 64% of the total diversity. Minor groups including aldehydes, alkanes, alkenes, furans, ester, sulfur and nitrogen combining substances, and ethers, contributing together to over 37% of the total diversity (Schenkel et al., 2015; Bennett and Inamdar, 2015).

Fungi produce various mixtures of volatile organic compounds (VOCs) that are originate from both primary and secondary metabolism processes (Korpi et al., 2009). The composition of these volatile blends can vary based on the fungi species, the intra- and interspecific interactions (Schulz-Bohm et al., 2015; Piechulla et al., 2017), and the growth conditions (temperature, pH, moisture level, substrate, nutrients, and duration of incubation) (Morath et al., 2012; Bennett et al., 2013; Plaszkó et al., 2020). For example, according to Savelieva et al. (2016), *Fusarium* fungi grown on potato sucrose agar medium (PSA) release a broader range and greater amounts of VOCs than those cultivated on autoclaved wheat kernels (WK). Schenkel et al. (2018) have also reported considerable variances in the VOC composition of the same fungal species when cultivated in soil or malt extract medium. Moreover, the work of Li et al. (2016) showed that VOC retention in soils is affected by various environmental parameters including, temperature,

moisture content, and pH that determine the polarity of VOCs and alter their evaporation pressure.

Microbial VOCs can reduce disease severity by inhibiting mycelial growth, creating unfavorable conditions for the development of diseases, stimulating soil-borne biocontrol agents, activating defense responses, and priming plants against future pathogen or pest attacks (Köhl et al., 2019).

One of the initial instances illustrating the inhibitory impact of microbial VOCs on plant pathogens were those generated by *Pseudomonas* isolates obtained from soybean and canola, which engaged in restraining and minimizing mycelial development of *Sclerotinia sclerotiorum* (Fernando et al., 2005).

Besides, VOCs released by two endophytic *Bacillus* have notably decreased both the mass and quantity of *S. sclerotiorum* persistent forms (sclerotia) (Massawe et al., 2018; Li et al., 2019). Similarly, research conducted by Fialho et al. (2011) demonstrated that the VOCs mixture emitted by *S. cerevisiae*, comprises alcohols like 3-methyl-1-butanol, ethanol, 2-methyl-1-butanol, and phenylethyl alcohol, and esters such as ethyl acetate and ethyl octanoate, have an effective control over *S. sclerotiorum* both *in vitro* and on bean seeds.

The substances 2-methyl-1-butanol, and 3-methyl-1-butanol showed the highest efficacy towards *S. sclerotiorum*, completely reducing its mycelial development at a concentration of 0.8 $\mu\text{L mL}^{-1}$, followed by ethyl acetate, at 1.2 $\mu\text{L mL}^{-1}$. Fumigating bean seeds with *S. cerevisiae* VOCs at 3.5 $\mu\text{L mL}^{-1}$ resulted in 75% decrease in *S. sclerotiorum* occurrence post 4 days.

Trichoderma species have long been considered one of the most promising biocontrol agents; they are capable to generate a wide range of secondary metabolites that could influence the process of their biological function (Li et al., 2016). The research work of Kumar et al. (2019) showed that VOCs emitted by three *Trichoderma* species *Trichoderma harzianum*, *Trichoderma viride*, and *Trichoderma konigii* have hindered the mycelium development of *Fusarium oxysporum* f. sp. *ciceri* by 79.25%, 62.27%, and 50%, respectively. Also, species of *Streptomyces* have exhibited great potential for controlling plant fungal diseases by producing antifungal compounds (Li et al., 2012). Research carried out by Amini et al. (2016) showed that the antagonistic bacteria *Streptomyces* spp. has strong inhibitory effects against chickpea wilt. The isolated strains of *Streptomyces* (KS55, KS58, KS112, KS62, and KS31) produced a mixture of VOCs that can reduce disease severity by inhibiting mycelial growth of the pathogen, ranging from 20.2 to 33.4%.

Moreover, Elbouzaoui et al. (2022) revealed that volatile compounds produced by *Bacillus* can inhibit the development of *Fusarium oxysporum* f. sp. *ciceri*, with a high percentage of inhibition exceeding 30% obtained from *B. subtilis*.

Concerning the role of VOCs in inducing plant defenses, Ballhorn et al. (2013) investigated the impact of rhizobial symbiosis on volatile production in lima bean plants (Fabaceae: *Phaseolus lunatus* L.) and their role in legume defenses against herbivores.

They have demonstrated that the volatile organic compounds stimulated by jasmonic acid in rhizobia-colonized lima bean plants

have repellent effects on the specialist herbivore pest (Mexican bean beetle; *Coccinellidae: Epilachna varivestis*). Results revealed that rhizobial symbiosis can induce plant defense via volatile production and can affect the choice behavior of beetles, so it can serve as a fundamental component of legume defenses against herbivores.

Additionally, VOCs produced by Lima bean plants colonized by rhizobia, a nitrogen-fixing bacteria, showed a repellent action on the Mexican bean beetles (*Epilachna varivestis*), which resulted in less damage from this pest (Bustos-Segura et al., 2024).

Microbial VOC can also control harmful plants and weed. For example, volatile compounds produced by fungi including 3-methyl-1-butanol, 1-octen-3-ol, 2-phenylethanol, 3-octanol, 1-hexanol, 3-octanone, and trans-2-octenal are categorized as toxic against plants. These compounds produced by different fungi can affect negatively the root growth and seed germination (Duc et al., 2022).

5 Conclusion and futures perspectives

In conclusion, the exploration of volatile organic compounds (VOCs) in the management of insect pests and diseases of food legumes holds significant promise and potential.

This assessment underscores the promising role of VOCs in enhancing disease and pest management strategies for cool season food legumes, offering a more sustainable and eco-friendly alternative to traditional control methods. Our research highlights several key findings and advancements in this field. The dynamic role of VOCs in mediating plant responses to biotic stresses, enabling plant to inhibit disease development, induce resistance to pathogens or herbivores, and control pest population in the field by acting as traps. Additionally, the attractive and repellent properties of plant VOCs are exploited in cropping systems of various food legumes, like bean plants, to either repel pest or attract natural enemies which reduce reliance on chemical pesticides and minimize production costs. Furthermore, traditional breeding programs that focus on genetic traits for resistance in food legumes can benefit from using VOCs as biomarkers for rapid, non-invasive plant phenotyping VOCs can also serve as diagnostic tool for an early disease or pest detection, which would allow grower to proactively intervene and select the appropriate control strategy ultimately, reducing yield losses and pesticides use. Integrating plant and microbial VOCs into crop management strategies represents a significant step and a cost-effective solution forward in sustainable agriculture, potentially improving yield quality and crop productivity.

Despite the encouraging prospects, challenges such as environmental sensitivity, inherent reactivity, and low concentrations of VOCs pose obstacles to their widespread implementation. Overcoming these challenges requires continued

research to develop advanced analysis techniques, understand the factors influencing VOC production, and their mechanisms of action.

In summary, the use of VOCs in pest and disease management represents an exciting and promising area of research. While there are still many challenges to overcome, continued research has the potential to lead to the development of new, sustainable, and eco-friendly methods for protecting crops and increasing yield.

Author contributions

LM: Formal analysis, Methodology, Writing – original draft. E-FK: Formal analysis, Methodology, Writing – review & editing. S-AK: Conceptualization, Visualization, Writing – review & editing. IM: Formal analysis, Writing – review & editing. IMK: Funding acquisition, Validation, Visualization, Writing – review & editing. ME-B: Conceptualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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