



# Essential oils – promising active ingredients of botanical insecticides or hidden risks for non-target organisms?

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## 1 Characteristics and importance of essential oils

Essential oils (EOs) are liquid mixtures of botanical origin and, very often, of complex chemical profile obtained from aromatic plants. Their chemical components are synthesized in plants using few biosynthetic routes and belong mostly to the terpenoid and phenylpropanoid groups. EOs have become firmly established over the past two decades as effective tools in crop protection and public health. Their insecticidal efficacy against target pests is well documented, and their biodegradability, low environmental persistence, and high chemical complexity make them attractive alternatives to synthetic pesticides. Consequently, EO-based products are often perceived as environmentally friendly, and their evaluation has traditionally focused primarily on efficacy and acute toxicity toward target organisms. Increasing evidence, however, indicates that the ecological role of EOs in agroecosystems is considerably more complex. However, as pointed out by Guedes et al. (2026a, b), even natural pesticides may exert significant side effects on non-target arthropods, which highlights the need for a more comprehensive assessment of their ecological impacts. Beyond pest suppression, EOs may exert both negative and positive effects on non-target arthropods through behavioural and chemosensory mechanisms.

## 2 Behavioral and sublethal effects of EOs on non-target organisms

Numerous studies demonstrate that EOs do not induce only acute or chronic toxicity, but also interfere with insect chemical communication, affecting orientation, foraging behaviour, and reproductive processes. These effects may, but do not necessarily, extend to non-target organisms, including predators, parasitoids, and pollinators. Systematic and comparable studies remain scarce. As noted by Gostin & Popescu (2024), research addressing the effects of EOs on bees has expanded markedly only since 2017 and reveals substantial variability among different EOs. While some EOs show little or no adverse effects, others are toxic or induce pronounced sublethal responses.

For example, comparative experiments on *Apis mellifera* (Hymenoptera: Apidae) and *Trigona hyalinata* (Hymenoptera: Apidae) demonstrated that *Origanum vulgare* L. and *Thymus vulgaris* L. based EOs are more toxic under contact exposure than *Mentha x piperita* L. or *Zingiber officinale* Roscoe ones, while sublethal doses altered movement patterns and reduced residence time on treated surfaces without eliciting a classical repellent response (Moreira da Silva et al. 2020). Similarly, laboratory-based risk assessment studies have shown that EO formulations and their individual constituents can trigger marked biochemical and physiological responses in honeybees such as modulation of detoxification enzymes

or inhibition of acetylcholinesterase without causing acute mortality (Giunti et al. 2022). The toxicity of EOs towards honeybees also appear to depend on the route of exposure. Modafferi et al. (2025a) highlighted a high mortality rate of honeybees workers fed with a sugar solution containing garlic EO-nanoemulsion, whereas the same formulation was found to be safe in contact toxicity trials (Modafferi et al. 2025b).

Beyond pollinators, lethal and sublethal effects of EOs have also been documented in predators and parasitoids, including reduced survival, vitality, and ability to locate prey or hosts. Such alterations may impair their ecological functions and weaken biological control in agricultural systems (Giunti et al. 2022).

### 3 Positive behavioral effects and ecological role of EOs

At the same time, it is important to emphasize that the behavioural effects of EOs are not inherently negative. EOs are mixtures of volatile compounds that are structurally and functionally diverse and closely related to plant semiochemicals naturally involved in interactions among plants, herbivores, pollinators, and natural enemies. Many terpenoids and aromatic compounds commonly act as attractive cues, enhancing orientation and foraging efficiency in beneficial arthropods. From a chemical-ecological perspective, EOs should therefore not be regarded solely as stressors, but also as modulators of the olfactory landscape, capable of redirecting arthropod behaviour in multiple directions. Moreover, negative effects reported in the literature often originate from laboratory experiments that do not account for environmental dynamics and the rapid biodegradation of EOs under field conditions.

This duality is particularly evident in natural enemies of crop pests. It is well established that plant-derived volatiles and herbivore-induced signals function as synomones, thereby enhancing biological control in agroecosystems (Bruce & Pickett 2011). Depending on chemical composition, dose, and application context, EO applications may therefore either disrupt or promote the recruitment of predators and parasitoids.

### 4 The risks of overlooking sublethal effects and ecological interactions

Differences in chemical profiles among individual EOs are ecologically critical. EOs rich in phenolic compounds such as thymol, carvacrol, or cinnamaldehyde (e.g. thyme, oregano, cinnamon) generally exhibit stronger toxic or irritant effects on pollinators and predators than EOs dominated by monoterpene alcohols or ketones, typical of mint or ginger (Moreira da Silva et al. 2020; Gostin & Popescu 2024). In addition, formulation technologies, including nanoencapsu-

lation, may increase persistence and bioavailability, thereby amplifying both efficacy against pests and potential impacts, negative or positive, on non-target organisms (Gostin & Popescu 2024). These factors clearly demonstrate that EOs cannot be treated as a homogeneous class of uniformly “safe” or “harmful” inputs. Current knowledge of their effects on non-target arthropods remains fragmented, and without systematic assessment of behavioural responses, it is difficult to determine when EO applications disrupt ecosystem services and when they may enhance them.

EOs will undoubtedly remain an important component of future crop protection strategies. The key question, however, is not whether to use them, but how – and under which ecological conditions. The prevailing tendency to assess EOs primarily through the lens of acute toxicity toward target pests is clearly insufficient and does not reflect current insights from chemical ecology or the requirements of sustainable agriculture. EOs are not inert inputs; they are active modifiers of olfactory landscapes, capable of profoundly altering the behaviour of a wide range of arthropods.

Ignoring behavioural and sublethal effects on non-target organisms poses a tangible risk not only to pollinators and natural enemies, but also to the stability of ecosystem services upon which modern agroecosystems depend. At the same time, these very properties, the capacity of EOs to influence orientation, foraging, and interactions across trophic levels, offer a largely untapped opportunity for more ecologically sophisticated crop protection strategies (Ayelo et al. 2021; Richardson et al. 2023).

### 5 Directions for future research

Future research should therefore shift decisively from asking whether EOs are “safe” to asking when, where, and for whom EOs are ecologically functional. Without systematic evaluation of behavioural responses, long-term field studies, and integration of EOs into concepts such as push-pull strategies or conservation biological control, their full potential will remain unrealized. Embracing this perspective would allow EOs to move beyond their current perception as merely “green pesticides” and toward their recognition as precision tools of ecological management, compatible with biodiversity conservation and sustainable food production.

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