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Review

Sustainable Potential of *Piper* Essential Oils Against Agricultural Pests of the Order Lepidoptera: A Review

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Abstract

Lepidopteran pests cause severe global economic damage; they are currently mitigated by synthetic pesticides that trigger widespread resistance and environmental toxicity. This systematic review evaluates the potential of *Piper* essential oils (EOs) as high-performance, sustainable bio-based insecticides, aligning with the 12 Principles of Green Chemistry. Analyzing studies covering *Piper* species, we identified phenylpropanoids (e.g., dillapiole and safrole) and terpenoids as key biodegradable scaffolds for pest management. The results highlight *P. aduncum* and *P. divaricatum* for their exceptional efficacy against *Spodoptera frugiperda* and *Plutella xylostella*, often exhibiting toxicity levels comparable to botanical standards like azadirachtin. Crucially, this review reveals that *Piper* EOs can outperform the synthetic industrial synergist piperonyl butoxide (BPO), with natural binary mixtures enhancing insecticidal potency by up to 11-fold. Furthermore, specific EOs contribute to a preventative green strategy by causing the structural disintegration of the egg chorion. By focusing on renewable biomass and design for degradation (Principles 7 and 10), this work anchors the *Piper* genus as a cornerstone for the circular bioeconomy and sustainable agricultural innovation, reducing the chemical footprint of modern crop protection.

Keywords: *Piper*; Lepidoptera; green chemistry; essential oils; biopesticides

1. Introduction

The order Lepidoptera is a taxonomic classification for insects possessing scales on their wings [1]. They are holometabolous, undergoing complete metamorphosis with distinct external and internal morphological changes [2,3]. As hexapods, they possess formed body segments (head, thorax, and abdomen) post-embryogenesis [1,3,4]. This broad order is the second largest in the class *Insecta*, ref. [2] encompassing over 150,000 species across 133 families, including moths and butterflies [5].

Several species within this order are classified as pests due to their high populations and the considerable economic damage they cause [6]. Notable examples include *Spodoptera littoralis* (cotton and soybean) [7,8], *Spodoptera frugiperda* (maize) [9], *Helicoverpa armigera* (maize, cotton, tomato, sunflower, garlic and beans) [9], and *Plutella xylostella* (cabbage), the latter of which causes losses of up to 5 billion dollars per year [10,11]. The transition to sustainable agricultural practices requires a departure from traditional chemical reliance to mitigate these losses safely [12].

Currently, management involves crop rotation [13], natural predators [14] and the use of natural or synthetic insecticides [15]. However, the environmental persistence of

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synthetic compounds necessitates the exploration of biodegradable alternatives. Essential oils (EOs) have received increasing attention as complex mixtures of low-molecular-weight secondary metabolites (<500 Da) produced by plants [16–18]. They offer properties such as a broad spectrum of biological activity, biodegradability, and a lower risk of resistance development [19–21]. In accordance with Green Chemistry Principle 10 (design for degradation), EOs are promising candidates for high-efficiency, low-impact pest management [22].

The inadequate use of agricultural pesticides is a primary cause of resistance in *Lepidoptera* [11,23,24]. To address this, the use of EOs from the *Piper* genus has emerged as a source of renewable molecules with insecticidal activity. This systematic review consolidates knowledge regarding the efficacy and potential of *Piper* EOs as specific, bio-based insecticides for the management of agricultural pests of the order Lepidoptera, emphasizing phytochemistry and treatment efficacy [25].

2. Methods

A systematic literature review was performed across the "SciELO," "Periódicos CAPES," "Web of Science," and "ACS Publication" databases. The search included manuscripts published up to July 2025, utilizing the keywords "Lepidoptera", "*Piper*" and "Essential oil". This systematic approach was strategically designed to identify renewable botanical sources that align with Green Chemistry principles, specifically focusing on identifying biodegradable secondary metabolites with high insecticidal potential. Following the initial identification phase, rigorous exclusion criteria were applied, including the removal of duplicate entries and the screening of studies based on thematic non-conformity regarding titles and abstracts. A total of twenty-three articles were selected for full-text analysis to evaluate their relevance, methodological rigor, and compliance with the core theme. The selection process prioritized studies providing detailed chemical profiles (chemotypes) and clear toxicological parameters, which are essential for assessing the sustainable industrial feasibility of these essential oils within a circular bioeconomy.

3. Phytochemistry and Efficacy of Piper Essential Oils

3.1. Piper Species EOs

The *Piper* genus comprises over 2400 species with a pantropical distribution [26,27]. Reflecting this global presence, the literature identified in this systematic review encompasses a geographic scope across three different countries: Brazil, India, and Indonesia. The Brazilian flora hosts 463 species; ref. [28] represents the largest share of the analyzed data (38 of 40 occurrences), and the inclusion of Asian studies underscores the genus's international relevance for pest control. Among the twenty-nine species evaluated worldwide, *P. aduncum* (8 occurrences), *P. marginatum* (5), and *P. hispidinervum* (4) were the most frequent (Table S1). Notably, the fact that less than 7% of known Brazilian species have been tested, combined with the emerging data from India and Indonesia, indicates a vast and underutilized global renewable biomass for sustainable biopesticide development (Table S2). This local availability supports the Green Chemistry goal of utilizing local, renewable feedstocks to minimize transportation impacts. Beyond insecticidal use, the genus shows antimicrobial, anti-inflammatory, and hypoglycemic potential, bioinsecticidal, and antioxidant properties [29–33].

Typically, *Piper* essential oils are extracted primarily from leaves and spikes. While conventional hydrodistillation remains the standard method, average extraction yields are often relatively low, generally ranging from 0.5% to 3.0% depending on the species and phenological stage (Table S3). To align with Green Chemistry principles and improve economic feasibility, recent trends suggest the adoption of green extraction technologies, such as Microwave-Assisted Extraction (MAE) or Supercritical Fluid Extraction (SFE).

These methods can significantly reduce energy consumption and extraction time while potentially increasing yields. Overcoming these extraction bottlenecks is critical, as low yields directly impact the cost of raw material production, currently representing a major hurdle for the large-scale commercialization of these biopesticides.

3.2. Main Metabolites Isolated from Piper EOs

Among the main compounds isolated from *Piper* species that exhibit insecticidal activity, terpenoids and phenylpropanoids stand out. Among these, the phenylpropanoids myristicin (7 occurrences), dillapiole (5), safrole (5), sarisan (4) and exalatacin (3) are particularly notable, as well as the terpenoids *trans*-caryophyllene (14 occurrences), bicyclogermacrene (11), terpinolene (7), δ-cadinene (7), α-pinene (5), δ-3-carene (4), germacrene B (4) and caryophyllene oxide (3) (Figure 1). In the evaluated chemotypes, major constituents frequently dominate the chemical profile, with compounds like safrole and dillapiole comprising between 40% and 80% of the total essential oil composition, depending on the specific species and geographical origin.

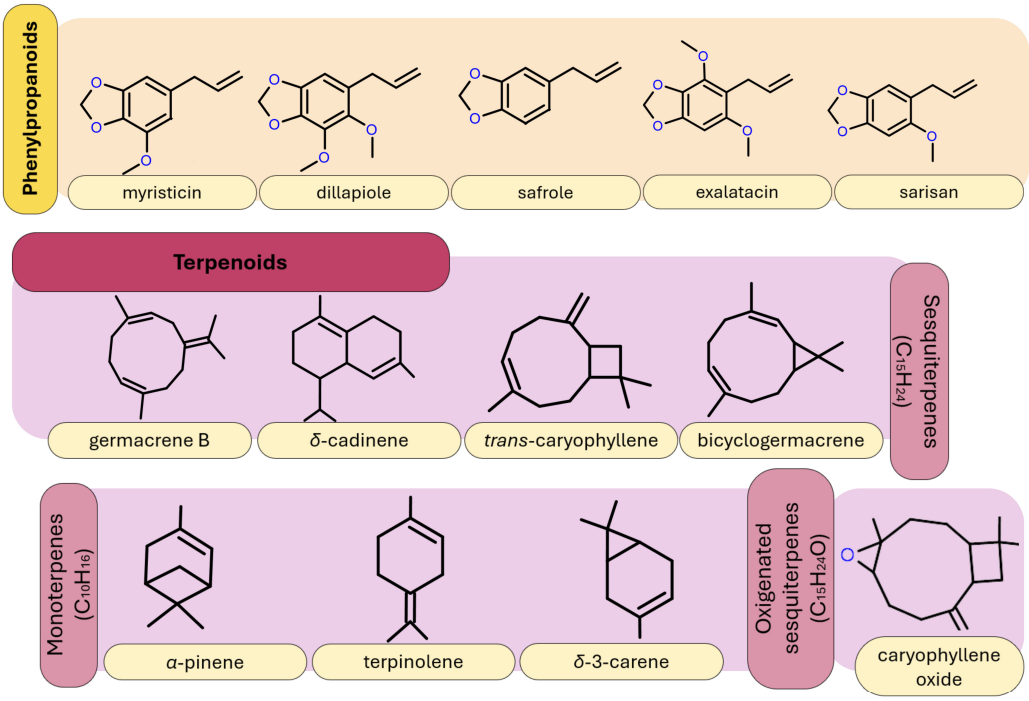


Figure 1. Some metabolites of *Piper* OES with insecticidal activity.

3.3. Methodologies in Toxicity Evaluation

To evaluate the toxic activity of EOs, the reviewed studies employed diverse methodologies and considered various developmental stages of the insects. The efficacy of their constituents was investigated through at least three exposure routes: topical exposure, ingestion, and inhalation [34]. The choice of these diverse pathways is essential in Sustainable Chemistry to determine the most efficient delivery system, minimizing waste and ensuring the bioinsecticide reaches its molecular target with the lowest possible environmental load [35].

The evaluation of EO toxic activity via topical application involved the application of treatment solutions to specific regions of the lepidopteran body to determine the degree of toxicity and the ability of the constituents to penetrate the cuticle, one of their primary defense barriers. This laboratory-based methodology aims to simulate field situations where insects are hit by the treatment solution through spraying [34]. Understanding cuticle penetration is vital for designing formulations that adhere to the Principles of

Green Chemistry to facilitate a reduction in active compound dosages while maintaining biological performance [35].

The analyzed studies utilized various techniques for topical application, including EO spraying methods using an airbrush at different concentrations and a sprayer [36–41]; application of treatment solutions [42] to the prothoracic region [41] using both internal methodologies and those developed by Hummelbrunner and Isman [43,44]; and application of solutions to the larvae's dorsum [44,45] using internal methodologies [46] and those developed by Al-Sarar [47–50]. Significant variation was observed in the experimental parameters of the studies, such as application volumes, ranging from 1 µL to 1 mL, and larval mortality evaluation periods, which varied from 24 to 96 h [44]. Despite this variability, the topical application method was widely tested and most frequently applied during the third instar larval stage [36,40,43,47,51].

Insecticidal activity was also evaluated to determine the effects of EOs via ingestion through food inhibition techniques [38,51,52], following the methodology developed by Santana et al. [53,54] and Akthar et al. [55,56]. Other assays conducted via this administration route included feeding experiments and food preference bioassays [42,57]. Ingestive bioassays are crucial for Integrated Pest Management (IPM), as they allow for higher selectivity, potentially protecting non-target organisms and pollinators that do not feed directly on the treated crop, thus promoting ecosystem sustainability [58].

The analysis of effects via inhalation was conducted through residual contact methods. These laboratory methods utilize surfaces treated with EOs to evaluate long-term insecticidal action [34]. Assessing long-term action is a core tenet of Green Chemistry, ensuring that the natural product remains effective without the environmental persistence of characteristics such as synthetic organochlorines [59]. Various techniques included leaf disc immersion [45], following the methodology of Bandeira et al. [34,49,56] and adapted from Bogoni and Vandramim [44,60], and the use of impregnated filter papers [46–49,61]. Variations were noted as exposure times (5 [42,60] to 30 s [55,56]) and drying times [34].

Although less frequent, ovicidal bioassays were employed to evaluate toxicity during early developmental stages [38,62]. Methodologies included egg deposition on treated discs, according to the methodology of Zago [55,63] and that developed by Tavares [42,64–66]; microscopic egg evaluation [67] and egg impregnation on surfaces followed by immersion in treatment solutions for 5 to 30 s [43]. Targeting the egg stage is a highly sustainable preventative strategy, as it eliminates the pest population before the onset of crop-damaging herbivory [55]. Additional methods included egg spraying and surface impregnation [66] followed by egg transfer [38]. Egg maturation stages ranged from 0 [38,67] to 48 h post-oviposition [42]. Similar to residual contact assays, effects are not immediate; therefore, mortality was observed according to the maturation stages of each species, sometimes reaching up to 7 days post-application [37].

Finally, larval repellency bioassays [57] according to Lobo et al. [58], phytotoxicity bioassays [53,55,68] and lethal concentration determinations [67] following the methodology of Prajapati et al. [66] were conducted, alongside an evaluation of synergistic effects [47,49]. These comprehensive toxicological profiles are essential for ensuring that bio-based insecticides are safe for both the crop and the broader environment, fulfilling the requirement for non-toxic end-products in Green Chemistry [36,69].

3.4. Toxicity Results of EOs in Lepidoptera

3.4.1. Topical Toxicity

Although methodologies for topical application vary across studies, their prevalence in the literature allows for a detailed analysis of the results. The toxicity of EOs from eight *Piper* species was tested against four Lepidopteran species (Table 1). This focus on

diverse botanical sources is fundamental to Sustainable Chemistry, as it explores renewable biomass to identify highly efficient, bio-based alternatives [69–71].

Table 1. Topical contact toxicity of *Piper* EOs against Lepidoptera.

Species	CT	Target Insect	Stage	Toxicity	Ref.
P. aduncum	1	*Chrysodeixis includens*	3rd instar	LC_{50} = 16.2 (14.7–17.7) (24 h)	[44]
Piper spp.		*Helicoverpa armigera*	1st instar	Mortality = 0%	[35]
P. aduncum	5	*Helicoverpa armigera*	1st instar	LT_{50} = 14.68 dias (±1.86) (5 mg/mL)	[45]
P. aduncum	5	*Helicoverpa armigera*	3rd instar	LT_{50} = 20.77 dias (±0.67) (5 mg/mL)	[45]
P. nigrum		*Plutella xylostella*	1st instar	4 live larvae in 10	[37]
P. arboreum		*Spodoptera frugiperda*	3rd instar	LD_{50} = 10.91 (8.37–14.20) mg/g of insect	[39]
P. corcovadensis		*Spodoptera frugiperda*	3rd instar	LD_{50} = 3.58 (3.10–4.02) mg/g of insect	[39]
P. marginatum		*Spodoptera frugiperda*	3rd instar	LD_{50} = 4.18 (3.18–5.30) mg/g of insect	[39]
P. aduncum	2	*Spodoptera frugiperda*	3rd instar	LD_{50} = 1.07 (1.59–6.31) µL/mg of insect	[46]
P. aduncum	3	*Spodoptera frugiperda*	3rd instar	LD_{50} = 1.28 (1.09–1.58) mg/g of insect	[42]
P. divaricatum		*Spodoptera frugiperda*	3rd instar	LD_{50} = 1.53 (0.95–2.19) mg/g of insect	[42]
P. aduncum	4	*Spodoptera frugiperda*	3rd instar	LD_{50} = 0.012 (7.1×10^{-3}–1.8×10^{-2}) µL/mg of insect	[47]
P. hispidinervum		*Spodoptera frugiperda*	3rd instar	LD_{50} = 361.38 (320.22–407.85) µg/ caterpillar	[50]

Abbreviations: CT = chemotype; LC = lethal concentration; LT = median lethal time; LD = lethal doses.

EO toxicity against *H. armigera* was evaluated in several studies. In one, spraying *Piper* spp. EOs (2% *v*/*v*) on first instar larvae resulted in 0% mortality [36]. In contrast, when larvae of the same species and stage were treated with 1 µL of *P. aduncum* (OEPAd) EO solution (Chemotype 5, containing myristicin 24.0%, isomyristicin 20.9%, sarisan 20.0%, and dillapiole 14.5%) at concentrations of 5.0, 10.0, 20.0, and 40.0 mg/mL, an increase in mortality was observed. The median lethal time (LT_{50}) decreased from 19.53 ± 1.89 days to 14.68 ± 1.86 days [45].

Other experiments were conducted on the third instar *S. frugiperda* larvae. A 1.0 µL dose was applied to the prothoracic region of OEPAd CT3 (dillapiole 78.4% and α-humulene 7.32%) and *P. divaricatum* (OEPDiv) EOs (safrole 49.3% and (Z)-methyl isoeugenol 30.9%), alongside other plant species. OEPAd presented the lowest LD_{50} among the tested oils, demonstrating superior efficacy. Although both EOs had LD_{50} values that were higher than the controls (azadirachtin and deltamethrin), an analysis based on the 95% confidence interval (CI 95%) shows that these EOs, along with the constituents safrole, citronellal, and limonene, possess toxicity levels comparable to the azadirachtin control [42]. This parity with established botanical standards highlights the potential of these natural scaffolds to replace standardized insecticides in sustainable management programs [72].

Another study evaluated the toxicity of *P. corcovadensis* (OEPCor), *P. marginatum* (OEPMar), and *P. arboreum* (OEPAr) EOs at different concentrations against third instar *S. frugiperda* larvae. Notably, OEPCor (1-butyl-3,4-methylenedioxybenzene 35.1%, terpinolene 13.7%, and *trans*-caryophyllene 6.02%) presented the lowest LD_{50}, followed by OEPMar (unidentified compound 22.1%, exalaticin 9.1%, and α-pinene 8.4%). However, comparing these LD_{50} results with previous data (OEPAd and OEPDiv)—given that the technique, developmental stage, and target species were identical—OEPAd and OEPDiv showed higher toxic activity, evidenced by their lower LD_{50} values, particularly due to the presence of dillapiole and safrole as major substances [42].

Additionally, *P. hispidinervum* (OEPHis) (safrole 82.0%) presented an LD_{50} of 361.38 µg/larva at 24 h and decreased to 264.54 µg/larva at 48 h. Safrole, which is present in OEPDiv, was also associated with antibacterial activity and was active against *S. typhimurium* and *P. aeruginosa* [70].

While phenylpropanoids showed action, monoterpenes in *Hyptis marrubioides* (OEHMar) (*β*-thujone 41.50%) and *Ocimum basilicum* (OEOBas) (linalool 35.68%) applied to the dorsum

of second instar larvae showed even more promising results (LD_{50} of 18.49 µg/larva and 38.21 µg/larva, respectively). However, these results are approximately 9700 and 20,000 times higher than the synthetic control of chlorpyrifos (LD_{50} of 0.00190 µg/larva) [71]. Despite the lower potency compared to synthetics in this case, the biodegradability and lower environmental persistence of *Piper* EOs align more closely with the goals of reducing the long-term chemical footprint in agriculture [72,73].

A major contribution to Sustainable Chemistry is the exploration of natural synergists to replace synthetic additives. Synergistic effects of *Piper* EOs with commercial insecticides were tested to overcome challenges such as resistance, residue volume, and formulation stability [73]. When comparing OEPAd CT4 (dillapiole 71.9%) with the industrial standard piperonyl butoxide (BPO), OEPAd was more effective as a synergistic agent for α-cypermethrin, fenpropathrin, and γ-cyhalothrin against *S. frugiperda* s [44,45]. This ability to outperform synthetic synergists proves that *Piper* EOs can enhance the efficacy of existing tools while promoting a more "green" formulation. Furthermore, dillapiole in mixtures demonstrated higher toxicity than in its isolated form; its combination with *β*-caryophyllene (1:1) reduced the LD_{50} from 0.35 ppm to 0.03 ppm, which is an 11-fold increase in potency [74]. Similar increases in toxicity (above 80%) were associated with the addition of *β*-caryophyllene to dillapiole [75].

Conversely, the activity of OEPAd (dillapiole 53.6% and myristicin 24.3%) against *Chrysodeixis includens* was not statistically significant [44]. In *Plutella xylostella*, *Piper nigrum* (OEPNig) (*trans*-caryophyllene 24.2%) showed 60% toxicity [37]. Finally, *Piper augustifolium* (OEPAug) resulted in an LD_{50} equivalent to lemongrass (*Cymbopogon citratus*) for *P. xylostella* control [38]. Lemongrass methanolic extracts presented an LD_{50} of 2.54 mg/mL via ingestion against second instar larvae [76].

3.4.2. Bioinsecticidal Activities via Ingestion

The effects of EOs through ingestion vary based on feeding deterrence to larvicidal activity (Table 2) using OEPHis [50], OEPAd, and OEPDiv [42]. EOs all presented feeding deterrence against *S. frugiperda*; however, although isolated safrole showed a preference index (PI) superior to azadirachtin (PI = 0.51 ± 0.06), it was twice as high as the deltamethrin control (PI = 0.25 ± 0.13) [42]. Targeted ingestive control is a highly sustainable strategy as it often minimizes the impact on non-target pollinators, fulfilling the ecological requirements of Green Chemistry [35].

Table 2. Ingestion toxicity of *Piper* EOs against Lepidoptera.

Species	CT	Target Insect	Stage	Toxicity	Ref.
P. hispidinervum	1	*Spodoptera frugiperda*	3rd instar	CD_{50} = 0.81 mg/mL (0.46–1.41)	[50]
P. aduncum	1	*Spodoptera frugiperda*	3rd instar	PI = 0.73 (±0.08)	[42]
P. divaricatum	1	*Spodoptera frugiperda*	3rd instar	PI = 0.58 (±0.07)	[42]
P. hispidinervum (1.5 atm)	2	*Spodoptera littoralis*	6th instar	EC_{50} = 3.1 µg/cm^2 (1.1–8.4)	[53]
P. dilatatum		*Spodoptera littoralis*	6th instar	FDI = 65.3% (±1.3)	[52]
P. divaricatum	2	*Spodoptera littoralis*	6th instar	FDI = 70.7% (±5.2)	[52]
P. hispidum		*Spodoptera littoralis*	6th instar	FDI = 76.2% (±2.5)	[52]
P. marginatum Jacq. (Acandi)		*Spodoptera littoralis*	6th instar	FDI = 64.3% (±17.9)	[52]
P. marginatum Jacq. (Turbaco)		*Spodoptera littoralis*	6th instar	FDI = 80.6% (±12.1)	[52]
P. sanctifelicis Trel.		*Spodoptera littoralis*	6th instar	FDI = 96.9% (±0.9)	[52]
P. aduncum	3	*Helicoverpa armigera*	1st instar	LT_{50} = 14.20 days (± 1.56) (5 mg/mL)	[45]
P. aduncum	3	*Helicoverpa armigera*	3rd instar	LT_{50} = 20.20 days (±1.27) (5 mg/mL)	[45]
P. krukoffii		*Plutella xylostella*	3rd instar	AC_{50} = 0.07 mg/mL (0.06–0.08)	[54]
P. capitarianum		*Plutella xylostella*	3rd instar	AC_{50} = 3.32 mg/mL (3.32–3.55)	[54]
P. aduncum	2	*Chrysodeixis includens*	3rd instar	LC_{50} = 3.5 (3.0–4.0) (24 h)	[44]

Abbreviations: CT = chemotype; CD = feeding deterrence concentration; PI = preference index; EC = feeding index inhibition; FDI = feeding index deterrence; LT = median lethal time; AC = antifeedant concentration values; LC = lethal concentration.

Safrole in OEPHis (CT2, 81.34%) was effective in antifeedant action against *S. littoralis* in a dose–response relationship and showed synergism with terpinolene [54]. Evaluation of EOs from several species [*P. dilatatum* (OEPDil), *P. hispidum* (OEPDil), *P. sanctifelicis* (OEPSan), *P. divaricatum* (OEPDiv), and *P. marginatum* (OEPMar)] revealed that, according to Pavela et al. [52], only OEPSan (containing *δ*-3-carene, limonene, and *p*-cymene) met the strict criterion for a significant antifeedant agent (FDI > 90%) [52]. This high level of deterrence is ideal for sustainable pest management, as it prevents crop damage without necessitating immediate chemical lethality [77].

OEPAd CT2 (dillapiole 53.6% and myristicin 24,3%) showed high ingestive efficacy in *C. includens*, where an 8% concentration reached 93% mortality within 24 h. These values were more efficient via ingestion than topical application for this species [44]. In *H. armigera*, OEPAd CT3 (myristicin 24%, isomiristicin 20% and sarisan 20%) reduced the lethal time by 7 days for first instars at 5 mg/mL [45]. Such findings highlight the importance of matching the delivery method to the specific phytochemical profile to ensure maximum sustainability and minimum chemical waste. Finally, *P. capitarianum* (OEPCap) showed AC_{50} values 2.2 times lower than the azadirachtin control against *P. xylostella* [55]. This is notable as azadirachtin is a potent antifeedant that causes anorexia by interfering with the neuroendocrine system [78].

3.4.3. Bioinsecticidal Activities Under Residual Contact

Several *Piper* species were identified for residual contact evaluation (Table 3), with OEPAd being the most prevalent for *P. xylostella* [37,54] and *S. frugiperda* [42,46,47]. OEPDiv (safrole 49.3% and (*Z*)-methyl isoeugenol 30.9%) presented a higher LC_{50} for *S. frugiperda* than other *Piper* EOs but remained significantly lower than EOs from other plant genera and lower than the azadirachtin control.

Table 3. Residual contact toxicity of *Piper* EOs against Lepidoptera.

Species	CT	Target Insect	Stage	Toxicity	Ref.
P. krukoffii		*Plutella xylostella*	3rd instar	LC_{50} = 6.37 (5.10–8.05) mg/mL	[54]
P. capitarianum		*Plutella xylostella*	3rd instar	LC_{50} = 0.21 (0.15–0.29) mg/mL	[54]
P. nigurm		*Plutella xylostella*	Adults	ODI = 117.4	[37]
P. aduncum	1	*Spodoptera frugiperda*	3rd instar	LC_{50} = 1169.70 (698.40–1755.40) ppm	[46]
P. aduncum	2	*Spodoptera frugiperda*	3rd instar	LC_{50} = 11.42 (9.73–12.95) mg/mL	[42]
P. divaricatum		*Spodoptera frugiperda*	3rd instar	LC_{50} = 15.05 (13.69–16.50) mg/mL	[42]
P. aduncum	3	*Spodoptera frugiperda*	3rd instar	$LC_{50} = 1.1 \times 10^{-4}$ (6.3×10^{-3}–1.6×10^{-4}) μL/cm^{-2}	[47]

Abbreviations: CT = chemotype; LC = lethal concentration; ODI = oviposition deterrence index.

Substituting synthetic synergists with natural alternatives remains a priority for the bioeconomy [71]. OEPAd (dillapiole 71.9% and α-humulene 7.32%) consistently showed a higher SF than BPO for several pyrethroids against third instar *S. frugiperda* [42]. BPO acts by inhibiting esterases or cytochrome P450 monoxygenases associated with insecticide resistance [79]. Furthermore, OEPAd (dillapiole 73.4%) was more effective than *Schinus terebinthifolius* and *Lippia sidoides* against *P. xylostella* [42,80]. In another study, OEPCap (*o*-cymene 40.74%, dehydro-aromadendrene 12.32% and β-chamigrene 9.96%) was 30 times more effective than *P. krukoffii* OEPKr (globulol 17.54%, 4-epi-*cis*-dihydroagarofuran 12.25% and γ-muurolene 11.03%) against *P. xylostella*, though the study lacked details on stability and structure–activity relationships [55]. It is important to consider the larvicidal and adulticidal activity of OEPCap in *Aedes aegypti* and *Aedes albopictus*, which has already been reported [79,80]. The efficacy of these natural compounds directly supports the Green Chemistry principle of using safer chemicals to reduce total pesticide application rates.

Finally, *P. nigrum* (OEPNig) showed a deterrent effect on *P. xylostella* oviposition superior to other EOs like *Artemisia abrotanum* and *Eucalyptus polybractea* [37].

3.4.4. Ovicidal Activities

Ovicidal bioassays were conducted with EOs against *Anticarsia gemmatalis* (Table 4). Only *P. hispidum* (biciclogermacrene 11.49% e and germacrene B 6.08%) failed to reduce larval hatching compared to the control. Conversely, *P. fuligineum* (OEPFul) (sarisan 10.80%) presented the best activity [61]. Sarisan is associated with oviposition suppression in several pests, such as *Plodia interpunctella* (Lepidoptera: Pyralidae) e *Rhyzoperta dominica* (Fabr.) (Coleoptera: Bostrichidae) and *Sitophilus oryzae* (Coleoptera: Curculionidae) [81]. Targeting the egg stage is a cornerstone of preventative green management, interrupting the pest cycle before herbivory can occur [55].

Table 4. Ovicidal toxicity of *Piper* EOs against Lepidoptera.

Species	CT	Target Insect	Stage	Toxicity	Ref.
P. abutiloides Kunth.		*Anticarsia gemmatalis*	Egg	LC_{50} = 1.9 (1.8–2.0)%	[62]
P. aduncum L.		*Anticarsia gemmatalis*	Egg	LC_{50} = 0.6 (0.3–0.9)%	[62]
P. amalago L.		*Anticarsia gemmatalis*	Egg	LC_{50} = 2.2 (2.1–2.3)%	[62]
P. arboreum Aubl.		*Anticarsia gemmatalis*	Egg	LC_{50} = 1.7 (1.4–1.9)%	[62]
P. caldense	1	*Anticarsia gemmatalis*	Egg	LC_{50} = 1.2 (0.6–1.8)%	[62]
P. caldense C. DC.	2	*Anticarsia gemmatalis*	Egg	LC_{50} = 1.1 (0.7–1.4)%	[62]
P. crassinervium Kunth		*Anticarsia gemmatalis*	Egg	LC_{50} = 1.3 (0.9–1.7)%	[62]
P. fuligineum Kunth.		*Anticarsia gemmatalis*	Egg	LC_{50} = 0.4 (0.3–1.1)%	[62]
P. gaudichaudianum	2	*Anticarsia gemmatalis*	Egg	LC_{50} = 1.5 (1.2–1.9)%	[62]
P. gaudichaudianum Kunth.	1	*Anticarsia gemmatalis*	Egg	LC_{50} = 12.9 (12.4–13.3)%	[62]
P. hispidum Sw.		*Anticarsia gemmatalis*	Egg	LC_{50} = 1091.4 (1095.2–1087.7)%	[62]
P. lhotzkyanum Kunth.		*Anticarsia gemmatalis*	Egg	LC_{50} = 1.6 (1.3–2.0)%	[62]
P. malacophyllum Prels.		*Anticarsia gemmatalis*	Egg	LC_{50} = 3.7 (3.6–3.8)%	[62]
P. marginatum L.	1	*Anticarsia gemmatalis*	Egg	LC_{50} = 1.0 (0.4–1.5)%	[62]
P. mikanianum (Kunth) Steud.		*Anticarsia gemmatalis*	Egg	LC_{50} = 1.6 (1.2–1.9)%	[62]
P. mollicomum	2	*Anticarsia gemmatalis*	Egg	LC_{50} = 0.4 (0.3–1.2)%	[62]
P. mollicomum Kunth.	1	*Anticarsia gemmatalis*	Egg	LC_{50} = 1.3 (0.8–1.8)%	[62]
P. mosenii C. DC.		*Anticarsia gemmatalis*	Egg	LC_{50} = 0.6 (0.0–1.1)%	[62]
P. solmsianum C. DC		*Anticarsia gemmatalis*	Egg	LC_{50} = 765.7 (771.1–760.3)%	[62]
P. tuberculatum Jacq.		*Anticarsia gemmatalis*	Egg	LC_{50} = 1.4 (1.0–1.9)%	[62]
P. umbellatum L.		*Anticarsia gemmatalis*	Egg	LC_{50} = 12.0 (11.6–12.3)%	[62]
P. aduncum		*Spodoptera frugiperda*	Egg	LC_{50} = 6.41 (5.42–7.32)	[42]
P. divaricatum		*Spodoptera frugiperda*	Egg	LC_{50} = 4.98 (10.84–21.14)	[42]
P. marginatum L.	2	*Spodoptera frugiperda*	Egg	LC_{50} = 152.95 ppm (132.55–176.60)	[67]
P. capitatum		*Plutellla xylostella*	Egg	LC_{50} = 0.079 mg/mL (0.068–0.092)	[55]
P. krukoffii		*Plutella xylostella*	Egg	LC_{50} = 2.68 mg/mL (2.39–3.03)	[56]

Abbreviation: LC = lethal concentration.

Other EOs with formidable activity included *P. aduncum* (myristicin 12.61%, sarisan 11.86% and (*E*)-β-ocimene 8.16%), *P. mollicomum* CT1 (OEPMol CT1) (biciclogermacrene 20.41%, sarisan 7.21% and germacrene B 6.38%), and *P. mosenii* (OEPMos) ((*E*)-caryophyllene 16.82%, caryophyllene oxide 9.82% and β-pinene 5.78%) [62]. It is worth noting that cashew nutshell liquid (*Anacardium occidentale*) also presented active compounds against *A. gemmatalis*. Against *P. xylostella*, OEPCap (*o*-cimene 40,74%, dehydro-aromadendrene 12.32% and β-chamigrene 9.96%) showed an LC_{50} nearly 34 times lower than *P. krukoffii* (OEPKru). This value is 2.25 times greater than that of the control azadirachtin and 1.19 times greater than the value for deltamethrin [55]. Such results are promising given the high resistance of *P. xylostella* to conventional insecticides like chlorantraniliprole and *Bacillus thuringiensis* [82,83]. In another study, OEPAd also exhibited ovicidal action against

S. frugiperda eggs. Although it presented a higher LC_{50} than *Eucalyptus citriodora* essential oils (citronellal 53.81% and limonene 25.73%) and citronellal alone, its values were still lower than the azacitidine control. OEPDiv (safrole 49%) also showed toxicity, but with lower efficacy, and it is surpassed by safrole when tested alone [42].

P. nigrum showed very low ovicidal activity against *P. xylostella* (approximately 30% lethality), which was independent of concentration and significantly inferior to oils like *Allium sativum* [38]. Finally, Guedes et al. observed that OEPMar caused embryonic non-formation and chorion disintegration in *S. frugiperda* eggs within 24 h [67]. By utilizing natural oils that degrade rapidly, this preventative approach avoids the long-term environmental accumulation of synthetic ovicides. This diversity in efficacy underscores the need for bio-diverse solutions tailored to specific pest–crop interactions in a sustainable agricultural framework [61,84].

While laboratory assays provide crucial baseline toxicity data, the economic sustainability of field application remains a significant challenge. Predictive studies and techno-economic assessments emphasize that optimizing extraction yields and formulation stability is essential to ensure the commercial viability and cost-effectiveness of botanical insecticides [85]. Although economic hurdles in field application remain, the successful global commercialization of other botanical bioinsecticides, such as azadirachtin-based formulations (e.g., Neemix®) and terpene-rich essential oil products (e.g., Requiem®), demonstrates that standardizing natural scaffolds for agriculture is industrially viable. The *Piper* genus, providing both active insecticidal agents and natural synergists, holds a similar commercial potential if extraction and formulation processes are optimized [86].

4. Conclusions

The evidence gathered in this systematic review confirms that essential oils from the *Piper* genus possess important bioinsecticidal efficacy against lepidopteran pests, frequently matching or surpassing established commercial controls. These findings position the genus as a high-value source of renewable biomass and biodegradable scaffolds for the immediate development of green pesticides. A significant strength of the analyzed literature is the frequent use of rigorous positive standards (such as azadirachtin, deltamethrin, and BPO), which consistently validate the competitive performance and potency of these natural extracts. This robust data set provides a solid foundation for the implementation of safer chemical scaffolds that can effectively reduce the chemical load in modern agriculture. Furthermore, the immense diversity of metabolites found in *Piper* species underscores their versatility as multi-target agents, capable of overcoming the high resistance often observed in Lepidoptera through natural synergism. The current literature provides a comprehensive framework, showcasing the adaptability and high potential of these natural extracts across various experimental models. To fully harness this potential and transition these laboratory successes into real, field-ready commercial products, the next phase of research should embrace collaborative standardization. While the natural phytochemical variation in *Piper* reflects its evolutionary strength and ecological adaptability, establishing targeted chemical standardization will ensure consistent field performance. Similarly, harmonizing the diverse and successful biotest protocols currently in use will facilitate direct comparability and accelerate industrial scaling. Future efforts focused on optimizing extraction yields through green technologies and addressing the economic feasibility of large-scale production will be pivotal. Surmounting these natural developmental milestones will solidify *Piper*-based bioproducts as a cornerstone of the global circular bioeconomy and modern sustainable pest management of lepidopteran pests, fully realizing the 12 Principles of Green Chemistry.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/suschem7020025/s1. Table S1: Species of the genus *Piper* that had essential oils tested against some Lepidoptera species; Table S2: Collection sites for *Piper* species; Table S3: Evaluation of plant parts used for extraction, extraction method and yield of extracts.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Antifeedant concentration values
CD	Feeding deterrence concentration
CI	Confidence interval
CT	Chemotype
EC	Feeding index inhibition
EO	Essential oil
FDI	Feeding index deterrence
LC	Lethal concentration
LD	Lethal doses
LT	Median lethal time
ODI	Oviposition deterrence index
PBO	Piperonyl butoxide
PI	Preference index

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