

Lippia alba essential oil as a botanical biopesticide: From chemotype diversity, crop protection potential, and value chain challenges

Aissatou Sakho^{a,b,1} , Madeleine Diouf^{c,d,1}, Aminata Diagne^{e,f,1}, Serigne Mbacké Diop^c, Papa Seyni Cissokho^c , Michel Bakar Diop^a, Amadou Sidy Aly Ba^e, Momar Talla Gueye^c, Imaneh Goli^f, Thomas Dogot^f, Frédéric Francis^d, Marie-Laure Fauconnier^{b,*,2} , Manon Genva^{b,2}

^a Laboratoire des Sciences Biologiques, Agronomiques, Alimentaires et de Modélisation des Systèmes Complexes (LaBAAM), Université Gaston Berger, Saint-Louis, BP 234, Senegal

^b Laboratoire de Chimie des Molécules Naturelles, Gembloux Agro-Bio Tech, Université de Liège, Passage des Déportés 2, Gembloux, 5030, Belgium

^c Laboratoire des Analyses Phytosanitaires, Institut de Technologie Alimentaire (ITA), Dakar, BP 2765, Senegal

^d Laboratoire d'Entomologie Fonctionnelle et Évolutive, Gembloux Agro-Bio Tech, Université de Liège, Passage des Déportés 2, Gembloux, 5030, Belgium

^e Laboratoire Saint-Louis Etudes et Recherche en Sciences de Gestion (SERGe), Université Gaston Berger, Saint-Louis, BP 234, Senegal

^f Laboratoire d'Économie et de Développement Rural, Gembloux Agro-Bio Tech, Université de Liège, Passage des Déportés 2, Gembloux, 5030, Belgium

ARTICLE INFO

Keywords:

Lippia alba
Essential oil
Chemotype
Biopesticides
Crop protection
Value chain development

ABSTRACT

Growing concerns regarding the environmental and health impacts of synthetic pesticides have intensified the search for sustainable crop protection alternatives. Among plant-derived bioproducts, essential oils (EOs) have attracted increasing attention due to their broad-spectrum biological activities and favourable environmental profile. In this context, *Lippia alba* (Mill.) N.E.Br. ex Britton & P. Wilson (*L. alba*, Verbenaceae), a chemically diverse and agronomically adaptable aromatic species, has emerged as a promising source of botanical biopesticides. This review synthesizes current knowledge on the geographical distribution, agronomic characteristics, EO yield, and chemotype variability of *L. alba*. Particular attention is given to the relationship between chemical composition and biological activity, highlighting the insecticidal, fungicidal, nematocidal, bactericidal, and acaricidal properties reported against major agricultural pests and pathogens. Available evidence indicates that citral-, carvone-, and linalool-rich chemotypes are among the most promising profiles for crop protection applications. Beyond biological efficacy, this review examines the opportunities and limitations associated with the valorization of *L. alba* EO as a commercial biopesticide. The species benefits from broad ecological adaptability, ease of propagation, and growing demand for bio-based crop protection products. However, large-scale deployment remains constrained by chemotype variability, standardization challenges, formulation limitations, insufficient field validation, and regulatory barriers. By integrating agronomic, chemical, biological, technological, and socio-economic perspectives, this review identifies key knowledge gaps and highlights strategic priorities to support the development of *L. alba* EO as a sustainable biopesticide within agroecological and bioeconomy-oriented production systems.

1. Introduction

The intensification of agriculture has led to the widespread use of synthetic pesticides, including insecticides, fungicides, and nematicides, to control pests affecting crops and stored food products (Kaur and Garg,

2014; Rattan, 2010). However, the continued dependence on synthetic pesticides poses significant environmental, economic, and public health challenges, including contamination of soil and water resources, harmful effects on non-target organisms, the development of resistant pest populations, and increasing societal concerns over food and

* Corresponding author.

E-mail address: Marie-Laure.Fauconnier@uliege.be (M.-L. Fauconnier).

¹ These authors contributed equally to the work and should be considered as first co-authors

² These authors contributed equally to the work and should be considered as last co-authors

environmental safety (Isman, 2006; Rattan, 2010; Villaverde et al., 2016). These concerns, together with growing consumer awareness, have stimulated interest in the development of more environmentally friendly alternatives to conventional chemical pesticides (Chandler et al., 2011). While regulatory frameworks governing the registration and commercialization of biopesticides remain fragmented or under development in many low- and middle-income countries (de Groot et al., 2026), regulatory policies in the European Union and the United States increasingly support the adoption of biopesticides through dedicated legislative frameworks and progressive restrictions on synthetic pesticides (Villaverde et al., 2016).

Within this context, biopesticides have emerged as promising alternatives to conventional synthetic pesticides (Regnault-Roger et al., 2012). Among plant-derived biopesticides, essential oils (EOs) have received increasing attention since the 1980s owing to their diverse biological activities and their potential compatibility with sustainable agricultural practices (Chandler et al., 2011; Rattan, 2010). These volatile mixtures of secondary metabolites are characterized by complex and highly variable chemical profiles, predominantly composed of terpenoids and phenylpropanoids (Isman, 2006; Tavares et al., 2011). Such chemical complexity underpins a broad spectrum of biological activities, including insecticidal, fungicidal, nematocidal, and repellent effects against numerous agricultural pests and pathogens (Isman, 2006; Peixoto et al., 2015). In addition, their rapid biodegradability and multi-target modes of action make EOs attractive candidates for integrated pest management strategies, as they may reduce environmental persistence and potentially delay the development of resistance compared with conventional synthetic pesticides (Isman, 2006).

Numerous aromatic plants belonging to botanical families, such as Lamiaceae, Myrtaceae, and Verbenaceae, have been investigated as sources of botanical pesticides owing to the biocidal properties of their EOs against a wide range of crop pests and post-harvest pathogens (Diop et al., 2016; Shukla, 2018). However, the practical implementation of many aromatic species as biopesticides remains limited by challenges related to agronomic performance, biomass production, chemical standardization, and large-scale commercialization (Pavela and Benelli, 2016). Consequently, increasing attention has been directed toward identifying species that combine biological efficacy, agronomic adaptability and production feasibility.

Among these, *Lippia alba* (Mill.) N.E.Br. Ex Britton & P. Wilson (*L. alba*, Verbenaceae), a perennial aromatic shrub native to South America, has emerged as a particularly promising candidate owing to its agronomic adaptability and the broad spectrum of biological activities exhibited by its EO (Acero-Godoy et al., 2019; Biasi and Costa, 2003; Gonçalves et al., 2016; Marino et al., 2012). Like other aromatic species, *L. alba* exhibits substantial chemical variability. However, the diversity of chemotypes reported for this species, each characterized by distinct dominant constituents, further expands its biopesticidal potential by providing diverse activity profiles against different agricultural targets (Da Silva Júnior et al., 2019; Hennebelle et al., 2006; Villamil, 2010). This remarkable diversity, while offering opportunities to tailor biopesticide applications, also creates challenges for ensuring consistent efficacy, product quality and reproducibility (Glamočlija et al., 2011; Linde et al., 2016). Consequently, chemotype characterization and standardization are essential for the development of reliable and commercially viable biopesticide products (Glamočlija et al., 2011; Linde et al., 2016; Siani et al., 2002).

Although previous reviews have examined the medicinal properties, phytochemistry, and antimicrobial activities of *L. alba*, its potential as a botanical biopesticide has rarely been assessed through an integrated agronomic, industrial, and socio-economic perspective. In particular, limited attention has been given to the relationships between chemotype diversity, biological efficacy, production constraints, and value-chain development. To address this gap, the present review critically examines the potential of *L. alba* EO for crop protection applications. We synthesize current knowledge on its geographical distribution,

agronomic characteristics, chemical variability, and biocidal activities, with particular emphasis on the links between chemotype composition and pest management performance. In addition, we discuss key factors influencing its valorization, including formulation challenges, regulatory considerations, market opportunities, and production constraints.

2. Botanical characteristics, geographical distribution, and ecological adaptability of *Lippia alba*

L. alba is a perennial aromatic shrub belonging to the Verbenaceae family. The species typically exhibits a bushy growth habit with long, slender branches that can reach up to 2 m in height (Acero-Godoy et al., 2019; Hennebelle et al., 2006; Villamil, 2010). Its leaves are petiolate, oppositely decussate, elliptical, and characterized by serrated margins and a rugose, pubescent surface (Barros et al., 2022; Hennebelle et al., 2008). Of particular importance for its economic value, the leaf epidermis contains abundant glandular trichomes that serve as the primary sites for the biosynthesis, secretion, and storage of the volatile metabolites constituting the EO (Tavares et al., 2011). The plant produces small hermaphroditic flowers (3–5 mm) grouped in capitate inflorescences with tubular corollas ranging from white to deep violet, followed by fruits that split into two indehiscent nutlets at maturity (Hennebelle et al., 2008; Villamil, 2010).

Native to South America, particularly Brazil, *L. alba* occurs across a broad range of ecological conditions, from seasonally dry environments to humid tropical ecosystems (Barros et al., 2022; Cicció and Ocampo, 2010; Linde et al., 2016). Fig. 1 summarizes the countries and regions in which the species has been reported in the literature. These records indicate a wide geographical occurrence extending beyond its native range, including the Caribbean (Hennebelle et al., 2006), parts of Southern Europe (Ricciardi et al., 2009), and several tropical regions of Asia and Africa (Linde et al., 2016). In West Africa, occurrences have been documented in Côte d'Ivoire, Cameroon, Burkina Faso, and Senegal (Bationo et al., 2024; Coulibaly et al., 2024; Ernest et al., 2025; Sabaly et al., 2024). However, the distribution illustrated in Fig. 1 should not be considered exhaustive, as it reflects available literature records rather than the full ecological range of the species. Given its adaptability to diverse climatic and edaphic conditions, *L. alba* is likely capable of establishment in additional regions presenting similar environmental conditions.

From a crop development perspective, the broad ecological amplitude of *L. alba* represents a valuable asset. The species is capable of thriving under contrasting agroecological conditions, including environments exposed to water stress, suggesting considerable potential for decentralized biomass production across tropical and subtropical regions (Álvarez et al., 2015; Sá Filho et al., 2022; Yamamoto et al., 2008). In addition, *L. alba* can be readily propagated vegetatively, facilitating the rapid multiplication of selected plant material and the preservation of desirable chemotypes (Biasi and Costa, 2003). This characteristic is particularly advantageous for commercial cultivation, as it may contribute to reducing genetic variability and improving the consistency of EO yield and composition.

3. *Lippia alba* essential oil

3.1. Extraction technologies and process optimization

The production of EO from *L. alba* relies on distillation-based techniques, whose selection depends largely on the intended production scale and application. At the laboratory scale, hydrodistillation using a Clevenger-type apparatus remains the most widely employed method for EO isolation, chemical characterization, and bioactivity evaluation (Villamizar-Véliz and Aular, 2022). For industrial production, particularly in the context of botanical biopesticides, steam distillation is generally preferred because of its higher processing capacity, operational efficiency, and suitability for large-scale implementation (Burt,

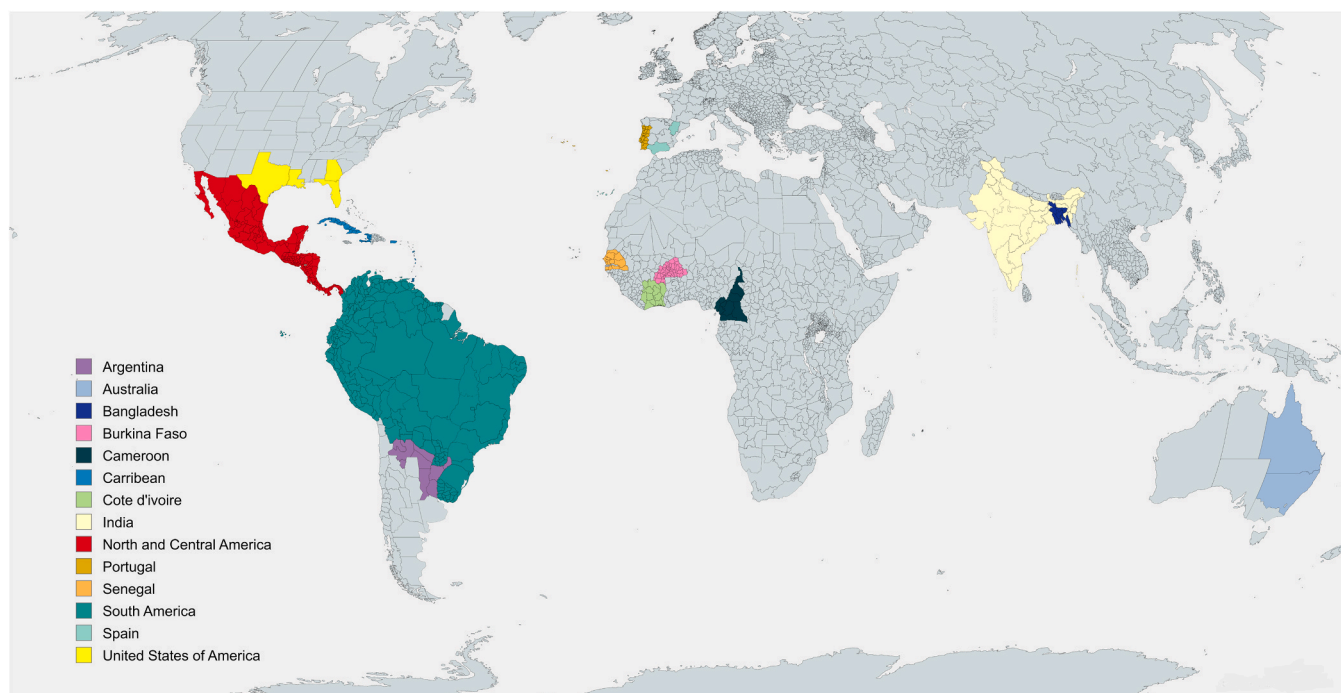


Fig. 1. Geographic occurrence of *Lippia alba* reported in the literature. Map compiled using World Flora Online data (WFO, 2026), and supplemented with records reported by Coulibaly et al. (2024), Bationo et al. (2024), Sabaly et al. (2024), Linde et al. (2016), Ernest et al. (2025).

2004; Pavela, 2015).

The choice of extraction parameters, specifically distillation time, can significantly affect both yield and the quality of the EO (Linde et al., 2016; Stashenko et al., 2004). For *L. alba*, hydrodistillation durations reported in the literature range from 1 to 6 h (Durán et al., 2007; Glamoclija et al., 2011; Sabaly et al., 2023; Tubay-Bermúdez et al., 2024). However, kinetic studies indicate that most of the EO is recovered within the first 45 min of distillation (Martínez et al., 2007), suggesting that unnecessarily prolonged extraction may increase the risk of thermal degradation or loss of thermolabile and highly volatile constituents without substantially improving EO recovery. Conversely, steam distillation generally provides better control of thermal conditions, preserving these active, thermolabile constituents more effectively than prolonged hydrodistillation (Regnault-Roger et al., 2012).

Alternative extraction technologies have also been explored for *L. alba*. Microwave-assisted hydrodistillation (MAHD), in particular, has been reported to reduce extraction time and energy consumption while maintaining EO quality (Borromeo et al., 2025; Durán et al., 2007; Villamizar-Véliz and Aular, 2022).

3.2. Essential oil yield: agronomic and technical determinants

For the commercial development of *L. alba* EO-based biopesticides, EO yield is a major determinant of production feasibility, strongly influenced by intrinsic and extrinsic factors. Intrinsic factors include genotype, plant age, phenological stage, and the organs harvested, whereas extrinsic factors encompass climatic conditions, soil characteristics, water availability, solar radiation, temperature, cultivation practices, post-harvest handling, and extraction methodology (Mugao, 2024; Teles et al., 2012).

Among these factors, climatic conditions have been shown to significantly influence EO productivity. For instance, Barros et al. (2022) reported a significant correlation ($p < 0.05$) between *L. alba* EO yield and climatic variables such as rainfall, relative humidity, and solar radiation, which partly explain the substantial differences observed among growing regions and seasons (Dias Alves et al., 2026; Stashenko et al., 2004). The type of plant material subjected to distillation also

influences EO recovery. While some studies focus exclusively on leaves, others process aerial parts composed of leaves and stems or include inflorescences harvested before or during flowering, resulting in different yield profiles (Fischer et al., 2004; García-Abarrio et al., 2014; Teles et al., 2012; Tubay-Bermúdez et al., 2024).

The drying process is one of the most critical factors influencing EO yield. Leaves are typically dried under shade at ambient temperature for up to 6 days or in forced-air ovens at 40–50 °C until reaching a moisture equilibrium of approximately 10% (Barbosa et al., 2006; Da Silva Júnior et al., 2019; García-Abarrio et al., 2014; Teles et al., 2012). Under ambient drying conditions, Martínez et al. (2007) identified an optimal drying period of approximately 4 days. Barbosa et al. (2006) reported higher EO yields from fresh leaves than from dried material, indicating that volatile compounds are progressively lost during the drying process. Consistent with these observations, prolonged drying periods (> 6 days) have been associated with significant reductions in EO yield (Álvarez et al., 2015; Conde-Hernández et al., 2021), likely due to the evaporation and degradation of volatile constituents.

Consequently, EO yields vary widely across studies. For dried biomass, hydrodistillation yields range from 0.2% to 0.4% in Uruguay (Lorenzo et al., 2001) and approximately 0.7% in Spain (García-Abarrio et al., 2014), to around 1.0% in Ecuador (Tubay-Bermúdez et al., 2024), reaching 2.2–4.3% in Brazilian accessions harvested during the rainy season (Da Silva Júnior et al., 2019). For fresh biomass, hydrodistillation of leaves generally yields between 0.2% and 0.9% in Brazil (Glamoclija et al., 2011; Siani et al., 2002) and up to 0.8% in India (Bahl et al., 2000). Alternative extraction methods may further enhance EO recovery. For example, microwave-assisted hydrodistillation applied to fresh aerial parts in Colombia produced yields ranging from 0.3% to 2.5% (Durán et al., 2007; Stashenko et al., 2004).

Overall, the wide range of EO yields reported for *L. alba* reflects the combined influence of growing environment, harvested plant material, post-harvest processing, and extraction methodology. Because these same factors also influence EO composition, agronomic and technological optimization should be integrated with chemotype selection to ensure both high productivity and chemical consistency (Álvarez et al., 2015).

3.3. Chemical composition and variability of *Lippia alba* essential oil

L. alba EO is characterized by remarkable chemical diversity, which distinguishes this species from many other aromatic plants and underpins its broad range of biological activities (Tavares et al., 2005). Like most EOs, it is composed predominantly of mono- and sesquiterpenes, including both hydrocarbon and oxygenated derivatives such as alcohols, aldehydes, ketones, esters, and oxides, together with smaller proportions of phenylpropanoids (Dhifi et al., 2016; Eslahi et al., 2017; Tavares et al., 2011). The relative abundance of these constituents varies considerably among populations, giving rise to distinct chemical profiles known as chemotypes (Table 1) (da Silva et al., 2018; Figueiredo, 2017).

Several chemotypes have been described for *L. alba*, defined by the predominance of one or a few major constituents. The most common include citral (neral and geranial isomers), carvone, linalool, limonene, and geraniol chemotypes, although other less frequent profiles have also been reported (Barros et al., 2022; Da Silva Júnior et al., 2019; Glamoclija et al., 2011; Ospina et al., 2016). To date, most chemotype characterization studies have been conducted in Latin America, reflecting the native distribution of the species (Barros et al., 2022; Tubay-Bermúdez et al., 2024). Citral- and geraniol-rich chemotypes are commonly reported in Brazil and Colombia (Glamoclija et al., 2011; Ospina et al., 2016), whereas carvone- and linalool-rich oils have been identified across several Latin American countries and in India (Bahl et al., 2000; Da Silva Júnior et al., 2019; Lorenzo et al., 2001; Tavares et al., 2005). Less common chemotypes include myrcene-rich populations in Argentina, γ -terpinene-rich accessions in Brazil, and camphor/1,8-cineole chemotypes in Uruguay (Hennebelle et al., 2006). Although information remains scarce for the African continent, recent studies have reported highly concentrated citral chemotypes in Côte d'Ivoire and Senegal, suggesting that this profile may also be prevalent in West African populations (Coulibaly et al., 2024; Sabaly et al., 2024).

These chemotypes result from complex interactions between genetic background and multiple environmental factors rather than from the effect of a single variable (Sá Filho et al., 2022). While the qualitative profile of an EO is largely genetically controlled, environmental conditions such as soil characteristics, water availability, temperature,

altitude, and seasonal fluctuations can significantly influence the relative abundance of major constituents (Barra, 2009; Do Nascimento Soares et al., 2019). Consequently, *L. alba* populations may exhibit substantial quantitative differences in their volatile composition depending on cultivation conditions and harvest period (Ricciardi et al., 2009). Despite this well-established influence of genotype and environment, the processes driving the exceptional chemotypic diversity of *L. alba* are still not fully elucidated and deserve further investigation.

From an industrial perspective, this phytochemical variability represents both a challenge and an opportunity. On one hand, fluctuations in EO composition can complicate product standardization and affect the reproducibility of biological activity. On the other hand, the existence of multiple chemotypes offers the possibility of selecting plant material enriched in specific bioactive compounds according to the intended application (de Moraes et al., 2022; Glamoclija et al., 2011; Siani et al., 2002). Therefore, the identification of stable, high-performing chemotypes and the evaluation of their compositional consistency across cultivation environments are essential steps toward the development of standardized *L. alba*-based biopesticides.

4. Biological activities and valorization potential of *Lippia alba* essential oil

Owing to its complex and chemically diverse composition, *L. alba* EO exhibits a wide variety of biological activities that have attracted considerable interest for pharmaceutical, food, cosmetic, and agricultural applications. Numerous studies have reported antimicrobial, antifungal, antiparasitic, insecticidal, anxiolytic, antioxidant, and cytotoxic properties, many of which have been linked to major constituents such as citral, carvone, geraniol, limonene, and linalool (Mesa-Arango et al., 2009; Quintero-García et al., 2024; Roxana Soto-Vásquez et al., 2018; Sales et al., 2022). Although most of these biological effects have been demonstrated under *in vitro* conditions, they collectively highlight the significant valorization potential of this species. Therefore, while acknowledging the broader pharmaceutical and industrial relevance of *L. alba*, this review focuses primarily on the biological activities that support its potential use in crop protection and post-harvest pest

Table 1

Major reported chemotypes of *Lippia alba* essential oils along with their dominant compounds and geographical origins.

Chemotype	Chemical class	Major Compounds (%)	Plant part	Origin (Location)	References
Citral	Oxygenated monoterpene	Citral (53.90), α -guaiane (6.30), ocimene (6.70)	Leaves	France (Guadeloupe)	Hennebelle et al. (2006)
		Citral (35.58), geraniol (17.63), limonene (7.96)	Leaves	Brazil	Tavares et al. (2005)
		Citral (39.90), E-carveol (25.40)	Leaves	Brazil	De Souza et al. (2017)
		Citral (58–76.40), geraniol (7–14)	Leaves and flowers	Colombia	López et al. (2011); Ospina et al. (2016)
		Citral (35.33), geraniol (14.52)	Leaves	Côte d'Ivoire	Coulibaly et al. (2024)
		Citral (84.30)	Leaves	Brazil	Glamoclija et al. (2011)
Carvone	Oxygenated monoterpene	Citral (81.20)	Leaves	Senegal	Sabaly et al. (2024)
		Carvone (52.80–67.80), limonene (16.98–18.50)	Leaves	France (Guiana)	Hennebelle et al. (2006); Tavares et al. (2005)
		Carvone (49.60–52.80), limonene (17–26)	Leaves	Brazil	Olivero-Verbel et al. (2014); Perez-Cordero et al. (2018)
Linalool	Oxygenated monoterpene	Linalool (60.10–66.60)	Leaves	Brazil	Fontana et al. (2021); Tavares et al. (2005)
Limonene/ piperitone	Monoterpene hydrocarbon	Linalool (65.20–69.20)	Leaves	India	Bahl et al. (2000); Saroj et al. (2019)
Geraniol	Oxygenated monoterpene	Limonene (43.60), piperitone (30.60)	Aerial parts	Guatemala	Senatore, Rigano, (2001)
Tagetenone	Oxygenated monoterpene	Geraniol (46.90), elemol (22.20)	Leaves	Brazil	Barros et al. (2022)
Myrcene	Oxygenated monoterpene	Tagetenone (71)	Leaves and flowers	Guatemala	Hennebelle et al. (2006)
γ -Terpinene	Monoterpene hydrocarbon	Myrcene (42), camphene (30)	Aerial parts	Argentina	
Camphor/1,8-cineole	Monoterpene hydrocarbon	γ -Terpinene (46)	Leaves	Brazil	
	Oxygenated monoterpenes	Camphor (18), 1,8-cineole (16)	Leaves	Uruguay	

management.

4.1. Application of *Lippia alba* essential oil in crop protection

The broad range of agricultural pests and pathogens targeted by *L. alba* EO underscores its potential as a versatile plant-based pesticide.

4.1.1. Insecticidal and repellent activities

The insecticidal activity of *L. alba* EO has been extensively documented, particularly against stored-product pests and major crop insects. In fumigation assays, a linalool-rich chemotype completely disrupted the life cycle of *Callosobruchus maculatus*, with a median lethal concentration (LC₅₀) of 0.1 mg/mL of air (Torre et al., 2024). This result highlights the relevance of linalool-rich oils for post-harvest protection. Contact toxicity has also been reported. Against third-instar larvae of *Spodoptera frugiperda*, different EO profiles, such as citral- and limonene-rich, produced median lethal doses (LD₅₀) ranging from 1.20 to 1.56 µg/mg per insect (Niculau et al., 2013). In another study, a carvone-rich EO induced 81.94% mortality in adults of *Acanthoscelides obtectus* after spray application at 120 µL/Petri dish (Rodríguez González et al., 2020). In addition to direct toxicity, *L. alba* EO shows strong repellent activity. A carvone- and limonene-rich chemotype achieved 70% repellency against *Tribolium castaneum* after 24 h at 52 µL/L (Ringuelet et al., 2014). More recently, both citral- and carvone-rich chemotypes produced complete repellency against *Ulo-moides dermestoides* at 16 µL/mL (Caballero-Gallardo et al., 2023). This suggests that different chemotypes may be suited to different insect-management strategies, with linalool-rich oils showing fumigant potential and carvone/citral-rich oils showing strong contact or repellent effects.

4.1.2. Fungicidal activities against phytopathogenic fungi

L. alba EO has also demonstrated substantial antifungal activity against a broad range of phytopathogenic fungi. Rao et al. (2000) reported complete inhibition of spore germination in *Ustilago scitaminea*, *Colletotrichum falcatum*, and *Curvularia lunata* at a concentration of 3 µL/mL. In the same study, the EO exhibited minimum inhibitory concentrations (MICs) ranging from 500 to 2000 ppm (0.5–2 mg/mL) against *Colletotrichum falcatum*, *Fusarium moniliforme*, *Curvularia lunata*, and *Cephalosporium paradoxum*. Notably, these MIC values were comparable to, and in some cases lower than, those obtained for conventional fungicides such as carbendazim, copper oxychloride, and mancozeb, which displayed MICs between 2000 and 4000 ppm (2–4 mg/mL) under identical experimental conditions. Similar levels of activity were reported by Glamočlija et al. (2011), who observed MIC values ranging between 0.3 and 1.25 mg/mL against several fungal species including *Aspergillus* spp., *Penicillium* spp., and *Trichoderma viride*. Although the reference antifungal agents ketoconazole and bifonazole showed greater potency, with MICs between 0.025 and 0.5 µL/mL, *L. alba* EO nevertheless exhibited significant inhibitory effects.

The antifungal efficacy of *L. alba* EO is also strongly influenced by its chemical profile. Among the chemotypes described, citral-rich oils consistently exhibit the highest antifungal activity (Glamočlija et al., 2011; Pandey et al., 2016; Peixoto et al., 2018; Rao et al., 2000; Sabaly et al., 2024). For instance, Peixoto et al. (2018) reported a Minimum Fungicidal Concentration (MFC) of 0.5 µL/mL against *Lasiodiplodia theobromae* and a MIC of 1 µL/mL against *Fusarium solani*. Likewise, a citral-rich chemotype completely inhibited the growth of *Aspergillus flavus* at 1000 ppm (1 mg/mL) (Sabaly et al., 2024), while complete inhibition of *Alternaria solani* was achieved at concentrations ranging from 0.5 to 1.5 µL/mL (Tomazoni et al., 2016). Other chemotypes also display relevant antifungal properties. For example, a linalool-rich chemotype inhibited the mycelial development of *Fusarium* spp. and *Sclerotinia sclerotiorum* at 1.4 and 0.4 µL/mL, respectively (Fontana et al., 2020).

Beyond growth inhibition, *L. alba* EO also exhibits noteworthy

antimycotoxigenic activity. Pandey et al. (2016) demonstrated that a citral-rich chemotype inhibited both the development of *A. flavus* and the production of aflatoxin B₁ (AFB₁) at 2 µL/mL. This effect is consistent with the activity of its major constituents, as pure geraniol completely suppressed AFB₁ production at only 0.6 µL/mL (Shukla et al., 2009). The ability to simultaneously inhibit fungal growth and mycotoxin biosynthesis represents a particularly valuable attribute for post-harvest protection and food preservation applications.

4.1.3. Nematicidal activities against root-knot nematodes

Several studies have highlighted the strong nematicidal activity of *L. alba* EO against root-knot nematodes (*Meloidogyne* spp.), one of the most economically damaging groups of plant-parasitic nematodes worldwide (De Souza, 2017; Gonçalves et al., 2016). Early evidence was provided by Marino et al., (2012), who reported that a linalool-rich chemotype containing 60.6% linalool induced 98.9% mortality in second-stage juveniles (J2) of *Meloidogyne incognita* race 1 at a concentration of 20 µL/mL. Subsequent studies demonstrated that this activity is not restricted to a single chemotype. Gonçalves et al. (2016) evaluated citral-rich EO and observed mortality rates exceeding 96% at 500 ppm, increasing to 99.6% at 1000 ppm against *M. incognita* juveniles. Additional evidence was provided by De Souza (2017), who reported complete mortality (100%) of *M. javanica* juveniles under in vitro conditions at 32 µL/mL of *L. alba* EO, while parallel *in vivo* trials on lettuce plants also confirmed strong nematicidal activity, with substantial reductions in gall numbers and egg masses, suggesting that the efficacy of *L. alba* EO extends beyond laboratory bioassays and remains effective under more realistic biological conditions.

4.1.4. Bactericidal activities against phytopathogenic bacteria

Although less extensively investigated than its antifungal or insecticidal properties, *L. alba* EO has also demonstrated antibacterial activity against several bacteria of agricultural and post-harvest importance. Available studies indicate that the efficacy of the EO is influenced by its chemical composition, with certain chemotypes exhibiting stronger antibacterial effects than others. Godoy et al. (2020) reported that limonene- and carvone-rich chemotypes inhibited the growth of *Xanthomonas axonopodis* and *Ralstonia* spp., two major phytopathogenic bacteria responsible for significant crop losses, at a concentration of 28 mg/mL. Antibacterial activity has also been reported against storage-associated bacteria. Pandey et al. (2012) observed growth inhibition of *Erwinia herbicola* and *Pseudomonas putida* at minimum concentrations of 4 µL/mL, indicating that *L. alba* EO may contribute not only to crop protection but also to the preservation of stored agricultural products. This reported efficacy against both phytopathogenic and storage-related bacteria highlights the potential of *L. alba* EO as a complementary tool for integrated disease management.

4.1.5. Acaricidal activities against agricultural mites

The acaricidal potential of *L. alba* EO has been demonstrated against phytophagous mites, particularly *Oligonychus coffeae*, a major pest affecting tea and several other perennial crops. Deka et al., (2021) reported that a geraniol- and neral-rich chemotype exhibited pronounced toxicity toward adult mites, achieving 100% mortality 48 h after fumigation at a concentration of 1500 ppm. In addition to its adulticidal activity, the same EO displayed remarkable ovicidal effects, reducing egg hatchability by 99.9% at 1000 ppm. The simultaneous efficacy against both adults and eggs is particularly noteworthy, as it may contribute to more effective population suppression by targeting multiple developmental stages of the pest. These findings suggest that geraniol- and neral-rich chemotypes of *L. alba* could represent promising candidates for the management of phytophagous mites.

It should be emphasized that most of the biological activities documented for *L. alba* EO have been demonstrated under controlled laboratory bioassays, whereas evaluations under greenhouse, semi-field, or commercial storage conditions remain limited. Accordingly, the

translation of these promising laboratory findings into consistent performance under practical conditions should be interpreted with caution, as strong biological activity under controlled conditions does not necessarily translate into robust agronomic or storage efficacy (Arteaga-Ojeda et al., 2026). Future research should therefore prioritize field-scale evaluations to confirm the agronomic relevance of these promising laboratory activities. Nevertheless, taken together, the biological activities reported for *L. alba* EO suggest a particularly promising application in post-harvest protection systems. Stored commodities such as maize, cowpea, peanut, and other cereal and legume grains are frequently exposed to co-infestations by insect pests and mycotoxigenic fungi (Table 2), resulting in substantial quantitative and qualitative losses, particularly in tropical and subtropical regions (Lamboni and Hell, 2009; Pandey et al., 2016; Peixoto et al., 2015; Torre et al., 2024). Current management strategies still rely largely on synthetic fumigants and fungicides, including phosphine and mancozeb, despite increasing concerns regarding resistance development, operator safety, and chemical residues in food products (Guèye et al., 2011; Hassane et al., 2025; Torre et al., 2024).

In this context, the multifunctional activity of *L. alba* EO represents a major advantage. Several chemotypes have demonstrated complementary biological activities against important stored-product pests and

fungi (Table 2). Linalool- and carvone-rich oils exhibit insecticidal and repellent activities against storage insects, whereas citral-rich chemotypes display strong antifungal and antimycotoxigenic effects against *A. flavus*, including inhibition of aflatoxin production (Caballero-Gallardo et al., 2023; Niculau et al., 2013; Pandey et al., 2016; Shukla et al., 2009). However, bioactivities likely result not only from dominant compounds but also from additive or synergistic interactions among minor constituents. Further constituent-by-constituent investigations would therefore be needed to disentangle individual contributions and better characterize these interaction effects.

4.2. Molecular and physiological mechanisms of action

While the biological activities of *L. alba* EO are increasingly documented, understanding the molecular and physiological mechanisms underlying these effects remains essential for its rational development as a biopesticide. Among the different biological activities reported, the molecular basis of insecticidal and antifungal effects is currently the best characterized; consequently, Fig. 2 highlights these two major modes of action and their relevance for post-harvest grain protection. Mechanistic studies not only help explain the broad-spectrum activity of the EO but also provide valuable information for optimizing field applications,

Table 2
Biological activities of *Lippia alba* essential oil chemotypes against major agricultural pests and pathogens.

Chemotype	Target pests	Pest category	Mode of action	Experimental condition	Effective dose (unit)	References
Carvone	<i>Acanthoscelides obtectus</i>	Insect	Lethal effect	Laboratory/ <i>in vitro</i>	120 µL/Petri dish	Rodríguez González et al. (2020)
	<i>Uromoides dermestoides</i>	Insect	Repellent	Laboratory/ <i>in vitro</i>	16 µL/mL	Caballero-Gallardo et al. (2023)
Citral	<i>Ustilago scitaminea</i>	Fungi	Spore germination inhibition	Laboratory/ <i>in vitro</i>	3 µL/mL (MIC)	Rao et al. (2000)
	<i>Colletotrichum falcatum</i>	Fungi	Mycelial growth inhibition	Laboratory/ <i>in vitro</i>	1 mg/mL (MIC)	Sabaly et al. (2024)
	<i>Curvularia lunata</i>					
	<i>Aspergillus flavus</i>	Fungi	Mycelial growth inhibition	Laboratory/ <i>in vitro</i>	1.24 µg/mg (LD ₅₀)	Dos Santos Niculau et al. (2013)
	<i>Spodoptera frugiperda</i>	Insect	Acute toxicity	Laboratory/ <i>in vitro</i>	0.5–1.5 (µL/mL)	Tomazoni et al. (2016)
	<i>Alternaria solani</i>	Fungi	Mycelial growth inhibition	Laboratory/ <i>in vitro</i>	1 µL/mL (MIC)	Peixoto et al. (2018)
	<i>Lasiodiplodia theobromae</i>	Fungi	Mycelial growth inhibition	Laboratory/ <i>in vitro</i>	0.3–1.25 mg/mL (MIC)	Glamočlija et al. (2011)
	<i>Aspergillus flavus</i>	Fungi	Mycelial growth inhibition	Laboratory/ <i>in vitro</i>	16 µL/mL	Caballero-Gallardo et al. (2023)
	<i>Uromoides dermestoides</i>	Insect	Repellent	Laboratory/ <i>in vitro</i>	500–1000 ppm	Gonçalves et al. (2016)
	<i>Meloidogyne incognita</i>	Nematode	Lethal effect	Laboratory/ <i>in vitro</i>		
Citral/ myrcene	<i>Aspergillus flavus</i>	Fungi	Growth suppression and aflatoxin inhibition	Laboratory/ <i>in vitro</i>	2 µL/mL (MIC)	Pandey et al. (2016)
Limonene/ carvone/ Carvone/ limonene	<i>Xanthomonas axonopodis</i>	Bacteria	Growth inhibition	Laboratory/ <i>in vitro</i>	28 mg/mL	Godoy et al. (2020)
	<i>Ralstonia sp.</i>	Insect	Repellent	Laboratory/ <i>in vitro</i>	52 µL/L	Ringuelet et al. (2014)
	<i>Tribolium castaneum</i>					
Linalool	<i>Spodoptera frugiperda</i>	Insect	Acute toxicity	Laboratory/ <i>in vitro</i>	1.20 µg/mg (LD ₅₀)	Dos Santos Niculau et al. (2013)
	<i>Sclerotinia sclerotiorum</i>	Fungi	Antifungal activity	Laboratory/ <i>in vitro</i>	0.4–1.4 µL/mL (MIC)	Fontana et al. (2020)
	<i>Callosobruchus maculatus</i>	Insect	Life cycle disruption	Laboratory/ <i>in vitro</i>	0.1 mg/mL (LC ₅₀)	Torre et al. (2024)
	<i>Spodoptera frugiperda</i>	Insect	Acute toxicity	Laboratory/ <i>in vitro</i>	1.56 µg/mg (LD ₅₀)	Dos Santos Niculau et al. (2013)
	<i>Meloidogyne incognita</i>	Nematode	Lethal effect	Laboratory/ <i>in vitro</i>	20 µL/mL	Marino et al. (2012)
Non-specified ^a	<i>Meloidogyne javanica</i>	Nematode	Lethal effect	Laboratory/ <i>in vitro</i> and Greenhouse/ pot experiment	32 µL/mL	De Souza et al. (2017)

^a Chemical composition was not reported in the original study. MIC: minimum inhibitory concentration; LD₅₀: median lethal dose; LC₅₀: median lethal concentration. Doses are presented in their original units, as reported by the authors, because bioassay conditions and dose-expression methods differed across studies.

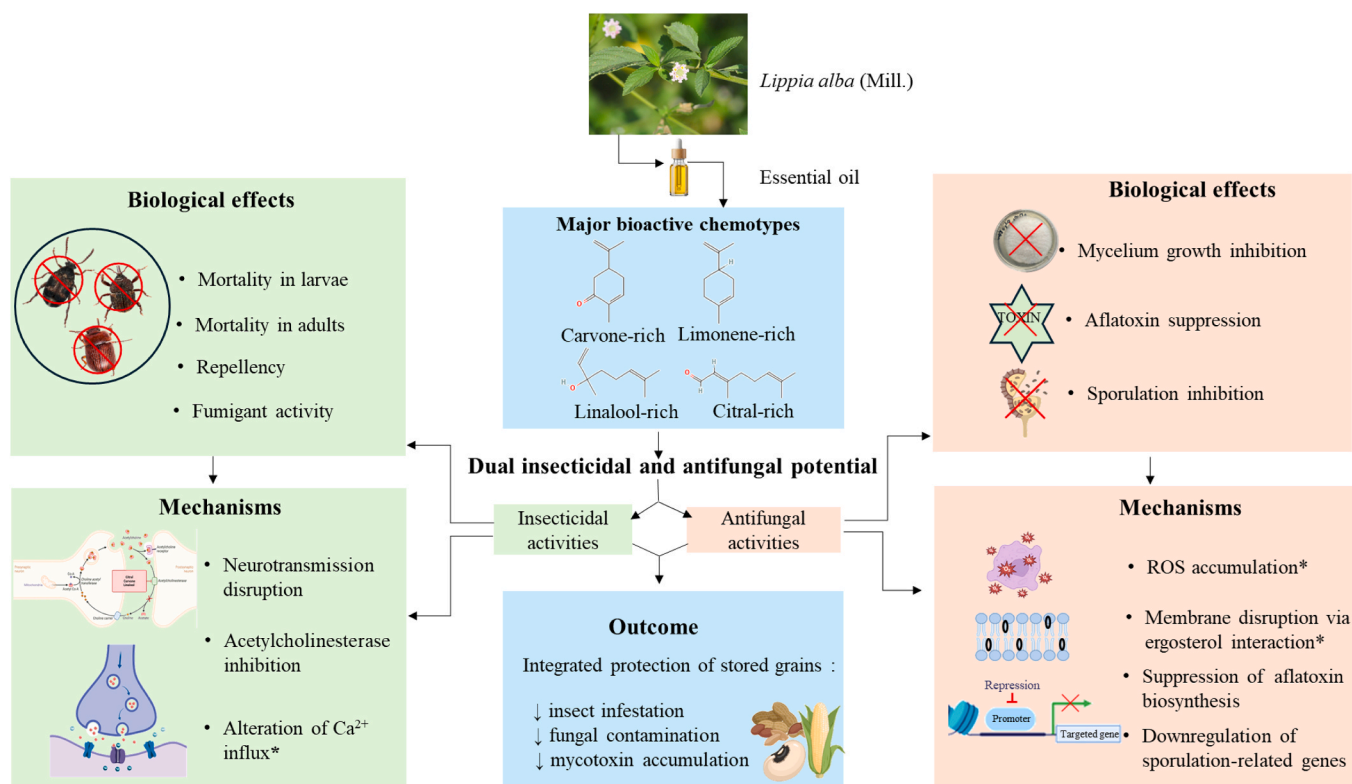


Fig. 2. Unraveling the dual insecticidal and antifungal mechanisms of *Lippia alba* essential oil for sustainable post-harvest grain protection. Mechanisms reflect direct evidence from the whole essential oil/chemotypes, except those marked (*), which are inferred from isolated constituents.

predicting potential resistance risks, and selecting the most appropriate chemotypes for specific targets.

In insect pests, direct evidence obtained with *L. alba* chemotypes suggests that their insecticidal activity may involve neurophysiological disruption. Studies of citral- (LA1), carvone- (LA2), and linalool-rich (LA3) chemotypes reported inhibition of acetylcholinesterase (AChE), a key enzyme involved in cholinergic neurotransmission (Silva Júnior et al., 2024). Additional evidence from studies of isolated compounds indicates that citral and carvone can interfere with synaptic transmission by reducing presynaptic Ca^{2+} influx and neurotransmitter release at the neuromuscular junction, as demonstrated in *Drosophila melanogaster* (da Silva et al., 2018). These constituent-level mechanisms may contribute to the insecticidal activity observed for *L. alba*, although their contribution to the activity of the complete EO remains to be established (Fig. 2).

In phytopathogenic fungi, the antifungal activity of *L. alba* EO appears to involve multiple complementary mechanisms (Fig. 2). At the EO level, citral-rich oils have been shown to contribute to the suppression of AFB₁ biosynthesis in *Aspergillus flavus* (Pandey et al., 2016; Shukla et al., 2009). Evidence from studies of citral showed that it disrupts mitochondrial oxidative phosphorylation and induces massive reactive oxygen species (ROS) accumulation in *Penicillium digitatum*, accompanied by a loss of mitochondrial membrane potential, depletion of intracellular ATP, and membrane damage (OuYang et al., 2018). These findings are consistent with the antifungal activity reported for citral as an isolated compound against *Aspergillus flavus* and *Aspergillus ochraceus*, where citral was shown to downregulate genes involved in fungal sporulation and growth, thereby inhibiting fungal development (Tang et al., 2018).

In plant-nematode systems, the available mechanistic evidence is also derived mainly from studies of individual constituents rather than from the complete *L. alba* EO. In tomato plants infested with *Meloidogyne incognita*, carvone and linalool stimulated the expression of the defense-related genes *Pathogenesis-Related Protein 1* and *Phenylalanine Ammonia-*

Lyase, indicating the induction of systemic acquired resistance in host tissues (Elsharkawy et al., 2022). These results suggest that constituents present in some *L. alba* chemotypes may contribute not only to direct nematocidal effects but also to the activation of plant defense responses.

The molecular basis of the antibacterial activity of *L. alba* EO remains less well understood. Most available evidence originates from studies conducted on isolated monoterpenes rather than on the complete EO. Citral has been shown to alter cell wall integrity and disrupt cytoplasmic organization in *Xanthomonas citri* subsp. *citri* (Mirzaei-Najafgholi et al., 2017), whereas linalool can interfere with the Psl/PSyR quorum-sensing system of *Pseudomonas syringae* pv. *tomato*, thereby reducing bacterial communication and virulence (Deepa et al., 2022). These observations suggest that EO constituents may affect both bacterial survival and pathogenicity.

Current evidence therefore indicates that the biological activity of *L. alba* EO may involve multiple and potentially complementary mechanisms, including neurotoxicity, membrane disruption, oxidative stress induction, inhibition of microbial virulence, and activation of plant defense pathways. However, the level of evidence supporting these mechanisms differs substantially. Whereas some effects have been directly demonstrated using *L. alba* EO or specific chemotypes, others are inferred from the documented activities of their major constituents. Future investigations should therefore prioritize whole-EO approaches, comparative studies among chemotypes, and the identification of experimentally validated molecular targets that could explain the variability in biological activity reported across *L. alba* populations.

4.3. Ecotoxicity and biosafety considerations

The increasing interest in plant-derived biopesticides is largely driven by their perceived environmental compatibility compared with many conventional synthetic pesticides. In this context, *L. alba* EO has been proposed as a potentially lower-persistence alternative; however, the available evidence remains insufficient to conclude that it is

environmentally safer than conventional pesticides (Giunti et al., 2022). In particular, the effects of *L. alba* EO and its formulated products on non-target organisms require further evaluation across different exposure pathways and environmental compartments.

Data on beneficial arthropods, including natural enemies and pollinators, are still lacking for *L. alba* EO. Available evidence from closely related *Lippia* species provides preliminary indications of comparatively low toxicity to pollinators. Matos et al. (2021) demonstrated that the EO of *Lippia sidoides* and its major constituents exhibited substantially lower toxicity to the stingless bee *Nannotrigona aff. testaceicornis* than synthetic organosulfur insecticides. Although species-specific evaluations remain necessary, these findings provide an initial indication that some *Lippia*-derived EOs may pose lower risks to beneficial insects than certain chemical alternatives.

Evidence for effects on soil organisms is currently more limited and is not always directly applicable to the EO itself. Regarding soil organisms, recent findings showed that solid residues from *L. alba* did not cause observable toxicity to the earthworm *Eisenia andrei* and may therefore be suitable for composting and vermicomposting (Cristina Noa-Rodríguez et al., 2025). Although these results concern post-distillation residues rather than the EO itself, they provide preliminary evidence of limited toxicity toward soil organisms. However, higher concentrations of aqueous extracts showed moderate phytotoxic effects, highlighting the importance of distinguishing between EO, its residues, and other plant-derived preparations when assessing environmental safety.

Aquatic organisms have also been investigated in several studies. Acute exposure studies in juvenile *Astyanax lacustris* reported mortality only at 20 mg/L after 96 h, while concentration-dependent gill lesions and behavioral alterations were observed, particularly at concentrations ≥ 10 mg/L (Oliveira et al., 2025). Similarly, *L. alba* EO showed acute toxicity toward *Daphnia magna*, with a 48-h EC_{50} of approximately 3.59 mg/L (Miura et al., 2021). In *Colossoma macropomum*, concentrations that achieved complete efficacy against monogenean parasites also caused physiological stress and severe gill lesions, indicating a narrow margin between antiparasitic efficacy and host safety under these exposure conditions (Soares et al., 2016). In contrast, short-term exposure to *L. alba* EO at concentrations used for anesthesia did not produce detectable genotoxic effects in *Astyanax lacustris* and *Oreochromis niloticus* (Nascimento et al., 2020). Together, these findings indicate that aquatic risk cannot be characterized solely in terms of acute mortality, but depends strongly on concentration, exposure context, and the biological endpoint considered.

Available toxicological data in mammals also highlight the importance of exposure conditions. Olivero-Verbel et al. (2010) reported neurotoxic effects and mild hepatic inflammation in mice following intraperitoneal administration of a high dose (1500 mg/kg) of citral-rich *L. alba* EO. In contrast, Neira (2018), who evaluated the toxicological profile of different *Lippia* chemotypes, reported no clinical signs of toxicity or skin irritation following topical application of citral-rich *L. alba* EO in mice. These contrasting outcomes illustrate the importance of considering chemotype, dose, and route of exposure when extrapolating toxicological risks from laboratory studies.

From a human health perspective, dermal contact and inhalation constitute the principal routes of exposure during handling and application (Maes et al., 2021). In this regard, several major compounds characterizing the main *L. alba* chemotypes, including citral, linalool, geraniol and limonene, are listed among the fragrance allergens recognized by the European Commission, warranting specific attention to dermal sensitization risks (Scientific Committee, 2012). Appropriate protective measures and good agricultural practices can substantially reduce operator exposure and associated risks (Maes et al., 2021). Human-health assessment should therefore be incorporated into the development of *L. alba*-based products alongside their intended agricultural use.

Regarding environmental fate, EOs generally undergo rapid degradation and have low environmental persistence compared with many

synthetic pesticides (Isman, 2020). These characteristics may reduce long-term environmental accumulation and contribute to a lower ecological footprint. However, the environmental safety of EO-based products also requires consideration of the formulation used for delivery. Although encapsulation can improve the stability and controlled release of EO constituents, its environmental and safety implications remain insufficiently characterized (Yammine et al., 2024). Potential effects on environmental exposure and non-target organisms should therefore be evaluated for the final formulated product rather than inferred solely from toxicity data obtained with the pure EO (Maes et al., 2019).

Overall, the available evidence does not yet allow a comprehensive assessment of the environmental safety of *L. alba* EO. The available studies indicate that toxicity can vary substantially according to the target organism, concentration, exposure route, formulation, and biological endpoint. Standardized, exposure-relevant studies covering beneficial arthropods, soil and aquatic organisms, environmental fate, and formulated products are therefore needed before broader conclusions on environmental safety can be drawn.

5. Opportunities along the *Lippia alba* essential oil value chain

The development of a sustainable *L. alba* EO value chain is supported by a unique combination of agronomic, environmental, and economic advantages. From an agronomic perspective, *L. alba* presents favorable characteristics that may support its cultivation for EO production. As a highly adaptable species, *L. alba* can grow under diverse climatic and edaphic conditions, including semi-arid environments and lands that are often unsuitable for conventional crops (dos Santos Marques et al., 2018; Teles et al., 2012). These characteristics offer opportunities for the productive use of degraded lands while limiting competition with food production systems, thereby contributing to both land restoration and food security objectives (Gelfand et al., 2013; Shortall, 2013). In addition, *L. alba* can be easily propagated through vegetative cuttings, facilitating the multiplication and dissemination of selected high-performing chemotypes (Álvarez et al., 2015; Biasi and Costa, 2003). Its perennial growth habit also allows multiple harvests per year, which may increase biomass productivity and reduce establishment requirements compared with annual aromatic crops (dos Santos Marques et al., 2018).

Field-level biomass and EO yields further illustrate the production potential of *L. alba*. A technical production reference from Martinique reported approximately 14.7 t/ha/year of fresh biomass, 4.0 t/ha/year of dried biomass of *L. alba*, and 24 kg EO per hectare at an EO yield of 0.6%. Under the conditions reported in this study, the first harvest was conducted three months after planting, allowing up to three harvests per year (Duportal, 2014). In Colombia, Barrientos et al. (2012) reported an annual fresh biomass production of approximately 18 t/ha/year from three harvests under open-field conditions, corresponding to an estimated 108 L EO/ha/year at an extraction yield of 6 L/t fresh biomass (0.6%). These contrasting estimates illustrate the strong influence of cultivation system, harvest frequency, biomass productivity, the fraction of biomass suitable for distillation, and EO yield on *L. alba* production potential. They should therefore be considered as condition-specific production estimates rather than universal or average yields for the species. Optimizing agronomic practices, harvest management, and the selection of suitable chemotypes may contribute to improving both biomass productivity and EO production.

Beyond its agronomic advantages, *L. alba* EO aligns well with current efforts to develop more sustainable crop protection strategies. Its complex chemical composition and multiple modes of action may reduce the risk of resistance development compared with single-target synthetic pesticides (Regnault-Roger et al., 2012). In addition, the natural biodegradability of EO constituents generally results in lower environmental persistence and reduced residue accumulation (Isman, 2020). Consequently, the integration of *L. alba*-based products into integrated

pest management programs may contribute to preserving agro-ecosystem health, supporting biodiversity conservation, and reducing dependence on synthetic agrochemicals (Altieri et al., 2017; Coulibaly et al., 2024; FAO, 2019).

The economic prospects for *L. alba* EO are further strengthened by the rapid expansion of global markets for natural products and bio-based solutions. The EOs market is projected to grow from USD 25.93 billion in 2025 to USD 52.70 billion by 2034 (Swar, 2026), while the global bio-pesticides market is expected to reach USD 36.43 billion by 2035 (Precedence Research, 2026). Positioned at the intersection of these two dynamic sectors, *L. alba* offers a particularly attractive opportunity for value creation. Its EO combines demonstrated biopesticidal activity with potential applications in agriculture, food preservation, cosmetics, pharmaceuticals, and wellness products, thereby diversifying market outlets and reducing dependence on a single sector (Abere and Adetunji, 2024; Chandler et al., 2011; Ferreira de Santana et al., 2024).

At the territorial level, the development of *L. alba* value chains may also generate important socio-economic benefits. Local production, processing, and commercialization of EO-based products can create additional income opportunities for rural communities while promoting local entrepreneurship. The establishment of producer cooperatives, contract farming schemes, and certification systems such as organic, fair-trade, or sustainably sourced labels may further enhance market access and product differentiation, particularly for smallholder farmers in tropical and subtropical regions (Hodson de Jaramillo and Stashenko, 2022; Montanari and Bergh, 2014).

6. Challenges and barriers to the implementation of the *Lippia alba* value chain

6.1. Formulation and field implementation challenges

Despite the promising biological activities reported for *L. alba* EO, translating laboratory efficacy into commercially viable biopesticide products remains a major challenge. Like most EOs, *L. alba* EO is characterized by high volatility, low water solubility, and susceptibility to oxidation and environmental degradation, all of which can reduce its stability, persistence, and efficacy under practical agricultural conditions (Isman, 2020; Pavela and Benelli, 2016). These physicochemical limitations represent one of the principal obstacles to the large-scale adoption of EO-based biopesticides. To overcome these constraints, considerable research efforts have focused on the development of advanced formulation technologies. Encapsulation approaches, in particular, have attracted increasing interest because they can protect volatile constituents from degradation, improve stability during storage, enhance dispersion in aqueous media, and enable controlled release of bioactive compounds (de Matos et al., 2019; Maes et al., 2019).

For *L. alba*, formulation studies remain relatively limited and have primarily focused on vectors of medical importance rather than agricultural pests. Among the few examples available, Ferreira et al. (2019) investigated poly-ε-caprolactone (PCL) nanoparticles as delivery systems for *L. alba* EO, demonstrating the feasibility of nanoencapsulation for this EO. Although similar formulations have not yet been evaluated in crop protection or post-harvest systems, studies conducted with other *Lippia* species provide encouraging evidence. For example, encapsulation of *Lippia origanoides* EO in gelatin/PCL nanoparticles resulted in complete insect mortality and effective fungal inhibition against major cacao pests at 1000 µg/mL (Rocha et al., 2022). These findings suggest that comparable formulation strategies could substantially enhance the agricultural performance of *L. alba* EO.

The effectiveness of EO-based biopesticides is also highly dependent on the application context. In post-harvest environments, where treatment occurs in confined spaces, the vapor-phase activity of EOs can be fully exploited, often resulting in improved efficacy and longer exposure of target pests (Raveau et al., 2020). By contrast, field applications expose EOs to sunlight, temperature fluctuations, rainfall, and wind,

accelerating photodegradation, evaporation, and leaching processes (Gupta et al., 2023). As a result, repeated applications may be necessary to maintain effective pest control, thereby increasing operational costs and limiting commercial competitiveness.

Beyond formulation design, determining the optimal application rate remains a critical challenge. For field application, effective doses must ensure sufficient pest control while minimizing phytotoxic effects on crops (Maes et al., 2019). Achieving this balance is often complex because both EO efficacy and plant tolerance vary according to crop species, developmental stage, environmental conditions, and chemical composition of the EO (Werrie et al., 2020). Furthermore, volatilization losses during formulation, storage, and application may reduce the actual concentration of active constituents reaching the target organism (de Matos et al., 2019).

Additional aspects beyond biological efficacy should also be considered, including potential effects on stored grains, sensory quality, residual odor, and seed germination capacity. To date, no study has specifically evaluated the persistence of residual aroma or its potential impact on consumer acceptance following treatment with *L. alba* EO. By contrast, available studies suggest that *L. alba* EO does not adversely affect seed germination at effective antifungal concentrations (Pandey et al., 2016; Shukla, 2018). Further investigations are nevertheless needed to assess the effects of repeated treatments on grain quality and storage performance under practical conditions.

6.2. Structural and systemic barriers to market integration

Despite its promising biological activity and multiple valorization opportunities, the large-scale commercialization of *L. alba* EO as a bio-pesticide still faces several technical, regulatory, and economic challenges. Addressing these constraints will be essential to ensure consistent product quality, market competitiveness, and long-term adoption by end-users.

One of the main technical challenges concerns the standardization of the botanical raw material. Although vegetative propagation is widely recognized as an effective strategy for maintaining selected chemotypes (Biaşi and Costa, 2003; dos Santos Marques et al., 2018), both EO yield and composition remain influenced by environmental conditions, agronomic practices, harvest timing, and post-harvest processing. Such variability can affect the consistency of the final product and complicate quality control during industrial production (Gimenes et al., 2021; Ricciardi et al., 2009). The development of standardized cultivation protocols, coupled with chemotype selection and quality certification systems, therefore represents a key prerequisite for reliable commercial production.

Industrial scaling also presents important operational challenges. Moving from laboratory- or pilot-scale extraction to commercial manufacturing requires substantial investments in distillation equipment, energy supply, water management, storage facilities, and quality-control infrastructure. Processing capacity is therefore a key consideration for commercial production. Álvarez et al. (2015) reported a pilot-scale steam-distillation unit specifically developed for *L. alba* with a capacity of 30 kg of dried plant material per batch, requiring approximately 3 h per distillation and allowing up to four distillations per day. At a larger production scale, Barrientos et al. (2012) described a steam-extraction system designed to process 600 kg of fresh biomass per batch, requiring approximately 7 h per cycle, with two cycles per day, corresponding to a nominal processing capacity of approximately 1.2 t of fresh biomass per day and 288 t per year under the operating schedule considered in that study. For this production system, the authors estimated the first-year cost of the extraction process at approximately USD 520,145, comprising about USD 16,749 in initial investment (steam-distillation unit and infrastructure) and USD 503,396 in annual operating costs, mainly associated with labour and inputs. Although these figures are specific to the Colombian production system and should not be extrapolated directly to other regions, they indicate the economic

requirements associated with large-scale extraction. Based on the reported annual operating costs and EO production, this corresponds to an indicative operating cost of approximately USD 291/L, excluding the initial investment. Including the initial investment, the total first-year cost of approximately USD 520,145 would correspond to approximately USD 301/L.

Treatment costs provide a complementary perspective on the economic feasibility of EO-based biopesticides. Available benchmarks for plant-derived EO biopesticides indicate application costs of approximately USD 35–50/ha compared with USD 15–25/ha for some conventional synthetic insecticides (Ashokkumar et al., 2026). These estimates provide a reference framework for EO-based applications but cannot be directly transferred to *L. alba*. Its treatment cost will depend on the price of EO production, formulation, effective concentration, application dose, and treatment frequency.

These capital and operating requirements may limit participation by smallholder producers and emerging enterprises, particularly in developing regions (dos Santos Marques et al., 2018; Isman, 2020; Tarazona-Pulido et al., 2025). Nevertheless, cooperative production models, shared processing facilities, and public-private partnerships could help reduce investment barriers and improve access to processing technologies.

The absence of harmonized quality standards for *L. alba* EO constitutes an additional constraint. Unlike several well-established aromatic crops, *L. alba* currently lacks internationally recognized specifications regarding chemical composition, purity criteria, and performance standards (Coulbaly et al., 2024; Henry, 2024). This situation complicates product standardization, formulation development, and market positioning. Furthermore, the existence of multiple chemotypes may create additional regulatory complexity, as variations in chemical composition can require separate evaluations of efficacy and safety (Ferreira de Santana et al., 2024; Hennebelle et al., 2008).

Regulatory approval remains another critical bottleneck. Registration procedures for biopesticides differ substantially among countries and regions. In some jurisdictions, such as the United States, certain EO-based products may benefit from simplified registration pathways, whereas in other markets, particularly within the European Union, authorization procedures can be lengthy, costly, and data-intensive (Es et al., 2017; Isman, 2020; Villaverde et al., 2014). These regulatory disparities increase development costs and may delay market access for innovative products.

Beyond production and regulatory issues, market adoption will ultimately determine commercial success. Farmers generally evaluate crop protection solutions based on efficacy, reliability, persistence, and economic return rather than environmental benefits alone (Assadpour et al., 2024; Gupta et al., 2023). Because EO-based products often exhibit lower persistence than conventional pesticides, repeated applications may be required under certain conditions, potentially increasing labor and operational costs. In addition, limited extension services and insufficient dissemination of technical knowledge may hinder adoption by growers, particularly in rural areas (Abere and Adetunji, 2024; Mounaimi et al., 2024).

Despite these challenges, several factors support the future development of *L. alba*-based biopesticides. Growing consumer demand for natural products, increasing regulatory restrictions on synthetic pesticides, and the expansion of bioeconomy-oriented markets create a favorable environment for innovation. However, realizing this potential will require strong coordination among researchers, producers, industry stakeholders, and policymakers. Investments in chemotype standardization, formulation technologies, certification systems, targeted training programs, and innovative financing mechanisms will be essential to strengthen the value chain and facilitate large-scale commercialization. Particular attention should also be given to supporting smallholder farmers and rural women, whose participation could significantly enhance the social and economic impact of *L. alba* value chains (Abere and Adetunji, 2024; Plumecocq et al., 2018).

7. Future research priorities for the standardization of *Lippia alba* essential oil

Developing *L. alba* EO as a reliable botanical biopesticide will require a stepwise standardization process beginning with the identification of well-defined and stable plant material. Elite accessions should be selected based on EO yield, chemical profile, and compositional stability, and subsequently evaluated across environments, seasons, and production cycles before being adopted for cultivation. The selection of stable chemotypes, such as that illustrated by the stability-based approach of Do Nascimento Soares et al. (2019), combined with vegetative or clonal propagation, could provide more homogeneous planting material and reduce chemical variability among production batches (Álvarez et al., 2015; Siani et al., 2002). Chemotype registration, together with botanical and genetic authentication and traceability of the selected accessions, would further strengthen the control of plant identity and provenance (Tarazona-Pulido et al., 2025).

A second priority is to establish a comprehensive quality specification for *L. alba* EO intended for biopesticide applications. This specification should define the identity and provenance of the raw material, plant part, relevant production and harvest conditions, and the physicochemical and compositional characteristics that a commercial batch should meet to be considered acceptable (Jasić et al., 2025). Existing standards for individual essential oils illustrate this type of framework. For example, International Organization for Standardization, (1974) for lemongrass oil defines specifications for appearance, colour, relative density, refractive index, optical rotation, citral content, and solubility in ethanol. Similarly, International Organization for Standardization, (2002) for lavender oil specifies physicochemical characteristics and chromatographic compositional ranges that vary according to origin and plant material, illustrating how provenance can be incorporated into an essential-oil quality standard. A future specification for *L. alba* should therefore include appropriate parameters such as appearance, colour, odour, relative density, refractive index, optical rotation, solubility, acid index, flash point, chromatographic profile, marker compounds, and chemotype, together with relevant storage and microbiological requirements (Jasić et al., 2025; Tubay-Bermúdez et al., 2024).

The establishment of such a specification should then be followed by the definition of scientifically justified acceptance ranges for each relevant parameter (Jasić et al., 2025). This will require the characterization of sufficiently large and representative datasets covering the main sources of variability affecting *L. alba* EO, including genotype, geographical origin, cultivation environment, harvest stage and season, post-harvest handling, and distillation conditions (Hennebelle et al., 2006; Sá Filho et al., 2022). Importantly, future research should also establish quantitative relationships between chemical composition, relevant physicochemical properties, and biopesticidal efficacy to identify reliable chemical markers or marker combinations. This would provide objective criteria for determining whether a batch meets the defined specifications and is both chemically consistent and biologically suitable for its intended application.

Ultimately, reproducibility should be demonstrated across the entire production chain, from authenticated plant material and controlled cultivation to extraction, chemical characterization, and biological efficacy. Once validated specifications have been established from multi-batch and multi-environment datasets, they could provide the basis for a formal quality standard at national or regional level and, in the longer term, support the development of a dedicated international standard for *L. alba* EO. Such a framework would strengthen the reproducible production and commercial development of defined *L. alba* chemotypes as botanical biopesticides.

8. Conclusion

This review highlights the considerable potential of *L. alba* EO as a multifunctional botanical resource for sustainable crop protection.

Owing to its broad geographical distribution, ecological adaptability, and ease of cultivation, *L. alba* represents an attractive candidate for the development of bio-based agricultural inputs. Its remarkable chemical diversity, expressed through multiple chemotypes, underpins a wide range of biological activities, including insecticidal, repellent, antifungal, antimycotoxigenic, nematocidal, antibacterial, and acaricidal effects. Collectively, these properties support the potential use of *L. alba* EO as a versatile biopesticide for both field applications and post-harvest protection, although further validation is needed under practical conditions. Its multifunctional activity makes *L. alba* EO an attractive candidate for protecting stored cereals and legumes against the combined pressure of insect pests and mycotoxigenic fungi.

Beyond its phytoprotective functions, *L. alba* offers promising opportunities for value creation within the emerging bioeconomy. The species combines agronomic resilience with potential for diverse applications, extending beyond agriculture to food preservation, cosmetics, and pharmaceutical products. Such diversification may strengthen the economic viability of *L. alba*-based value chains while creating opportunities for rural development, particularly in tropical and subtropical regions where the species is naturally adapted.

Beyond its phytoprotective functions, *L. alba* offers promising opportunities for value creation within the emerging bioeconomy. The species combines agronomic resilience with potential for diverse applications, extending beyond agriculture to food preservation, cosmetics, and pharmaceutical products. Such diversification could contribute to the economic viability of *L. alba*-based value chains while creating opportunities for rural development, particularly in tropical and subtropical regions where the species is naturally adapted.

Despite these promising attributes, several challenges must still be addressed before large-scale commercialization can be achieved. The high variability in EO yield and composition among chemotypes remains a major obstacle to product standardization and regulatory approval. In addition, the intrinsic volatility, hydrophobicity, and limited persistence of EOs continue to constrain field performance, although advances in formulation technologies offer encouraging prospects for overcoming these limitations. Further research is also needed to validate efficacy under realistic agricultural conditions, improve understanding of chemotype-specific mechanisms of action, and generate the ecotoxicological and economic data required for regulatory acceptance and market adoption.

Ultimately, the successful development of *L. alba*-based biopesticides will depend on an integrated approach combining scientific innovation, agronomic optimization, value-chain organization, and supportive public policies. Strengthening collaboration among researchers, producers, industry stakeholders, and policymakers will be essential to transform the biological potential of *L. alba* into commercially viable and socially inclusive solutions. By addressing current limitations while capitalizing on its unique biological and agronomic attributes, *L. alba* could emerge as a model tropical species for the development of next-generation biopesticides and contribute meaningfully to the transition toward a more sustainable and circular bioeconomy.

Highlights

- Chemotype diversity underpins the biopesticide potential of *Lippia alba* essential oil.
- Major mechanisms underlying *L. alba* EO bioactivity are critically discussed.
- Dual insecticidal and antifungal activities support post-harvest applications.
- Value chain opportunities and commercialization barriers are thoroughly analyzed.
- Key challenges for large-scale commercialization are identified.

CRedit authorship contribution statement

Aissatou Sakho: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Madeleine Diouf:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Aminata Diagne:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Serigne Mbacké Diop:** Writing – review & editing. **Papa Seyni Cissokho:** Writing – review & editing. **Michel Bakar Diop:** Writing – review & editing. **Amadou Sidy Aly Ba:** Writing – review & editing. **Momar Talla Gueye:** Writing – review & editing. **Imaneh Goli:** Writing – review & editing. **Thomas Dogot:** Writing – review & editing. **Frédéric Francis:** Writing – review & editing. **Marie-Laure Fauconnier:** Writing – review & editing, Conceptualization. **Manon Genva:** Writing – review & editing, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used generative AI Tools (ChatGPT, Claude AI, Gemini) to assist with language editing and text refinement. The authors reviewed, edited, and verified all content and take full responsibility for the content of the published article.

Funding

This work was supported by the Académie de Recherche et d'Enseignement Supérieur (ARES), grant number [PRD-2023-Sénégal-Fauconnier].

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Florian Martini for assistance in designing the graphical abstract.

Data availability

No data was used for the research described in the article.

References

- Abere, B.O., Adetunji, C.O., 2024. Socioeconomic factors and major setbacks involved in the application of essential oil in food systems: what we need to do. In: Sharifi-Rad, C.O.A., J. (Eds.), Applications of Essential Oils in the Food Industry. Elsevier, pp. 255–262. <https://doi.org/10.1016/B978-0-323-98340-2.00014-6>.
- Acero-Godoy, J., Guzmán-Hernández, T., Muñoz-Ruiz, C., 2019. Revisión documental de uso de los aceites esenciales obtenidos de *Lippia alba* (Verbenaceae), como alternativa antibacteriana y antifúngica. Rev. Tecnol. En. Marcha 32, 3–11. <https://doi.org/10.8845/tm.v32.i1.4114>.
- Altieri, M., Nicholls, C., Montalba, R., 2017. Technological approaches to sustainable agriculture at a crossroads: an agroecological perspective. Sustainability 9, 349. <https://doi.org/10.3390/su9030349>.
- Álvarez, I.J., Uribe, C.A., Acevedo, J.O., Lesmes, R., 2015. Análisis de la producción de aceite esencial de *Lippia alba* por destilación mediante arrastre de vapor en planta móvil. Rev. Integr. Investig. Apl. Desarro. Tecnol. ógico e Innovación 2, 5–34.
- Arteaga-Ojeda, R.M., Larralde-Corona, C.P., Cometta, S., Narváez-Zapata, J.A., 2026. Bridging the lab-field gap: towards scalable biocontrol applications for sustainable maize protection. Agronomy 16, 1–27. <https://doi.org/10.3390/agronomy16060598>.
- Ashokkumar, K., Murugan, M., Prasath, G.A., Dhanya, M.K., 2026. Botanical sources, mechanisms and efficacy of biopesticides derived from plant essential oils. Discov. Plants 2026 31 3, 180. <https://doi.org/10.1007/S44372-026-00662-5>.
- Assadpour, E., Can Karaça, A., Fasamanesh, M., Mahdavi, S.A., Shariat-Alavi, M., Feng, J., Kharazmi, M.S., Rehman, A., Jafari, S.M., 2024. Application of essential oils

- as natural biopesticides; recent advances. *Crit. Rev. Food Sci. Nutr.* 64, 6477–6497. <https://doi.org/10.1080/10408398.2023.2170317>.
- Bahl, J.R., Garg, S.N., Singh, S.C., Bansal, R.P., Naqvi, A.A., Kumar, S., 2000. Composition of linalool rich essential oil from *Lippia alba* grown in Indian plains. *Flavour. Fragr. J.* 15, 199–200. [https://doi.org/10.1002/1099-1026\(200005/06\)15:3<199::AID-FFJ892>3.0.CO;2-S](https://doi.org/10.1002/1099-1026(200005/06)15:3<199::AID-FFJ892>3.0.CO;2-S).
- Barbosa, F.D.F., Barbosa, L.C., Melo, E.C., Botelho, F.M., Santos, R.H., 2006. Effect of drying air temperature upon the content and chemical composition of the essential oil from *Lippia alba* (Mill) NE Brown. *Quim. Nova* 29, 1221–1225.
- Barra, A., 2009. Factors affecting chemical variability of essential oils: A review of recent developments. *Nat. Prod. Commun.* 4, 1147–1154. <https://doi.org/10.1177/1934578X0900400827>.
- Barrientos, J.C., Reina, M.L., Chacón, M.I., 2012. Potencial económico de cuatro especies aromáticas promisorias para producir aceites esenciales en Colombia The economic potential of four promising aromatic species for the production of essential oils in Colombia. *Rev. Colomb. Ciencias Hortic.* 6, 225–237.
- Barros, L. de S.P., Santos da Cruz, E. de N., de Araújo Guimarães, B., Setzer, W.N., Veras Mourão, R.H., do Rosário da Silva, J.K., Silva da Costa, J., Baia Figueiredo, P.L., 2022. Chemometric analysis of the seasonal variation in the essential oil composition and antioxidant activity of a new geraniol chemotype of *Lippia alba* (Mill.) N.E.Br. ex Britton & P. Wilson from the Brazilian Amazon. *Biochem. Syst. Ecol.* 105, 104503. <https://doi.org/10.1016/j.bse.2022.104503>.
- Bationo, R., Kaboré, D., Abdoulaye, Y., Arrouman, N., 2024. Phytochemical constituent and cumulative or antagonistic effects of crops plant organ combination on free radical scavenging capacity and antioxidant activity. *Asian J. Chem. Sci.* 14, 10–28.
- Biasi, L.A., Costa, G., 2003. Propagação vegetativa de *Lippia alba*. *Cienc. Rural.* 33, 455–459. <https://doi.org/10.1590/S0103-84782003000300010>.
- Borromeo, I., Giordani, C., Forni, C., 2025. Efficacy of *Lippia alba* essential oil in alleviating osmotic and oxidative stress in salt-affected bean plants. *Horticulturae* 11. <https://doi.org/10.3390/horticulturae11050457>.
- Burt, S., 2004. Essential oils: their antibacterial properties and potential applications in foods: A review. *Int. J. Food Microbiol.* 94, 223–253. <https://doi.org/10.1016/j.jfoodmicro.2004.03.022>.
- Caballero-Gallardo, K., Fuentes-Lopez, K., Olivero-Verbel, J., Stashenko, E.E., 2023. Chemical composition, repellent action, and toxicity of Essential Oils from *Lippia origanoides*, *Lippia alba* chemotypes, and *Pogostemon cablin* on adults of *Ulmoides dermestoides* (Coleoptera: Tenebrionidae). *Insects* 14, 41. <https://doi.org/10.3390/insects14010041>.
- Chandler, D., Bailey, A.S., Mark Tatchell, G., Davidson, G., Greaves, J., Grant, W.P., 2011. The development, regulation and use of biopesticides for integrated pest management. *Philos. Trans. R. Soc. B Biol. Sci.* 366, 1987–1998. <https://doi.org/10.1098/rstb.2010.0390>.
- Ciccio, F.J., Ocampo, R., 2010. Distribución biogeográfica de *Lippia alba* (Mill.) NE Br. ex Britton & Wilson y quimiotipos en América y el Caribe. *Norm. óN. De. Prod. Nat. Obtenidos De. Especies De. La Flora Aromática Latinoam.* 107–130.
- Coulibaly, F.H., Rossignol, M., Haddad, M., Carrasco, D., Azokou, A., Valente, A., Ginibre, C., Koné, M.W., Chandre, F., 2024. Biological effects of *Lippia alba* essential oil against *Anopheles gambiae* and *Aedes aegypti*. *Sci. Rep.* 14, 3508. <https://doi.org/10.1038/s41598-024-52801-1>.
- Cristina Noa-Rodríguez, A., Linares, Y.D., Cecilia, O., Castro, B., Gutiérrez Gaitén, Y., Scull Lizama, R., Paz, C., Becerra, J., Carlos, J., Miranda, C., González, A.F., 2025. Ecotoxicological evaluation of *Lippia alba* Mill plant residues on terrestrial ecosystem representatives. *J. Chil. Chem. Soc.* 70, 6413–6417.
- da Silva, L.V.F., Veras Mourão, R.H., Manimala, J., Lnenicka, G.A., 2018. The essential oil of *Lippia alba* and its components affect *Drosophila* behavior and synaptic physiology. *J. Exp. Biol.* 221, jeb176909. <https://doi.org/10.1242/jeb.176909>.
- da Silva, R.E.R., Santiago, I.C., de Carvalho Nilo Bitu, V., Kerntopf, M.R., de Menezes, I.R. A., Barbosa, R., 2018. *Lippia alba* (Mill.) N.E.Br. ex Britton & P. Wilson. *Med. Aromat. Plants South. Am.* 289–298. https://doi.org/10.1007/978-94-024-1552-0_25.
- Da Silva Júnior, A.Q., Da Silva, D.S., Figueiredo, P.L.B., Sarrazin, S.L.F., Bouillet, L.E.M., de Oliveira, R.B., Maia, J.G.S., Mourão, R.H.V., 2019. Seasonal and circadian evaluation of a citral-chemotype from *Lippia alba* essential oil displaying antibacterial activity. *Biochem. Syst. Ecol.* 85, 35–42. <https://doi.org/10.1016/j.bse.2019.05.002>.
- de Groot, G.S., Morales, C.L., Aldea-Sanchez, P., Aizen, M.A., Antúnez, K., Arbulo, N., Basualdo, M., Branchicella, B., Correa Benitez, A., Gutiérrez-Gamio, E.Y., Herrera Salazar, N., Juri, P., Martinez, S.I., Molina, G.A.R., Pimentel Betancurt, D., Rodriguez-Fernández, J., Salvarrey, S., Silva-Neto, C.M., Vázquez, D.E., Bogo, G., 2026. Global inequities in pesticide legislation: nearly half of pesticides approved in major crops in Latin America are not allowed in the European Union. *Proc. R. Soc. B Biol. Sci.* 293. <https://doi.org/10.1098/rspb.2025.0267>.
- de Matos, S.P., Lucca, L.G., Koester, L.S., 2019. Essential oils in nanostructured systems: Challenges in preparation and analytical methods. *Talanta* 195, 204–214. <https://doi.org/10.1016/j.talanta.2018.11.029>.
- de Morais, S.M., Sobrinho, A.C.N., Liberato, H.R., Pereira, R., de, C.A., Pessoa, C., Alves, D.R., Fontanelle, R.O., dos, S., 2022. Biotechnological potential of essential oils from different chemotypes of *Lippia alba* (Mill.) N.E.Br. ex Britton & P. Wilson. *Bol. Latinoam. Y. Del. Caribe Plantas Med. Y. Aromat.* 21, 725–736. <https://doi.org/10.37360/blacpma.22.21.6.44>.
- De Souza, R.C., da Costa, M.M., Baldissarroto, B., Heinzmann, B.M., Schmidt, D., Caron, B.O., Copatti, C.E., 2017. Antimicrobial and synergistic activity of essential oils of *Aloysia triphylla* and *Lippia alba* against *Aeromonas* spp. *Microb. Pathog.* 113, 29–33. <https://doi.org/10.1016/j.micpath.2017.10.013>.
- De Souza, R.N., 2017. Potencial do óleo essencial de *Lippia alba* (Mill.) N. E. Brown. no controle de *Meloidogyne javanica* em plantas alface. Universidade Federal do
- Recôncavo da Bahia. *Cent. De. Ciências Agr. árias Ambient. e Biol. ógicas Tecnol. em Agroecol.*
- Deepa, N., Chauhan, S., Kumari, P., Rai, A.K., Tandon, S., Singh, A., 2022. Linalool reduces the virulence of *Pseudomonas syringae* pv. tomato DC 3000 by modulating the Psl/PSYR quorum-sensing system. *Microb. Pathog.* 173, 105884. <https://doi.org/10.1016/j.micpath.2022.105884>.
- Deka, B., Pandey, A.K., Babu, A., Baruah, C., Sarkar, S., 2021. Acaricidal and ovicidal properties of *Lippia alba* essential oil and its chemical constituents against red spider mite, *Oligonychus coffeae* Nietner (Acari: Tetranychidae) infesting tea crops. *Arch. Phytopathol. Plant. Prot.* 54, 1738–1752. <https://doi.org/10.1080/03235408.2021.1938354>.
- Dhifi, W., Bellili, S., Jazi, S., Bahloul, N., Mnif, W., 2016. Essential oils' chemical characterization and investigation of some biological activities: A critical review. *Medicines* 3, 25. <https://doi.org/10.3390/medicines3040025>.
- Dias Alves, R., Bauman Quieregati, J.P., Pereira de Souza, J.S., Brandão-Silva, M.H., Pereira da Silva, A., Scortecchi, K.C., do Carmo Barreto, J., Oliveira Rocha, H.A., 2026. Impact of dry and rainy seasons on the chemical profile and antioxidant activity of *Lippia alba* essential oil. *Molecules* 31, 1035. <https://doi.org/10.3390/molecules31061035>.
- Diop, S.M., Guèye, M.T., Ndiaye, I., Hadji, E., Ndiaye, B., Diop, M.B., Heuskin, S., Fauconnier, M.-L., Lognay, G., Guèye, T., 2016. Chemical composition of essential oils and floral waters of *Mentha longifolia* (L.) Huds. Senegal. *Am. J. Essent. Oils Nat. Prod.* 4, 46–49.
- Do Nascimento Soares, N.C.H., de Mello Campos, I., dos Santos Amorim, G.T., do Carmo, M.G.F., de Almeida Chaves, D.S., de Souza, M.A.A., 2019. Selection of genotypes (citral chemotype) of *Lippia alba* (Mill.) NE Brown regarding seasonal stability of the essential oils chemical profile. *Ind. Crop. Prod.* 139, 111497. <https://doi.org/10.1016/j.indcrop.2019.111497>.
- dos Santos Marques, C.T., Gama, E.V.S., da Silva, F., Teles, S., Caiafa, A.N., Lucchese, A. M., 2018. Improvement of biomass and essential oil production of *Lippia alba* (Mill.) N.E. Brown with green manures in succession. *Ind. Crops Prod.* 112, 113–118. <https://doi.org/10.1016/j.indcrop.2017.10.065>.
- Duportal, M., 2014. Fiche technique – *Lippia alba* (Mill.) N.E. Br. – Brisee / Brizé chromosome-extension://efaidnbmnnnibpcjpcgclefindmkaj/https://opera-connaissances.cham bres-agriculture.fr/doc_num.php?explnum_id=211310 (accessed 8.26.26).
- Durán, G.D.C., Monsalve, L.A., Martínez, J.R., Stashenko, E.E., 2007. Estudio comparativo de la composición química de aceites esenciales de *Lippia alba* provenientes de diferentes regiones de Colombia, y efecto del tiempo de destilación sobre la composición del aceite. *Sci. Tech.* 1, 435–438.
- Elsharkawy, M.M., Al-Askar, A.A., Behiry, S.I., Abdelkhalek, A., Saleem, M.H., Kamran, M., Derbalah, A., 2022. Resistance induction and nematocidal activity of certain monoterpenes against tomato root-knot caused by *Meloidogyne incognita*. *Front. Plant. Sci.* 13, 982414. <https://doi.org/10.3389/fpls.2022.982414>.
- Ernest, D., Sephora, N., Yimta, F., Denis, W., 2025. Formulation of *Lippia alba* (Verbenaceae) leaves capsules for the treatment of high blood pressure. *GSC Biol. Pharm.* 32, 371–381. <https://doi.org/10.30574/gscbps.2025.32.1.0299>.
- Es, I., Khaneghah, A.M., Akbariirad, H., 2017. Global regulation of essential oils. *Essent. oils Food Process. Chem. Saf. Appl.* 327–338. <https://doi.org/10.1002/9781119149392.CH11>.
- Eslahi, H., Fahimi, N., Sardarian, A., 2017. Chemical composition of essential oils. *Essent. oils Food Process. Chem. Saf. Appl.* 119–171. <https://doi.org/10.1002/9781119149392.ch4>.
- FAO, 2019. Challenges and opportunities in a global world. <https://openknowledge.fao.org/items/c60844cc-4690-4042-94e2-33baf6dfc1a3> (accessed 9.24.25).
- Ferreira, R.M.A., Duarte, J.L., Cruz, R.A.S., Oliveira, A.E.M.F.M., Araújo, R.S., Carvalho, J.C.T., Mourão, R.H.V., Souto, R.N.P., Fernandes, C.P., 2019. A herbal oil in water nano-emulsion prepared through an ecofriendly approach affects two tropical disease vectors. *Rev. Bras. Farmacogn.* 29, 778–784. <https://doi.org/10.1016/j.bjp.2019.05.003>.
- Ferreira de Santana, C., Cirino, I., Souza, L., Silva, M., Navarro, D., Aguiar, J., Figueiredo, R., Silva, A., Gonçalves Lima, C.M., Júnior, E., Coutinho, H., Leal Balbino, T.C., 2024. Antimicrobial and cytotoxic effects of *Lippia alba* essential oil on multidrug-resistant *Acinetobacter baumannii* clinical isolates. *South. Afr. J. Bot.* 175, 479–485. <https://doi.org/10.1016/j.sajb.2024.10.019>.
- Figueiredo, A.C., 2017. Biological properties of essential oils and volatiles: Sources of variability. *Volatiles Essent. Oils* 1–13.
- Fischer, U., Lopez, R., Pöll, E., Vetter, S., Novak, J., Franz, C.M., 2004. Two chemotypes within *Lippia alba* populations in Guatemala. *Flavour. Fragr. J.* 19, 333–335. <https://doi.org/10.1002/FFJ.1309>.
- Fontana, D.C., Neto, D.D., Pretto, M.M., Mariotto, A.B., Caron, B.O., Kulczynski, S.M., Schmidt, D., 2021. Using essential oils to control diseases in strawberries and peaches. *Int. J. Food Microbiol.* 338, 108980. <https://doi.org/10.1016/J.IJFOODMICRO.2020.108980>.
- Fontana, D.C., Schmidt, D., Kulczynski, S.M., Caron, B.O., Pretto, M.M., Mariotto, A.B., Dos Santos, J., Holz, E., 2020. Fungicidal potential of essential oils in control of *Fusarium* spp. and *Sclerotinia sclerotiorum*. *Arq. Inst. Biol. (Sao Paulo)* 87, e0612019. <https://doi.org/10.1590/1808-1657000612019>.
- García-Abarrío, S.M., Martín, L., Burillo, J., Della Porta, G., Mainar, A.M., 2014. supercritical fluid extraction essential oil *Lippia alba* cultivated in Aragón (Spain). *J. Supercrit. Fluids* 94, 206–211. <https://doi.org/10.1016/j.supflu.2014.07.016>.
- Gelfand, I., Sahajpal, R., Zhang, X., César Izaurralde, R., Gross, K.L., Robertson, G.P., 2013. Sustainable bioenergy production from marginal lands in the US Midwest. *Nature* 493, 514–517. <https://doi.org/10.1038/nature11811>.
- Gimenes, L., Silva, J.C.R.L., Facanali, R., Hantao, L.W., Siqueira, W.J., Marques, M.O.M., 2021. Essential oils of new *Lippia alba* genotypes analyzed by flow-modulated

- comprehensive two-dimensional gas chromatography (GC×GC) and chemometric analysis. *Molecules* 26, 2332. <https://doi.org/10.3390/molecules26082332>.
- Giunti, G., Benelli, G., Palmeri, V., Laudani, F., Ricupero, M., Ricciardi, R., Maggi, F., Lucchi, A., Guedes, R.N.C., Desneux, N., Campolo, O., 2022. Non-target effects of essential oil-based biopesticides for crop protection: Impact on natural enemies, pollinators, and soil invertebrates. *Biol. Control* 176, 105071. <https://doi.org/10.1016/j.biocontrol.2022.105071>.
- Glamočlija, J., Soković, M., Tešević, V., Linde, G.A., Colauto, N.B., 2011. Chemical characterization of *Lippia alba* essential oil: an alternative to control green molds. *Braz. J. Microbiol.* 42, 1537–1546. <https://doi.org/10.1590/S1517-83822011000400041>.
- Godoy, J.A., Hernández, T.D.J.G., Leal, L.C.S., Mora, R.M.S., Catiblanco, G.N.C., Ávila, W.A.D., Archila, E.G., 2020. Effect of essential oils of *Cymbopogon citratus* (DC.) Stapf (lemon grass) and *Lippia alba* (Mill.) NE Br. ex Britton & P. Wilson (bushy matgrass) on *Xanthomonas axonopodis* and *Ralstonia* sp. *Rev. Cuba. Plantas Med.* 25, 14.
- Gonçalves, F.J.T., Barbosa, F.G., Lima, J.S., Coutinho, I.B.L., Oliveira, F.C., Rocha, R.R., Andrade Neto, M., 2016. Atividade antagonista do óleo essencial de *Lippia alba* (Mill.) N. E. Brown (Verbenaceae) sobre *Meloidogyne incognita* (Kofoid & White) Chitwood. *Rev. Bras. Plantas Med.* 18, 149–156. <https://doi.org/10.1590/1983-084X/15.127>.
- Guéye, M.T., Seck, D., Wathelet, J.-P., Lognay, G., 2011. Lutte contre les ravageurs des stocks de céréales et de légumineuses au Sénégal et en Afrique occidentale: synthèse bibliographique. *Biotechnol. Agron. Soc. Env* 15, 183–194.
- Gupta, I., Singh, R., Muthusamy, S., Sharma, M., Grewal, K., Singh, H.P., Batish, D.R., 2023. Plant essential oils as biopesticides: Applications, mechanisms, innovations, and constraints. *Plants* 12, 2916. <https://doi.org/10.3390/plants12162916>.
- Hassane, B.A., Lawaly, M.M., Mansour, A.M., Adamou, B., 2025. Vitro Evaluation of a Commercialized Fungicide on Radial Mycelial Growth of *Aspergillus* Species Associated with Groundnut Seeds Collected in Niger Republic. *Am. J. Life Sci.* 13, 29–34.
- Hennebelle, T., Sahpaz, S., Dermont, C., Joseph, H., Baillieu, F., 2006. The essential oil of *Lippia alba*: Analysis of samples from french overseas departments and review of previous works. *Chem. Biodivers.* 3, 1116–1125. <https://doi.org/10.1002/CBDV.200690113>.
- Hennebelle, T., Sahpaz, S., Joseph, H., Baillieu, F., 2008. Ethnopharmacology of *Lippia alba*. *J. Ethnopharmacol.* 116, 211–222. <https://doi.org/10.1016/j.jep.2007.11.044>.
- Henry, M., 2024. Chemical composition and bioactivity of essential oils from *Lippia alba* and *Aloysia citrodora*. *Rev. Latinoam. Química* 51, 13–15. <https://doi.org/10.52783/rliq.11>.
- Hodson de Jaramillo, E., Stashenko, E., 2022. Catalogue of useful plants of Colombia, chapter 8 bioeconomy: A sustainable and responsible option for making the most of Colombian plant resources. pp. 112–119.
- International Organization for Standardization, 1974. Oil of lemongrass (*Cymbopogon citratus*). Geneva.
- International Organization for Standardization, 2002. Oil of lavender (*Lavandula angustifolia* Miller). Geneva.
- Isman, M.B., 2006. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annu. Rev. Entomol.* 51, 45–66. <https://doi.org/10.1146/ANNUREV.ENTO.51.110104.151146>.
- Isman, M.B., 2020. Botanical Insecticides in the Twenty-First Century—Fulfilling Their Promise? *Annu. Rev. Entomol.* 65, 233–249. <https://doi.org/10.1146/annurev-ento-011019-025010>.
- Jasić, M., Aleksovski, A., Džudžević-Čančar, H., Dautović, E., Divković, A., 2025. Current Status and the Need to Improve the Standardization of Essential Oils Intended for the Production of Food Supplements. *Food Heal. Dis. Sci. J. Nutr. Diet.* 14, 89–95.
- Kaur, H., Garg, H., 2014. Pesticides: Environmental impacts and management strategies. *Pestic. - Toxic. Asp.* 8. <https://doi.org/10.5772/57399>.
- Lamboni, Y., Hell, K., 2009. Propagation of mycotoxigenic fungi in maize stores by post-harvest insects. *Int. J. Trop. Insect Sci.* 29, 31–39. <https://doi.org/10.1017/S1742758409391511/METRICS>.
- Linde, G.A., Colauto, N.B., Albertó, E., Gazim, Z.C., 2016. Quimiotipos, extração, composição e uso do óleo essencial de *Lippia alba*. *Rev. Bras. Plantas Med.* 18, 191–200. <https://doi.org/10.1590/1983-084X/15.037>.
- López, M.A., Stashenko, E.E., Fuentes, J.L., 2011. Chemical composition and antigenotoxic properties of *Lippia alba* essential oils. *Genet. Mol. Biol.* 34, 479–488. <https://doi.org/10.1590/S1415-47572011005000030>.
- Lorenzo, D., Paz, D., Davies, P., Vila, R., Caguieral, S., Dellacassa, E., 2001. Composition of a new essential oil type of *Lippia alba* (Mill.) N.E. Brown from Uruguay. *Flavour. Fragr. J.* 16, 356–359. <https://doi.org/10.1002/FFJ.1011>.
- Maes, C., Bouquillon, S., Fauconnier, M.L., 2019. Encapsulation of essential oils for the development of biosourced pesticides with controlled release: A review. *Molecules* 24, 1–15. <https://doi.org/10.3390/molecules24142539>.
- Maes, C., Meersmans, J., Lins, L., Bouquillon, S., Fauconnier, M.L., 2021. Essential oil-based bioherbicides: Human health risks analysis. *Int. J. Mol. Sci.* 22. <https://doi.org/10.3390/ijms22179396>.
- Marino, R.H., Gomes, L.A.A., Cruz, E.M.O., Silva, A.C., Bianchini, F.G., Meneses, T.N., Santos, H.R., Blank, A.F., 2012. Controle de *Meloidogyne incognita* raça 1 com óleo essencial de *Lippia alba*. *Sci. Plen.-.* 8, 8.
- Martínez, J.R., Diego Camilo Durán, G., Gómez, G.A., Verbel, J.O., 2007. Comparación de la composición química y de la actividad biológica de los aceites esenciales de *Lippia alba* (Mill.) N.E. Br., obtenidos variando las condiciones de extracción y secado. *Sci. Tech.* 1, 227–229.
- Matos, W.B., Santos, A.C.C., Lima, A.P.S., Santana, E.D.R., Silva, J.E., Blank, A.F., Araújo, A.P.A., Bacci, L., 2021. Potential source of ecofriendly insecticides: Essential oil induces avoidance and cause lower impairment on the activity of a stingless bee than organosynthetic insecticides, in laboratory. *Ecotoxicol. Environ. Saf.* 209, 111764. <https://doi.org/10.1016/j.ecoenv.2020.111764>.
- Mesa-Arango, A.C., Montiel-Ramos, J., Zapata, B., Durán, C., Betancur-Galvis, L., Stashenko, E., 2009. Citral and carvone chemotypes from the essential oils of Colombian *Lippia alba* (Mill.) N.E. Brown: composition, cytotoxicity and antifungal activity. *Mem. Inst. Oswaldo Cruz* 104, 878–884. <https://doi.org/10.1590/S0074-02762009000600010>.
- Mirzaei-Najafgholi, H., Tarighi, S., Golmohammadi, M., Taheri, P., 2017. The effect of *Citrus* essential oils and their constituents on growth of *Xanthomonas citri* subsp. citri. *Molecules* 22, 591. <https://doi.org/10.3390/molecules22040591>.
- Miura, P.T., Queiroz, S.C.N., Jonsson, C.M., Chagas, E.C., Chaves, F.C.M., Reyes, F.G., 2021. Study of the chemical composition and ecotoxicological evaluation of essential oils in *Daphnia magna* with potential use in aquaculture. *Aquac. Res.* 52, 3415–3424. <https://doi.org/10.1111/are.15186>.
- Montanari, B., Bergh, S.I., 2014. The challenges of ‘participatory’ development in a semi-authoritarian context: the case of an essential oil distillation project in the High Atlas Mountains of Morocco. *J. North. Afr. Stud.* 19, 828–851. <https://doi.org/10.1080/13629387.2013.878247>.
- Mounaimi, S., Hamim, A., El Boukhari, M.E.M., Elarroussi, H., Lyamlouli, K., 2024. A comprehensive review of integrating biostimulants and biopesticides for organic berry farming: exploring challenges and opportunities for Africa. *Front. Sustain. Food Syst.* 8, 1452823. <https://doi.org/10.3389/fsufs.2024.1452823>.
- Mugao, L., 2024. Factors influencing yield, chemical composition and efficacy of essential oils. *Int. J. Multidiscip. Res. Growth Eval.* 5, 169–178. <https://doi.org/10.54660/IJMRGE.2024.5.4.169-178>.
- Nascimento, H. dos S., Crispim, B. do A., Francisco, L.F.V., Merey, F.M., Kummrow, F., Viana, L.F., Inoue, L.A.K.A., Barufatti, A., 2020. Genotoxicity evaluation of three anesthetics commonly employed in aquaculture using *Oreochromis niloticus* and *Astyanax lacustris*. *Aquac. Rep.* 17, 100357. <https://doi.org/10.1016/j.aqrep.2020.100357>.
- Neira, L., 2018. Toxicidad, genotoxicidad y actividad anti-Leishmania de aceites esenciales obtenidos de cuatro (4) quimiotipos del género *Lippia*. *Boletín Latinoam. Y Del Caribe Plantas Med. Y Aromáticas* 17, 68–83.
- Nicula, E. dos S., Alves, P.B., Nogueira, P.C. de L., Moraes, V.R. de S., Matos, A.P., Bernardo, A.R., Volante, A.C., Fernandes, J.B., Silva, M.F.G.F. da, Corrêa, A.G., Blank, A.F., Silva, A. de C., Ribeiro, L. do P., 2013. Atividade inseticida de óleos essenciais de *Pelargonium graveolens* l'Herit e *Lippia alba* (Mill.) N. E. Brown sobre *Spodoptera frugiperda* (J. E. Smith). *Quim. Nova* 36, 1391–1394. <https://doi.org/10.1590/S0100-40422013000900020>.
- Oliveira, F.C., dos Santos Bastos, G.S., Bonfin, B.C., de Campos, C.M., Chagas, E.C., Chaves, F.C.M., Junior, M.V.V., 2025. Toxicity and gill alterations in *Astyanax lacustris* exposed to *Lippia alba* essential oil, 2025 335 *Aquac. Int.* 33, 334. <https://doi.org/10.1007/S10499-025-02020-W>.
- Olivero-Verbel, J., Barreto-Maya, A., Bertel-Sevilla, A., Stashenko, E.E., 2014. Composition, anti-quorum sensing and antimicrobial activity of essential oils from *Lippia alba*. *Braz. J. Microbiol.* 45, 759–767. <https://doi.org/10.1590/S1517-83822014000300001>.
- Olivero-Verbel, J., Guerrero-Castilla, A., Stashenko, E., 2010. Toxicidad del aceite esencial de *Lippia alba* (Mill.) N. E. Brown quimiotipo citral. *Acta Toxicol.* 18, 18–24.
- Ospina, J.D., Orozco, M.S.S., Correa, C.R.B., 2016. Efecto del secado y la edad de las plantas en la composición de los aceites esenciales de *Lippia alba* (Mill.) N.E.Br. ex Britton & P. Wilson y *Lippia origanoides* Kunth. *Acta Agron. ómica* 65, 170–175. <https://doi.org/10.15446/ACAG.V65N2.47576>.
- OuYang, Q., Tao, N., Zhang, M., 2018. A damaged oxidative phosphorylation mechanism is involved in the antifungal activity of citral against *Penicillium digitatum*. *Front. Microbiol.* 9, 1–13. <https://doi.org/10.3389/fmicb.2018.00239>.
- Pandey, A.K., Singh, P., Palni, U.T., Tripathi, N.N., 2012. vitro antibacterial activities of the essential oils of aromatic plants against *Erwinia herbicola* (Lohnis) and *Pseudomonas putida* (Kris Hamilton). *J. Serb. Chem. Soc.* 77, 313–323. <https://doi.org/10.2298/JSC110524192P>.
- Pandey, A.K., Sonker, N., Singh, P., 2016. Efficacy of some essential oils against *Aspergillus flavus* with special reference to *Lippia alba* oil an inhibitor of fungal proliferation and Aflatoxin B1 production in green gram seeds during storage. *J. Food Sci.* 81, M928–M934. <https://doi.org/10.1111/1750-3841.13254>.
- Pavela, R., 2015. Essential oils for the development of eco-friendly mosquito larvicides: A review. *Ind. Crops Prod.* 76, 174–187. <https://doi.org/10.1016/j.indcrop.2015.06.050>.
- Pavela, R., Benelli, G., 2016. Essential oils as ecofriendly biopesticides? Challenges and constraints. *Trends Plant. Sci.* 21, 1000–1007. <https://doi.org/10.1016/j.tplants.2016.10.005>.
- Peixoto, M.G., Bacci, L., Fitzgerald Blank, A., Araújo, A.P.A., Alves, P.B., Silva, J.H.S., Santos, A.A., Oliveira, A.P., da Costa, A.S., Arrigoni-Blank, M. de F., 2015. Toxicity and repellency of essential oils of *Lippia alba* chemotypes and their major monoterpenes against stored grain insects. *Ind. Crops Prod.* 71, 31–36. <https://doi.org/10.1016/j.indcrop.2015.03.084>.
- Peixoto, M.G., Blank, A.F., Arrigoni-Blank, M.F., Gagliardi, P.R., De Melo, J.O., Nizio, D. A.C., Pinto, V.S., 2018. Activity of essential oils of *Lippia alba* chemotypes and their major monoterpenes against phytopathogenic fungi. *Biosci. J.* 34, 1136–1146. <https://doi.org/10.14393/BJ-V34N5A2018-39385>.
- Perez-Cordero, A., Vitola-Romero, D., Merquez-Castillo, M., 2018. Chemical profile and antifungal Activity against *Phytophthora cinnamomi* of essential oils from *Lippia alba* and *Lippia origanoides*. *Indian. J. Sci. Technol.* 11, 1–8. <https://doi.org/10.17485/ijst/2018/v11i25/127786>.
- Plumecocq, G., Debril, T., Duru, M., Magrini, M.-B., Sarthou, J.-P., Therond, O., 2018. Caractérisation socio-économique des formes d'agriculture durable. *Économie Rural. Agric. Aliment. Territ.* 99–120. <https://doi.org/10.4000/economierurale.5430>.

- Precedence Research, 2026. Biopesticides Market Size, Share and Trends 2026–2035 <https://www.precedenceresearch.com/biopesticides-market> (accessed 6.8.26).
- Quintero-García, W.L., Espinel-Mesa, D.X., Moreno, E.M., Stashenko, E., Mesa-Arango, A. C., García, L.T., 2024. Enhancing selectivity and inhibitory Effects of chemotherapy drugs against myelogenous leukemia cells with *Lippia alba* essential oil enriched in citral. *Int. J. Mol. Sci.* 25, 8920. <https://doi.org/10.3390/ijms25168920>.
- Rao, G.P., Singh, S.P., Singh, M., Singhh, P., Singh, S.P., Catalan, C., Kapoor, I.P.S., Singh, G., 2000. Studies on chemical constituents and antifungal activity of leaf essential oil of *Lippia alba* (Mill.). *Indian. J. Chem. Technol.* 7, 332–335.
- Rattan, R.S., 2010. Mechanism of action of insecticidal secondary metabolites of plant origin. *Crop. Prot.* 29, 913–920. <https://doi.org/10.1016/J.CROPRO.2010.05.008>.
- Raveau, R., Fontaine, J., Lounès-Hadj Sahraoui, A., 2020. Essential oils as potential alternative biocontrol products against plant pathogens and weeds: A review. *Foods* 9. <https://doi.org/10.3390/foods9030365>.
- Regnault-Roger, C., Vincent, C., Arnason, J.T., 2012. Essential oils in insect control: low-risk products in a high-stakes world. *Annu. Rev. Entomol.* 57, 405–424. <https://doi.org/10.1146/annurev-ento-120710-100554>.
- Ricciardi, G., Ciccio, J.F., Ocampo, R., Lorenzo, D., Ricciardi, A., Bandoni, A., Dellacassa, E., 2009. Chemical variability of essential oils of *Lippia alba* (Miller) N. E. Brown growing in Costa Rica and Argentina. *Nat. Prod. Commun.* 4, 853–858. <https://doi.org/10.1177/1934578X0900400623>.
- Ringuet, J.A., Ocampo, R., Henning, C., Padin, S., Urrutia, M.I., Dal Bello, G., 2014. Actividad insecticida del aceite esencial de *Lippia alba* (Mill.) NE Brown sobre *Tribolium castaneum* Herbst. en granos de trigo (*Triticum aestivum* L.). *Rev. Bras. Agroecol.* 9, 214–222.
- Rocha, A.L.F., de Aguiar Nunes, R.Z., Matos, R.S., da Fonseca Filho, H.D., de Araújo Bezerra, J., Lima, A.R., Guimarães, F.E.G., Pamplona, A.M.S.R., Majolo, C., de Souza, M.G., Campelo, P.H., Tãlu, S., Bagnato, V.S., Inada, N.M., Sanches, E.A., 2022. Alternative controlling agent of *Theobroma grandiflorum* pests: Nanoscale surface and fractal analysis of gelatin/PCL loaded particles containing *Lippia organoides* essential oil. *Nanomater* 2022, 12. <https://doi.org/10.3390/nano12152712>.
- Rodríguez González, Á., Da Silva, F., Gutiérrez, S., Casquero, P., 2020. *Lippia* spp. essential oil as a control agent against *Acanthoscelides obtectus*, an insect pest in *Phaseolus vulgaris* beans. In: *Proceedings*, 4. <https://doi.org/10.3390/IECPS2020-08767>.
- Roxana Voto-Sáquez, M., Alan Arkin Alvarado-García, P., Pablo, J.I., 2018. Anxiolytic-like effect of *Lippia alba* essential oil: A randomized, placebo-controlled trial. *J. Complement. Med. Res.* 7, 101–107. <https://doi.org/10.5455/JCMR.20171019022824>.
- Sá Filho, J.C.F. de, Nizio, D.A. de C., Oliveira, A.M.S. de, Alves, M.F., Oliveira, R.C. de, Luz, J.M.Q., Nogueira, P.C. de L., Arrigoni-Blank, M. de F., Blank, A.F., 2022. Geographic location and seasonality affect the chemical composition of essential oils of *Lippia alba* accessions. *Ind. Crops Prod.* 188, 115602. <https://doi.org/10.1016/J.INDCROP.2022.115602>.
- Sabaly, S., Tine, Y., Diallo, A., Faye, A., Cisse, M., 2023. Chemical Composition and *Lippia alba* Essential Oils against *Aspergillus flavus* Isolated from Chemical Composition and Antifungal Activity of *Cyperus articulatus*. *Cyperus rotundus* *Lippia alba* Essent. Oils *Aspergillus flavus* Isol. Pea. <https://doi.org/10.20944/preprints202310.1256.v1>.
- Sabaly, S., Tine, Y., Diallo, A., Faye, A., Cisse, M., Ndiaye, A., Sambou, C., Gaye, C., Wele, A., Paolini, J., Costa, J., Kane, A., Ngom, S., 2024. Antifungal activity of *Cyperus articulatus*, *Cyperus rotundus* and *Lippia alba* essential oils against *Aspergillus flavus* isolated from peanut seeds. *J. Fungi* 10, 591. <https://doi.org/10.3390/JOF10080591>.
- Scientific Committee, 2012. Opinion on Fragrance Allergens in Cosmetic Products; SCCS/1459/11; Scientific Committee on Consumer Safety, Brussels, Belgium.
- Sales, G., Medeiros, S., Soares, I., Sampaio, T., Bandeira, M., Nogueira, N., Queiroz, M., 2022. Antifungal and modulatory activity of lemon balm (*Lippia alba* (Mill.) N. E. Brown) essential oil. *Sci. Pharm.* 90, 31. <https://doi.org/10.3390/SCIPHARM90020031>.
- Saroj, A.Y.A., Chanotiya, C.S., Maurya, R., Pragadheesh, V.S., Samad, A., 2019. Antifungal action of *Lippia alba* essential oil in *Rhizoctonia solani* disease management. *SN Appl. Sci.* 1, 1–12. <https://doi.org/10.1007/s42452-019-1207-8>.
- Senatore, F., Rigano, D., 2001. Essential oil of two *Lippia* spp. (Verbenaceae) growing wild in Guatemala. *Fragr. J.* 16, 169–171. <https://doi.org/10.1002/ffj.972>.
- Shortall, O.K., 2013. “Marginal land” for energy crops: exploring definitions and embedded assumptions. *Energy Policy* 62, 19–27. <https://doi.org/10.1016/J.ENPOL.2013.07.048>.
- Shukla, A.C., 2018. Essential oils as green pesticides for postharvest disease management. *Acta Hort.* (1210), 199–206. <https://doi.org/10.17660/ActaHortic.2018.1210.28>.
- Shukla, R., Kumar, A., Singh, P., Dubey, N.K., 2009. Efficacy of *Lippia alba* (Mill.) N.E. Brown essential oil and its monoterpene aldehyde constituents against fungi isolated from some edible legume seeds and aflatoxin B1 production. *Int. J. Food Microbiol.* 135, 165–170. <https://doi.org/10.1016/j.ijfoodmicro.2009.08.002>.
- Siani, A.C., Tappin, M.R., Ramos, M.F., Mazzei, J.L., Ramos, M.C.K., de Aquino Neto, F. R., Frighetto, N., 2002. Linalool from *Lippia alba*: Study of the reproducibility of the essential oil profile and the enantiomeric purity. *J. Agric. Food Chem.* 50, 3518–3521. <https://doi.org/10.1021/jf011592n>.
- Silva Júnior, A.Q., Rodrigues, G. dos S., Alcântara de Sousa, K., Maduro Bouillet, L.E., Bianchi dos Santos, G., de Sousa Barroso, A., Veras Mourão, R.H., 2024. Molecular modelling and anticholinesterase activity of the essential oil from three chemotypes of *Lippia alba* (Mill.) N.E.Br. ex Britton & P. Wilson (Verbenaceae). *Heliyon* 10, e29063. <https://doi.org/10.1016/j.heliyon.2024.e29063>.
- Soares, B.V., Neves, L.R., Oliveira, M.S.B., Chaves, F.C.M., Dias, M.K.R., Chagas, E.C., Tavares-Dias, M., 2016. Antiparasitic activity of the essential oil of *Lippia alba* on ectoparasites of *Colossoma macropomum* (tambaqui) and its physiological and histopathological effects. *Aquaculture* 452, 107–114. <https://doi.org/10.1016/j.aquaculture.2015.10.029>.
- Stashenko, E.E., Jaramillo, B.E., Martínez, J.R., 2004. Comparison of different extraction methods for the analysis of volatile secondary metabolites of *Lippia alba* (Mill.) NE Brown, grown in Colombia, and evaluation of its in vitro antioxidant activity. *J. Chromatogr. A* ExTech 2003 - 5th Int. Symp Adv. Extr. Technol. 1025, 93–103. <https://doi.org/10.1016/j.chroma.2003.10.058>.
- Swar, V., 2026. Essential oils market size, share and trends 2026–2035 <https://www.precedenceresearch.com/essential-oils-market> (accessed 6.8.26).
- Tang, X., Shao, Y.-L., Tang, Y.-J., Zhou, W.-W., 2018. Antifungal activity of essential oil compounds (geraniol and citral) and inhibitory mechanisms on grain pathogens (*Aspergillus flavus* and *Aspergillus ochraceus*). *Molecules* 23, 2108. <https://doi.org/10.3390/molecules23092108>.
- Tarazona-Pulido, L., Rugeles-Silva, P.A., Cardona Tobar, K.M., Díaz-Ariza, L.A., Muñoz Florez, J.E., López-Álvarez, D., 2025. Approach of genetic diversity of *Lippia alba* (Mill.) and *Petiveria alliacea* L.: Medicinal plants of Colombia. *Plant. Mol. Biol. Report.* 43, 602–616. <https://doi.org/10.1007/s11105-024-01484-z>.
- Tavares, E.S., Julião, L.S., Lopes, D., Bizzo, H.R., Lage, C.L.S., Leitão, S.G., 2005. Analysis of the essential oil from leaves of three *Lippia alba* (Mill.) NE Br.(Verbenaceae) chemotypes cultivated on the same conditions. *Rev. Bras. Farmacogn.* 15, 1–5.
- Tavares, I.B., Momenté, V.G., do Nascimento, I.R., 2011. *Lippia alba*: chemical, pharmacological and agronomical studies. *Appl. Res. Agrotechnology* 4, 204–220. <https://doi.org/10.5777/paet.v4i1.1397>.
- Teles, S., Pereira, J.A., Santos, C.H.B., Menezes, R.V., Malheiro, R., Lucchese, A.M., Silva, F., 2012. Geographical origin and drying methodology may affect the essential oil of *Lippia alba* (Mill.) N.E. Brown. *Ind. Crops Prod.* 37, 247–252. <https://doi.org/10.1016/J.INDCROP.2011.12.029>.
- Tomazoni, Z.E., Pansera, M.R., Pauletti, G.F., Moura, S., Ribeiro, R.T.S., Schwambach, J., 2016. vitro antifungal activity of four chemotypes of *Lippia alba* (Verbenaceae) essential oils against *Alternaria solani* (Pleosporaceae) isolates. *An. Acad. Bras. Cienc.* 88, 999–1010. <https://doi.org/10.1590/0001-3765201620150019>.
- Torre, R., Medeiros, E.A.D.P., Pereira, C.S.B., Menezes, A.C.R., Fontes, I.S., Pereira, L.V. R., Paiva, D.H.F., Santos, A.M., Damasceno, J.P.C., Souza, M.A.A., 2024. Protection of cowpea seeds and toxicity against cowpea weevils by the essential oils from *Lippia alba* (verbenaceae) and *Schinus terebinthifolius* (anacardiaceae). *Crop. Prot.* 180, 106670. <https://doi.org/10.1016/J.CROPRO.2024.106670>.
- Tubay-Bermúdez, C., Neves, C.A., Dueñas-Rivadeneira, A.A., Peña, A.M., Mendoza, L.A. Z., Escobar, K.R., Rivas-Navia, D.M., Maddela, N.R., 2024. Physical-Chemical Characterisation and Biological Activities of the Essential Oil of *Lippia alba* (Mill.) NE Br Ex Britton Obtained in Ecuador. *J. Herb. Med.* 48, 100951. <https://doi.org/10.1016/J.HERMED.2024.100951>.
- Villamil, J., 2010. El modelo *Lippia alba*. *Norm. óN. De. Prod. Nat. Obtenidos De. Especies De. La Flora Aromática Latinoam.* 97–105.
- Villamizar-Véliz, M., Aular, Y., 2022. Métodos de extracción del aceite esencial de *Lippia alba*. *Rev. Ing. UC* 29, 3–14. <https://doi.org/10.54139/revinguc.v29i1.90>.
- Villaverde, J.J., Sevilla-Morán, B., López-Goti, C., Alonso-Prados, J.L., Sandín-España, P., 2016. Trends in analysis of pesticide residues to fulfil the European Regulation (EC) No. 1107/2009. *TRAC. Trends Anal. Chem.* 80, 568–580. <https://doi.org/10.1016/J.TRAC.2016.04.017>.
- Villaverde, J.J., Sevilla-Morán, B., Sandín-España, P., López-Goti, C., Alonso-Prados, J.L., 2014. Biopesticides in the framework of the European Pesticide Regulation (EC) No. 1107/2009. *Pest. Manag. Sci.* 70, 2–5. <https://doi.org/10.1002/PS.3663>.
- Werrie, P.Y., Durenne, B., Delaplace, P., Fauconnier, M.L., 2020. Phytotoxicity of essential oils: opportunities and constraints for the development of biopesticides: A review. *Foods* 9, 1–24. <https://doi.org/10.3390/foods9091291>.
- WFO, 2026. *Lippia alba* (Mill.) N.E.Br. ex Britton & P. Wilson <https://www.worldfloraonline.org/taxon/wfo-0000228665> (accessed 2.2.26).
- Yamamoto, P.Y., Colombo, C.A., Azevedo Filho, J.A., Lourenção, A.L., Marques, M.O.M., Morais, G.D.D.S., Chiorato, A.F., Martins, A.L.M., Siqueira, W.J., 2008. Performance of ginger grass (*Lippia alba*) for traits related to the production of essential oil. *Sci. Agric.* 65, 481–489. <https://doi.org/10.1590/S0103-90162008000500006>.
- Yammine, J., Chihib, N.-E., Gharsallaoui, A., Ismail, A., Karam, L., 2024. Advances in essential oils encapsulation: development, characterization and release mechanisms. *Polym. Bull.* 81, 3837–3882. <https://doi.org/10.1007/s00289-023-04916-0>.