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Review Article

A Comprehensive Review of Lavender (*Lavandula* spp.): Taxonomy, Pollination Biology, Essential Oil Applications and Breeding Developments

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ABSTRACT

Lavandula (*Lavandula* spp.) is a perennial aromatic plant belonging to the Lamiaceae family and is well known for its rich essential oil content. Lavender is widely cultivated for the extraction of valuable essential oils from its flowers and leaves. The major components of these essential oils are linalyl acetate, linalool, cineole, and camphor. The oil obtained from *Lavandula angustifolia* has a long history of use in various sectors. In addition to its application as a natural fragrance in medical treatments, perfumery, and the cosmetic industry, it is also used in soap production and other industrial applications. The most important active constituents in lavender flowers are the essential oils, which are colorless or slightly yellow in appearance. The quality of these oils is determined by both species characteristics and environmental factors. Breeding efforts aimed at improving the quality and yield of these oils are ongoing. In recent years, traditional breeding methods such as hybridization and selection have achieved significant progress. This advancement can be attributed to the emergence of genomic and molecular techniques, which play a key role in optimizing yield and quality traits in lavender breeding. With the increasing interest in lavender cultivation, the scientific emphasis on advanced breeding techniques for this plant has also grown considerably. The present review focuses on lavender taxonomy, uses of essential oils, pollination biology, and the developments in traditional and molecular breeding approaches.

Keywords: Lavender, Lavender Essential Oil, Lavender Breeding, Lavender Molecular Breeding, Molecular Markers

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Lavanta (*Lavandula* spp.)'nin Kapsamlı Bir İncelemesi: Taksonomi, Tozlaşma Biyolojisi, Esansiyel Yağ Uygulamaları ve Islah Gelişimleri

ÖZET

Lavandula (*Lavandula* spp.), Lamiaceae familyasına ait çok yıllık, aromatik bir bitkidir ve zengin uçucu yağ içeriğiyle tanınmaktadır. Lavanta, çiçekleri ve yapraklarından değerli uçucu yağlar elde etmek amacıyla yaygın olarak yetiştirilmektedir. Uçucu yağların en önemli bileşenlerinin linalil asetat, linalool, sineol ve kafur olduğu bilinmektedir. Özellikle *Lavandula angustifolia* türünden elde edilen uçucu yağ, tıbbi tedavilerde, parfümeri ve kozmetik endüstrisinde doğal koku verici olarak kullanılmasının yanı sıra, sabun üretimi ve diğer endüstriyel alanlarda da yaygın kullanım bulmaktadır. Lavanta çiçeklerinde yer alan en önemli aktif bileşen, renksiz veya hafif sarı tonlarda olan uçucu yağlardır. Bu yağların kalitesi, hem tür özelliklerine hem de çevresel koşullara bağlı olarak değişmektedir. Günümüzde ıslah çalışmaları, bu yağların verimini ve kalitesini artırmaya yönelik olarak sürdürülmektedir. Son yıllarda, melezleme ve seleksiyon gibi geleneksel ıslah yöntemlerinde önemli ilerlemeler kaydedilmiştir. Bu gelişmeler, lavanta ıslahında verim ve kalite özelliklerinin optimize edilmesinde etkili olan genomik ve moleküler tekniklerin kullanımına bağlanmaktadır. Lavanta yetiştiriciliğine olan ilginin artmasıyla birlikte, bu bitki üzerine yürütülen ileri ıslah tekniklerine yönelik bilimsel araştırmaların önemi de giderek artmıştır. Bu inceleme, lavanta taksonomisi, uçucu yağının kullanım alanları, tozlaşma biyolojisi ile geleneksel ve moleküler ıslah yaklaşımlarındaki gelişmelere odaklanmaktadır.

Anahtar kelimeler: Lavanta, Lavanta Esansiyel Yağı, Lavanta Islahı, Lavanta Moleküler Islahı, Moleküler Markörler

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INTRODUCTION

Due to the increasing demand for special materials produced from medicinal and aromatic plants and having a wide range of applications, the market for these products is also expanding worldwide (Govindasamy et al., 2011). . Different organs of plants (e.g. flowers or leaves) emit volatile aroma compounds that circulate freely in the air and can be detected by the olfactory systems of animals (Frauendorfer and Schieberle, 2006). Essential oils are among the most valuable of all unique substances obtained from aromatic, therapeutic plants (Hanif et al., 2019). It is a fact that approximately one third of the nearly 300 plant families growing in nature contain essential oil. Of the approximately 3000 essential oil oils currently known, only 150 are of commercial importance (Barbieri and Borsotto, 2018). Essential oils are constituted from a blend of complex, naturally-occurring volatile compounds that contain aromatic substances in their volatile state. These are synthesised as secondary metabolites by medicinal and aromatic plants. Essential oils have a very powerful structure in the form of volatile droplets. These naturally form by plants for protection against infection. They also regulate and develop growth. In addition, they repair damaged tissue (Chouhan et al., 2017; Dhifi et al., 2016). These volatile droplets, which have a dense and strong structure, are stored in the veins, glands and vesicles of plants and their aromas are released when crushed or rubbed. The storage of these volatile droplets, namely essential oils, obtained from plants such as lavender, rose, rosemary, mint, eucalyptus, etc. varies from plant to plant, and some plants store high amounts of essential oils while others store low amounts, making them difficult to obtain (Buckle, 2013; Bilgiç, 2017).

The Lamiaceae (Labiatae) family has approximately 240 known genera and 7000 species in the world (Napoli et al., 2020). Türkiye is one of the important gene centers for the Lamiaceae family, and there are 45 naturally occurring genera, 565 species and 735 taxa belonging to this family (Erdem et al., 2017). Plants belonging to the family, also called Lamiaceae, grow in almost all habitats and altitudes (Zaman et al., 2022). It is distributed over a very wide area from the Poles to the Himalayas, from South East Asia to Hawaii and Australia, Africa and America (Heywood, 1996). Lavender, a very valuable essential oil plant, is one of the most important aromatic and medicinal plants of the family due to its increasing economic value worldwide (Gallotte et al., 2020). The essential oil, obtained from the flowers and stems of the plant, is responsible for the distinctive scent for which lavender is renowned. It is cultivated in many countries, including France and Bulgaria, as well as in Spain, Italy, Greece, England, Russia, the USA, Austria and North African countries (Ceylan, 1996). Lis-Balchin (2002) underlines the difficulties in naming species, hybrids and varieties, stating that the number of lavender varieties in the world began to increase in the early 1600s. Based on the research of Lis-Balchin (2002), Cristea and Boros-Iacob (2017) refer to 132 scientific plant names in the genus *Lavandula*, of which only 47 are accepted as species names. There are three economically and commercially important lavender species in world lavender cultivation (Cesur Turgut et al., 2017: Yenikalayci et al., 2019). These species are given in Table 1 along with their essential oil contents and proportions.

Table 1: Variations in the essential oil content of several lavender species (Aslancan & Karadoğan, 2016).

Essential oil	Ratio %		Linalylacetata	Borneol	Camphor	Cineole
Camphor	0.5-1	***Lavandula angustifolia (L. officinalis)***	30-60	1.8-4.6	0.2	1-3.4
Caryophyln	3-12	***L. spica***	2-8	30-40	7.2	22.4-32.0
Cineole	1-2	***L. intermedia***	15-30	0-7.6	2.3-8.0	9.2-13.0
Linalool	30-49					
Ocimene	2.5-6					
Linalylacetata	30-45					

Lavender essential oil, fresh flowers, and dried products are produced for food and other purposes. Owing to the essential oil extracted from its flowers, lavender is considered a highly valuable aromatic plant and is widely used in the perfume, cosmetic, flavoring, pharmaceutical, and detergent industries (Habán et al., 2023;

Aprotosoaie et al., 2017). As well, lavender exhibits a wide range of biological activities, including insecticidal, repellent, and feeding-deterrent properties, as well as the fumigant toxicity of its essential oil against the eggs of stored-product insects (Papachristos and Stamopoulos, 2004; Kheloul et al., 2020; Fadia et al., 2015; Sayada et al., 2022). Moreover, lavender is a valuable species with a high capacity to be considered as an ornamental and landscape plant, as well as for industrial and traditional uses (Vijulie et al., 2022). In addition, lavender essential oil is widely employed in aromatherapy because of its beneficial pharmacological properties (Rathore & Kumar, 2022). From past to present, lavender (*L. angustifolia* Mill.) has been considered the most important and economically most valuable of the entire *Lavandula* genus and is known as the highest quality lavender species, as it is a unique rosmarinic acid producer and contains high quality essential oil (Salahudin et al., 2023). Because its essential oil (1–3%) contains less camphor and higher amounts of linalyl acetate and linalool compared to other Lavandula species, it shows distinctive properties (Kara & Baydar, 2013). Linalool has sedative effects, while linalyl acetate exhibits pronounced narcotic effects (Tisserand & Balacs, 1999; Koulivand et al., 2013). The quality of the essential oil is evaluated according to the ratio of linalyl acetate and linalool in the oil (Marincaş and Feher, 2018; Wesołowska et al., 2023; Patil and Waghmare, 2024). In addition, lavender contains components such as camphor, terpinen-4-ol, β-ocimene and 1,8-cineole (Caprari et al., 2021) (Table 2).

Table 2: Studies Examining Variations in Lavender Essential Oil Composition

Study	Major Constituents	Key Findings
Singh et al. (2015)	Linalool (29.70%), Linalyl acetate (39.10%), α-Terpineol (4.35%), Trans-caryophyllene (3.76%)	Identified 34 compounds; oil content: 0.55% (dry weight)
Barut et al. (2022)	Linalool (16.33–24.79%), Linalyl acetate (25.63–31.63%), Nerol (8.83–13.43%), β-Farnesene (3.67–5.70%)	Highest oil yield at mid-flowering stage of 3rd-year plantation
Lučić et al. (2021)	Linalool (28.01%), Linalyl acetate (27.59%), Terpinene-4-ol (4.86%)	Chemical composition of essential oils of lavender plants grown in Herzegovina
Eldeghedy et al. (2022)	Camphor (28.45%), β-Cymene (7.20%), Eucalyptol (19.08%), Endo-borneol (17.47%),	Comparative analysis of *L. angustifolia* and *L. hybrida* essential oils
Kozuharova et al. (2023)	Linalyl acetate (27.5%), Linalool (24.1%), E-β-ocimene (7.0%), Terpinen-4-ol (5.1%)	Variability in composition based on cultivar and origin; pharmacological applications

Lavender Taxonomıc Classıficatıon

Lavender, belonging to the genus *Lavandula*, is part of the Lamiaceae family, commonly known as the mint family (Nazar et al., 2022). Important species of this family with medicinal and aromatic properties include mint (*Mentha piperita*), thyme (*Thymus vulgaris*), marjoram (*Origanum majorana*), sage (*Salvia officinalis*), mountain tea (*Sideritis syriaca*), lemon balm (*Melissa officinalis*), rosemary (*Rosmarinus officinalis*), and lavender (*Lavandula officinalis*) (Alp Furan et al., 2025; Seçmen et al., 2000). Lavender taxonomy is of particular interest due to the variety of species and cultivars grown for ornamental, medicinal, and aromatic purposes. Lavender is also an important essential oil-producing plant, highly valued for its aromatic and medicinal properties. The chemical composition of lavender essential oils varies among species. True lavender

(*Lavandula angustifolia*) oil contains higher concentrations of linalyl acetate compared to lavandin (*L.* × *intermedia*), whereas spike lavender (*L. latifolia*) and lavandin oils are richer in linalool. Camphor content is lower in true lavender (<0.5%) than in lavandin (>5%), which affects the quality and aroma profile of the essential oils (Baydar, 2022). Understanding lavender taxonomy provides insight into the plant's evolutionary history, diversity, and the different varieties available for cultivation. Moja et al. (2016) identified six sections in their phylogenetic study of the genus *Lavandula*: Lavandula, Dentata, Stoechas, Pterostoechas, Chaetostachys, and Subnudae.The full taxonomic classification of Lavender is shown in Table 3.

The full taxonomic classification of Lavender is as follows:

Table 3: Taxonomic classification of lavender (Sivrikaya, 2013; Habán et al., 2023).

Taxonomic Rank	***Name***
Kingdom	Plantae
Division	Magnoliophyta
Class	Magnoliopsida
Order	Lamiales
Family	Lamiaceae
Genus	*Lavandula*
Species	*Lavandula angustifolia* Miller (There are over 39 species and 79 subspecies taxa and hybrids)

The genus *Lavandula* was first described by Swedish botanist Carl Linnaeus in 1753 and included in the Lamiaceae family by Linnaeus (Linnaeus, 1753; Passalacqua et al., 2017). The name *Lavandula* originates from the Latin word for "to wash," reflecting the plant's long-standing role in cleaning and hygiene practices (Young, 2017; Giray, 2018; Polk, 2018). Lavender plants are generally characterized by aromatic, narrow leaves and small, tubular flower spikes with hermaphrodite flowers ranging in color from purple to blue and sometimes white or pink (Perović et al., 2024). The genus comprises more than 40 species, most of which are native to the Mediterranean region but are also found in parts of Europe, North Africa, and Asia. The *Lavandula* genus is highly diverse, differing in forty morphological descriptors such as plant size, leaf color intensity, leaf length, flower color, spike length, and oil content (Scariolo et al., 2021). In cases where phenotypic characterization and morphological markers are limited and morphological descriptions are inadequate, the use of molecular markers becomes unquestionably important (Ibrahim et al., 2017).**Important Lavender Species** Some of the most commonly cultivated lavender species are illustrated in Figure 1, which highlights the distinctive features of each species. Figure 2 provides a comparative view of key morphological characteristics across the selected species, facilitating easier identification and analysis. ***Lavandula angustifolia (*English Lavender*):*** *Lavandula angustifolia*, known as medicinal lavender, is a perennial and evergreen plant with multiple stems, reaching a height of 20–60 cm (Giannoulis et al., 2020; Manushkina et al., 2023). Its roots have a depth of 80 to 100 cm, depending on climate and environmental conditions. The thin, elongated green leaves, covered with fine hairs, usually contain essential oils rich in linalool and linalyl acetate. *L. angustifolia* is perhaps the best-known lavender species, valued for its high-quality essential oils (Dobreva et al., 2023). English lavender is characterized by its compact growth, soft, narrow, silvery-green leaves, and purple or blue flowers (Saadatian et al., 2013). Its flowers and leaves are used to make herbal medicine, often in aromatherapy, perfumes and as a culinary herb.

***Lavandula stoechas*:** *Lavandula stoechas*, commonly known as Spanish lavender or crested lavender, is easily recognized by its unique flower shape with tufted, pine cone-like structures at the top of the flower spike (Miraj, 2016.) It is used for its medicinal benefits, especially due to its volatile oil content, which includes camphor, fenchone and 1,8-cineole compounds (Ez zoubi et al., 2020). *Lavandula stoechas* is a flowering plant species belonging to the Lamiaceae family, which is naturally widespread especially in Mediterranean countries. This evergreen plant, also known as black pepper, can generally grow up to 40 to 50 cm in length (Gür and Kahraman, 2021). *Lavandula stoechas* is less resistant to winter cold and more brittle than *Lavandula angustifolia* but is more heat-resistant than *L. angustifolia*. Its essential oil is stronger and more resinous, and some selected forms are grown as ornamental plants (Lis-Balchin, 2002).

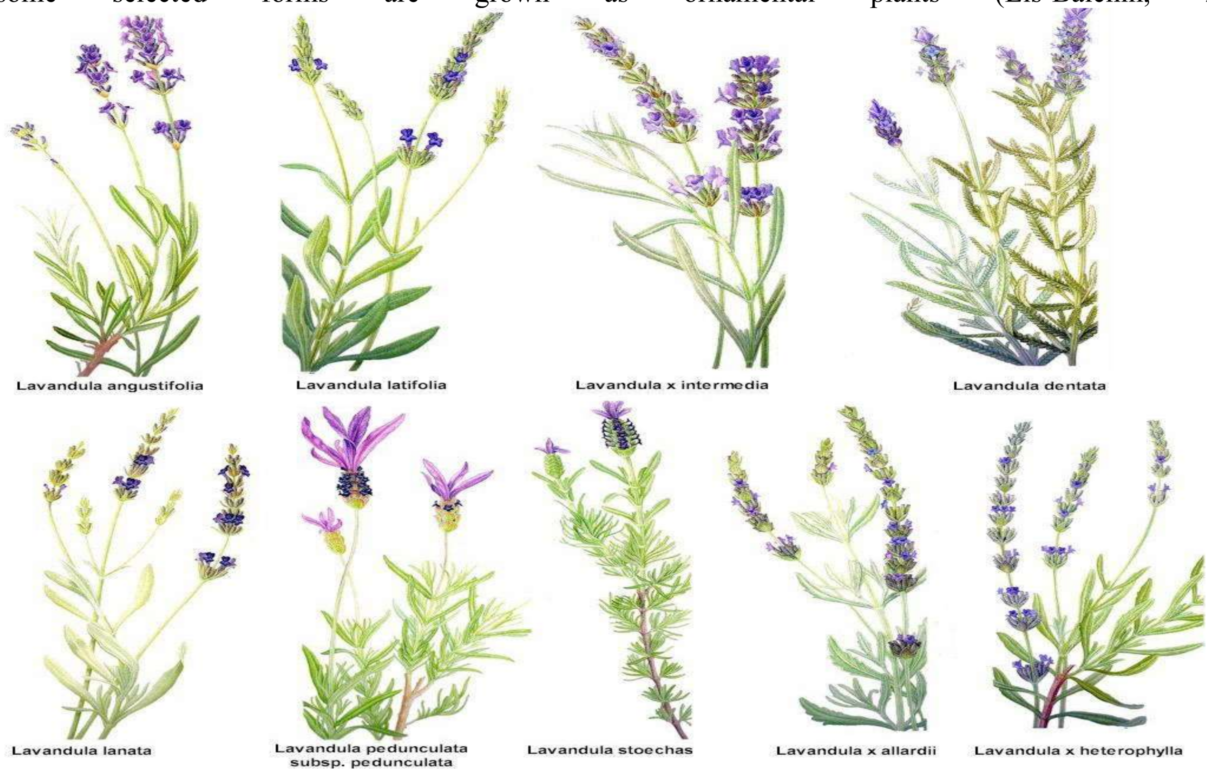

Figure 1: Presentation of Distinctive Images of Different Lavender Species (Kara, 2023).

***Lavandula dentata* (French Lavender):** *Lavandula dentata*, also known as French lavender, belongs to the Lamiaceae (Labiatae) family and the *Lavandula* genus (Bouyahya et al., 2023). *L. dentata* grows frequently in rocky and scrubby areas, especially in Morocco and mainly in the North, in the more arid Mediterranean or Saharan regions (Lis-Balchin, 2002). When *L. dentata* is examined morphologically, it reaches a height of 75 cm. Leaves are generally sessile and toothed, and their color can vary between gray and green.The flowers are purple, a terminal spike of up to seven cm is observed in the inflorescence, and it has distinct bracts in structure (Nuru et al., 2015). This species is often used in ornamental horticulture, but its essential oil content is not as high as *L. angustifolia* or *L. x intermedia* (Upson & Andrews, 2004).

***Lavandula viridis*:** The lemon aroma of *L. viridis* distinguishes it from other lavender species (Zuzarte et al., 2022). The monoterpene 1,8-cineole, commonly referred to as eucalyptus, is the primary component of L. viridis essential oil (Vairinhos and Miguel, 2020). This species has greenish-grey leaves and white flowers, unlike other lavenders, and is often used as a food flavoring agent, in cosmetic or fragrance products, and in herbal and medicinal products due to the pleasant taste and smell of its essential oil (Zuzarte et al., 2011).

***Lavandula x intermedia* (Lavandin):** It is a hybrid species obtained from the cross between *L. angustifolia* and *L. latifolia* (spike lavender) (Pokajewicz et al., 2022). It has fuller and more showy flowers compared to its parents. In terms of essential oil, it has a high oil yield and contains a higher amount of camphor (Bajalan and Pirbalouti, 2015).

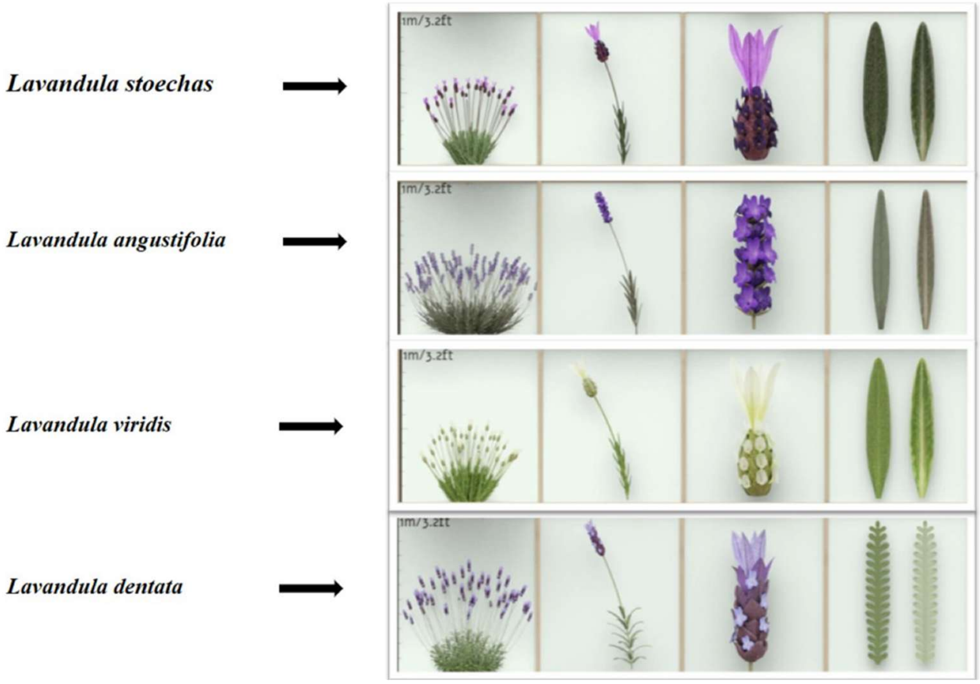

Figure 2: One may observe the comparative characteristics of several segments of the chosen Lavenders (Anonymous, 2025; Modified).

Lavender (Lavander and Lavandin) Morphological Characteristics

Lavender, a perennial herbaceous plant, is widely used in herbal medicine as well as in the food, cosmetics, perfume and aromatherapy industries (Perović et al., 2025). Lavender typically reaches a height of 40-60 cm (Batiha et al, 2023), while lavandin (*Lavandula x intermedia*) variations can reach up to 1,5 m and Lavander (*Lavandula angustifolia*) is a multi-branched plant that can reach up to 80 cm (Pokajewicz et al., 2023). Lavender is a taprooted dicotyledonous plant with many lateral branches that can reach a depth of 60 cm depending on the soil environment (Ceylan, 1987).Lavender leaves are linear or lanceolate with curved edges (Brailko et al., 2017). The lowermost part of the petiole is woody, while the upper part is green. The leaves of this plant are protected by a layer of tomentum from wind, intense sunlight, and excessive water loss (Prusinowska and Śmigielski, 2014). *L. angustifolia* has thin, long, pinnate-toothed leaves covered with fine hairs, always green and usually contain essential oils (Lis-Balchin, 2002). It may have pointed, smooth or ribbon-shaped leaves. When the leaf structure is examined, it has a length between 2 and 6 cm and is attached to the trunk in a short or stemless manner on upright stems (Fakhriddinova et al., 2020). *L. x intermedia* has linear-lanceolate to spatulate leaves generally covered with gray hairs. The stem of the lavender plant is four-sided and can be characterized as bare or hairy (Yücedağ et al., 2024).

L. angustifolia blooms between April and June and its flower petals support purple flowers, while *L. x intermedia* blooms in July and August and both species have a bitter taste and emit a strong odor (Ceylan, 1996; Baytop, 1999). Lavender grows as spikes arranged in circles on the upper part of the stem, which is about 20–30 cm long, and the flower spike is 16–20 cm tall and often consists of clusters of 4–6 flowers (Tăbăraşu et al., 2023). As the flower develops, it secretes rich, sweet-smelling nectar from a nectar-secreting disk at the flower base. Lavender has long, oval-shaped, shiny brown seeds that are two millimeters long and one millimeter wide (Ceylan 1996). It is clear that the coloration of flower tones varies according to species and varieties. The dominant coloration tends towards pale violet; however, it has been observed that varieties with white color (Alba and Nana Alba) and pink color (Rosea) have also been cultivated (Karakoyun et al., 2023).

A Brief Introduction to the Various Applications of Lavender and Its Essential Oil

Lavender, in addition to being produced for food and other purposes, is a very valuable plant due to the essential oil produced from its flowers and the content of linalool, linalyl acetate and camphor in this oil

(Pokajewicz et al., 2021). The concentration and therapeutic benefits of the composition of lavender oil vary depending on the species (Aprotosoaie et al., 2017; Dušková et al., 2016). Besides essential oils, lavender also contains anthocyanins, phytosterols, sugars, minerals, ursolic acid, coumaric acid, glycolic acid, valeric acid and its esters, herniarin, coumarin and tannins (Radu et al., 2020). Lavender essential oil is highly sought after worldwide and has significant commercial value (Perović et al., 2025). Due to its phenolic metabolites, lavender essential oil is used to make expensive perfumes, fragrances and essences, as well as medical treatments, cosmetics and foodstuffs (Lesage-Meessen et al., 2015). Lavender essential oil is widely used in the fragrance industry (soaps, colognes, perfumes, skin lotions, and other cosmetics), in aromatherapy for its sedative effects (Lamadah and Nomani, 2016), and for its antispasmodic (Heghes et al., 2019), antioxidant and antibacterial (Hui et al., 2010), and antiviral (Abou Baker et al., 2021) activities. It also possesses anxiolytic properties (Donelli et al., 2019).Additionally, lavender essential oil at concentrations of 4.0–9.0 mg/mL has been shown to have bactericidal properties (Mayaud et al., 2008).

The history of lavender dates back to ancient times, when it was used for cosmetics, medicine, and aromatherapy (Habán et al., 2023). Ancient Greek and Roman cultures used lavender for bathing, mummification, and producing perfume (Woronuk et al., 2011). Traditional uses of lavender range from perfumery to antimicrobial applications (Wińska et al., 2019). This powerful herb, with its long history of use, is still a common ingredient today. Özkaraman et al. (2018) found that inhaling lavender oil for thirty days before sleep reduced anxiety and improved sleep quality in cancer patients. So, there's been a lot of studies on different types of lavender, and they've shown that lavender has a bunch of different pharmacological activities. For example, it can fight off fungal infections (Behmanesh et al., 2015), stop bacteria from growing (Adaszyńska et al., 2013), and even deal with rheumatic diseases (Ghannadi et al., 2013), anticancer (Dakhlaoui et al., 2022), antimicrobial (Ciocarlan et al., 2021), antiparasitic (Moon et al., 2006) and antihypertensive (Gultom et al., 2016) properties. These biological activities can be attributed to the chemical structure of lavender, which contains a wide range of bioactive substance classes, such as flavonoids, terpenoids, tannins and anthracene derivatives.

The flowers, buds, and leaves of the lavender (*L. angustifolia*) plant are edible and can be used to make tea and jelly, but not raw (Crișan et al., 2023). Lavender essential oil is gaining importance because it can be used as an insect repellent/repellent in the pharmaceutical industry (Saeed et al., 2023) and the insecticide industry (Sayada et al., 2022) if the amount of camphor and 1·8-cineole, which are other components of lavender essential oil, is rich in the oil (Zeshan et al., 2024). O'Brien (1999) and Perrucci et al., (1994) demonstrated the insecticidal effect of lavender aroma to repel moths and flies. Rozman et al. (2007) reported that linalool and camphor compounds caused 100% mortality in *R. dominica* at the lowest dose in their study investigating the fumigant effects of lavender and other aromatic plants. Kara (2016), conducted a 14-day study on the effects of different doses of lavender plant extract on germination and seedling growth of maize and lentils. The results showed that 15% n-hexane extract of lavender had allelopathic effects on both crops.

Luteolin type flavonoids in lavender essential oil have bacteriostatic and spasmolytic effects. Inhalation of lavender oil has been found to provide relaxation by reducing heart rate, respiratory rate and body temperature (Watanabe et al., 2015; Vora et al., 2024). Akhondzadeh et al (2003) found that tinctures and injections containing lavender flowers have analgesic properties and help relieve depression. A different study found that inhaling lavender oil reduced fatigue, improved sleep quality, and increased energy levels in breast cancer patients (Pruthi, 2009). In particular, a study conducted on rats (Kashani et al., 2011) found lavender extract to reduce dementia associated with Alzheimer's disease. In a study of the effects of lavender extract on lung cancer, it was found to halt the growth of carcinogenic cells (Shou-Dong et al., 2009).

Pollination Biology in Lavender Production and Contradiction in Pollination Status: Self-Pollination or Foreign-Pollination?

Lavender essential oil is economically very important and has a large demand worldwide (Li et al., 2019). In lavender production, since the seeds of lavandin varieties are sterile, they are propagated only vegetatively, while lavender varieties are propagated both generatively and vegetatively (Bona et al., 2012). However, the cause of seed sterility in lavandin cultivars has not yet been fully explained (Beetham and Entwistle 1982). Pollination is necessary for optimum production of essential oil, which is of economic importance in the lavender plant (Radev, 2023). Therefore, the flowering, pollination and fertilization biology of lavender/lavandin plants needs to be intensively investigated, especially for an effective lavender breeding and seed certification processes. Although lavender is primarily considered to be cross-pollinated, there are studies that claim the opposite (Ingram et al., 2024: Balfour et al., 2013). The paradox is that under certain conditions plants can essentially self-pollinate, especially when there is limited pollinator activity, and this reveals the diversity in pollination methods of plants. If bees or other outdoor pollinators are not accessible or the climate is not conducive to cross-pollination, lavender flowers may occasionally self-pollinate. This self-pollination process is considered a fallback method that allows for continued fertilization in the event of insufficient pollinators, but lavender is more amenable to cross-pollination, which improves seed production and population genetic diversity (Korkunc, 2018).

When previous studies are examined, some studies report that the lavender plant has the ability to self-pollinate, while other studies report that lavender needs pollinators to pollinate. Valchev et al. (2022), in their study to understand whether the lavender plant is self-pollinated, emphasized the importance of pollinators and reported that self-pollination of lavender did not occur in applications where no pollinators were used. It has also been observed that bumblebees are the dominant pollinators. In their study, Baydar & Tuğlu (2024) ıt has also been observed that honey bees visit lavender and lavender flowers only to collect nectar rather than to collect pollen. In a study testing lavender pollination, seed production and seed viability, it was reported that self-pollination was observed in lavender population plants. However, it was observed that pollination by various bee species in lavender plants increased both seed production and viability in these seeds (Ingram et al., 2024). In the study examining the pollination of *L. angustifolia*, it was reported that lavender is not self-pollinating and requires insect pollinators for fruit and seed formation. It has been reported that lavender does not have the ability to self-pollinate and that some bee species are effective in pollination and act as primary pollinators, especially the leading/sufficient pollinators being *Bombus* spp. (followed by *Apis mellifera*). While fruit set was 0% in all flowers (N=683) in the experimental area without pollinators, this rate was 85.9% in the control (N=64), clearly indicating the absence of self-pollination (Valchev et al., 2022).In another study, Benachour (2017) investigated the inventory of insects visiting flowers of *Lavandula officinalis*, and examined three insect orders, Hymenoptera, Lepidoptera and Diptera. It was observed that 73% of the taxa identified in lavender plants were bees and the visitation rates of bees were higher than Lepidopterans. According to the "quantitative" relationship between the plant and its primary visitors, the most important pollinators of the plant, evaluated according to abundance and visitation rates, were reported to be *B. terrestris* and *A. mellifera*. Lavender essential oil manufacturers claim that the highest oil content is found near the end of the inflorescence's blooming period and that pollination affects oil content when unpollinated flowers fall off (Radev, 2023). Furthermore, the continuous increase of monoterpenes (especially important linalool) and decrease of sesquiterpenes during flower ontogeny has been shown to be linked to the improvement in oil quality at the end of the flowering period (Détár, et al., 2021; Hassiotis and Vlachonasios, 2025). Although more data are available on lavender pollination, insect pollination has been surprisingly little studied as a factor in fruit set. Besides these, there is limited information about the fertilization biology of *L. angustifolia* self-pollination (Romanenko and Buyukli 1980). Although studies have been conducted on the biology of pollination in lavender plants, findings are contradictory as to whether the plant requires pollinators or is self-pollinating (Kozuharova et al., 2024). Therefore, it is obvious that more research is needed to compare the flowering, pollination and fertilization characteristics of lavender varieties, and especially to scientifically understand the problem of high seed sterility in lavandin.

Traditional Lavender Breeding

Cultivation of medicinal and aromatic plants started later than traditional field, garden or some other plants (Geetha and Maiti, 2025). The basis for obtaining superior varieties in medicinal and aromatic plants, as in other plants, is the search for germ plasm sources, which is where breeders started (Wang et al., 2020). Endurance to biotic and abiotic stress factors, productivity increase, and climate resistance are among the breeding objectives for both medicinal and aromatic plants and lavender (Aishwath and Lal, 2016; Shreedevasena et al., 2024). It is necessary to actively develop breeding processes to develop new, highly productive plant varieties, especially those improving aromatic properties, which can ensure a stable supply of plant raw materials (Pant et al., 2025). Lavender is cultivated commercially to obtain quality essential oils (Lesage-Meessen et al., 2015). Species characteristics and environmental influences determine the quality of these oils. Attempts are made to improve the quality of these oils through breeding. Breeding is the process of trying to make these oils of higher quality (Kryuchkova et al., 2025). A schematic representation of both classical and modern methods used in lavender breeding is provided in Figure 3.

Lavender breeding is of great importance both economically and environmentally. Thanks to breeding studies, more productive, durable and high-quality lavender varieties can be obtained (Van Oost et al., 2021). Although breeding programs have been carried out to obtain lavender varieties that can provide a stable supply of plant raw material from past to present, these studies may be insufficient (Verlet, 1992). Selection of wild populations for field cultivation based on their production and essential oil quality has resulted in the domestication of *L. angustifolia* ssp. angustifolia (Despinasse et al., 2020). The ability of lavender producers to adapt quickly to environmental changes and market demands is a necessity to increase their competitiveness in the sector (Panda, 2005). Successful varieties obtained through lavender breeding will both increase agricultural productivity and provide more income for the industrial sector. There are now more lavender varieties than there were in 1600, and occasionally the same genotype is discovered and described under several names. Some sources claim that the 'Alba' variety is the oldest (Lis-Balchin, 2002).

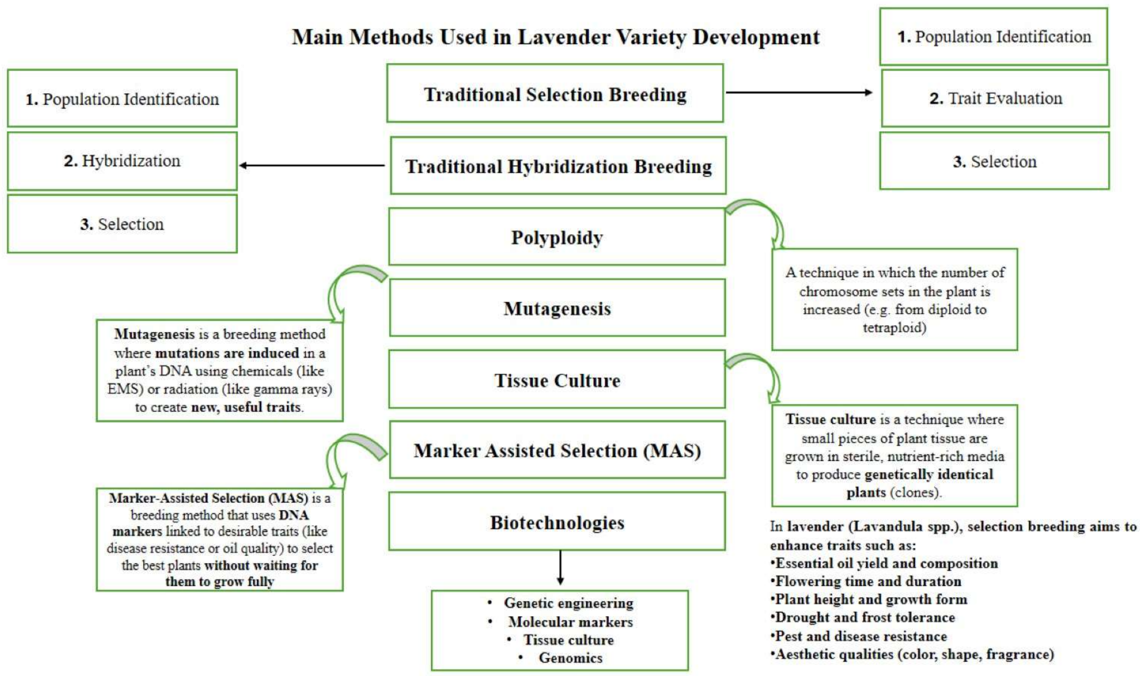

Figure 3: Schematic Representation of Classical and Modern Methods Used in Lavender Breeding

Selection breeding in lavender is the selection and reproduction of individuals with desired characteristics within the existing genetic diversity (Stanev et al., 2016). Since lavender species generally have a clonal structure, stable transfer of desired characteristics can be achieved through selection. However, this process can be time-consuming and limited genetic diversity can reduce the effectiveness of selection. Increasing and frequent water stress in the Mediterranean region, as in the rest of the world, threatens lavender production, as in other plants, and leads to crop losses (Ciais et al., 2005). Therefore, in order to investigate the responses of *L. angustifolia* and *L. x intermedia* varieties cultivated in France to water stress during the flowering period, primary metabolic (such as photosynthesis and stomatal conductance properties) and secondary metabolic (such as terpene storage) properties were evaluated under water stress conditions. In the control environment, plants were provided with three hundred mL of water per day. In contrast, the stress environment experienced a reduced irrigation schedule of one hundred mL every two days. As a result, both species exhibited a competitive strategy against water stress. It has been reported that water stress caused changes in the amount of stored terpenes in both species, which may have a negative economic impact on the essential oil production sector. Moreover, it has been noted that certain compounds, including bornyl acetate, may act as possible protective agents under water stress conditions. In conclusion, the study revealed that the types 'Rapido' (*L. angustifolia*) and 'Sumian' (*L. x intermedia*) cultivated in the French region can be grown under severe water stress conditions and can be used as a breeding source in the future (Saunier et al., 2022).

Hybridization allows different lavender varieties to be crossed to obtain new genetic combinations. In lavender breeding, hybridization of valuable parent plants for desired traits can only be achieved through sexual reproduction of plants (Crișan et al., 2023). A remarkable example of the effectiveness of lavender hybridization can be observed in the cultivar 'Etherio', which shows a 78.8% increase in essential oil yield in branches and inflorescences compared to the parent plants from which it was developed. In addition, the quality of the obtained essential oil was found to be higher due to the high linalool and linalyl acetate and low eucalyptol and camphor percentages (Hassiotis et al., 2010). Such hybridization studies aim to increase yield and quality by taking advantage of the heterosis effect. Mashcovteva and Gonceariuc 2012, ın the study where some quantitative traits and heterosis effect of F_1 polycross hybrids of *Lavandula angustifolia* Mill. were investigated, it was observed that plant height of hybrid plants varied between 38.0 cm and 75 cm, inflorescence peduncle length varied between 12.4 and 24.0 cm and essential oil content varied between 3.150% and 5.790% (dry matter). The rates at which heterosis affected various hybrid plants also varied to different degrees. According to reports, plant height trait varied from 1.9% to 14.0%, inflorescence number varied from 35.0% to 155.0%, inflorescence stem length varied from 1.3% to 39.0%, and essential oil content varied from 6.1% to 101%. According to reports, the bush height, inflorescence number and essential oil concentration of F_1 lavender polycross hybrids clearly showed the heterosis effect. The hybrid polycross Fr.5S-8-24 was the most promising hybrid for new variety-clone selection.

In the study where 140 F_1 polycross hybrids of *Lavandula angustifolia* Miil were evaluated, ten promising hybrid plants were selected according to the heterosis effect rate seen in these traits, which differed in terms of flower petal color and vegetation period. It was observed that these promising hybrid plants had plant heights ranging from 48 to 67 cm, inflorescence lengths ranging from 24.0 to 35.3 cm, flower spike lengths ranging from 4.5 to 7.4 cm, and essential oil contents ranging from 4.032% to 5.165%. It was observed that in polycross F_1 hybrids, the effect of heterosis depending on the maternal form on plant height varied between +1.0% and +36.1%, 1.3% and 82.0% depending on the length of the inflorescence, and +11.4% and 10-9.8% depending on the number of flower stalks. When the essential oil content was examined, the effect of heterosis was reported to be high in the range of +64.3% to +110.5% (Butnaraș et al., 2013). Gonceariuc et al. 2018, in their study to obtain intraspecific hybrid plants of *Lavandula angustifolia* Mill, crossbreedings were performed between the parents of Moldovan varieties Moldoveanca 4, Vis Magic 10 and Alba 7. It was observed that the quantitative characters examined varied between the hybrid and parent forms and especially the essential oil content was higher in the hybrid plants (3.939%–5.480%, dry matter) than in the maternal forms they originated from (2.722%–3.413%). In the study where the effects of heterosis were also examined for the essential oil content, it was reported that there were significant changes in hybrid plants obtained from different parents. As a result of the study, it was reported that new varieties named Fr.5S8-24, VM-18V and Fr.8-5-15V were developed by selecting hybrid plants with higher essential oil content (4.939-6.164%, dry matter), different vegetation periods and drought resistance.

Despite the high value and popularity of lavender essential oil in the world market, the biological potential of this product cannot meet the ever-increasing demand. For this reason, scientists in many countries are conducting breeding studies (Despinasse et al., 2020). Work is underway to create high-yielding hybrids of lavandins that are twice as productive as lavender, 4-5 times more productive than essential oil, and provide a gross income of $4,500-5,000 per hectare. The ratio of lavender to lavandin planting areas in the world is 1:5; this is explained by the higher yield of the aboveground mass of the hybrid plant, increased essential oil content and yield, and resistance to diseases and pests compared to lavender (Markovska et al., 2020). However, traditional breeding methods may be inadequate in some cases, especially in developing varieties of lavender plants. Both the difficulty of breeding and the complexities in fertilization biology hinder the future of lavender breeding. Therefore, in recent years, researchers believe that traditional breeding methods such as hybridization and selection will become more efficient by supporting them with genomic and molecular techniques in order to improve the yield and quality characteristics of these plants (Malli et al., 2019).

Traditional Lavender Breeding The Key Role of Molecular Markers in Lavender Breeding

Traditional breeding methods are becoming more effective when supported by biotechnology tools, especially genomic and molecular techniques (Ahmar et al., 2020). For example, genetic individuals with desired traits can be selected more quickly using molecular markers (Song et al., 20223). In addition, a better understanding of genetic diversity allows breeding programs to be more targeted and efficient. In lavender breeding, studies using genomic and molecular techniques have gained momentum today (Ražná et al., 2023). Nowadays, in breeding programs, identification and classification of genotypes through morphological, biochemical and molecular marker studies as well as determination of markers for important traits are of great importance in terms of saving time in breeding studies (David, 2007). This integrated approach enables lavender producers to obtain higher quality and more productive varieties, increasing both economic and environmental sustainability. Lavender (*Lavandula* spp.), especially the species *Lavandula angustifolia* and *Lavandula × intermedia*, has an important economic value worldwide due to its aromatic and medicinal properties (Héral et al., 2021). In recent years, traditional breeding methods such as hybridization and selection have become more efficient with the backing of genomic and molecular methods in order to improve the yield and quality characteristics of these plants (Scariolo et al., 2021).

With the use of DNA technology in plants, the phenotype, metabolic abilities, macromolecular components and morphological changes of plants have become determinable. Markers identify sources of DNA variation that, when closely linked to desired genes, allow selection based on genotype rather than phenotype (Lema, 2018). Molecular marker techniques are important techniques used in biodiversity studies, plant breeding, animal breeding, human forensic sciences, genetic mapping and map-based gene cloning (Deka, 2024; Gupta et al., 2021; Srivastava et al., 2023). It is used intensively in areas such as identifying cultivated varieties or newly developed varieties, genetic mapping (Qu et al., 2021), QTL (Quantitative Trait Loci) analyses (Chao et al., 2021), determining genetic relationships, understanding the structure of genetic material (Delfini et al., 2021), characterizing gene resources (Kushanov et al., 2021), reorganizing genetic material, phylogenetic studies (Sevindik et al., 2023) and selecting parents to be used in breeding programs. Molecular characterization measures genetic variation independent of environmental effects and allows distinguishing genotypes with similar phenotypes (Bunjkar et al., 2024). Such studies provide information about the genetic origins of plant resources by establishing relationships between genotypes and identify plants with common characteristics (Singh et al., 2020; Li et al., 2011; Shah et al., 2023).

Table 4: Molecular Marker Types and Their Important Properties

Marker Type	Full Form	Features	General Usage Areas
SSR	Simple Sequence Repeats	Co-dominant, highly polymorphic, reproducible	High-resolution genotyping
SNP	Single Nucleotide Polymorphism	Abundant, high-throughput, stable	Fine mapping and genomic selection
SRAP	(Sequence-Related Amplified Polymorphism)	Dominant, Simple and cost-effective, high reproducibility	Genetic diversity, linkage mapping, QTL mapping
AFLP	Amplified Fragment Length Polymorphism	High multiplex ratio, dominant marker	Genetic diversity and fingerprinting
RAPD	Random Amplified Polymorphic DNA	Quick and inexpensive, but low reproducibility	Preliminary screening
ISSR	Inter-Simple Sequence Repeat	Dominant marker, moderate reproducibility	Genetic diversity and mapping

Molecular marker techniques are important techniques developed to examine the genetic diversity, biotechnological potential and resistance to stress factors of lavender (Babanina et al., 2023). The studies conducted offer great potential in areas such as examining genetic diversity to obtain new varieties, determining resistance to stress factors, and improving the content and ratio of important chemical compounds

(Adal et al., 2015; Zagorcheva et al., 2020). Molecular markers are the key to understanding interspecies relationships. They reveal differences between lavender species (Ibrahim et al., 2017). Molecular markers and their characteristics used to determine genetic diversity are listed in Table 4. The AFLP marker analysis identified five clusters in 82 lavender genotypes, 15 of which were composite (Van Oost et al., 2021). The RAPD approach was utilized to assess the genetic diversity of *Lavandula multifida* populations in Tunisia (Hnia et al., 2013). Of late years, there have been significant developments in lavender breeding with the development of marker technologies. Traditional methods in lavender breeding are becoming more effective and efficient when combined with molecular markers. In lavender breeding, especially in breeding studies, the purpose of determining valuable parents and determining important relationships between genotypes allowed us to obtain valuable information about the origin of lavender genetic resources (Ražná et al., 2023; Georgieva et al., 2025). Although molecular marker studies conducted with the lavender plant are limited, these studies have gained momentum with the rapid development of marker technology today and some of the studies are presented in Table 5.

Table 5: Outline of Studies Using Molecular Markers in Lavandula Species

Lavanta Genus	Methodology	Marker Type	Referances
L. pubescens Decne, *L. angustifolia* Miller *Lavandula×heterophylla* Viv	To investigate genetic links, taxonomic traits, and variations in the production and content of essential oils.	Biochemical Marker (α-fenchene and Camphene)	Ibrahim et al., (2017)
L. angustifolia, *L. latifolia* and *L. x intermedia*	To examine evidence for genetic differentiation.	MatK, rbcL, the nuclear internal transcribed spacer (ITS), and the plastid trnH-psbA spacer,	Hind et al., (2018)
Lavandula angustifolia, Lavandula x intermedia	EST-SSRs identification, verification, and cross-species transferability	EST-SSRs	Adal et al., (2015)
Bulgarian (10) and foreign lavender (5)	Evaluation of the genetic diversity	SRAP (51 primers)	Zagorcheva et al., (2020)
Lavandula dentata (Six populations)	Applying cluster analysis to molecular phylogeny study	RAPD (8 primers)	Gadouche et al., (2019)
Lavandula spp.(Twelve genotypes)	Evaluation of Diversity	RAPD (4 primers)	Ražná et al., (2023)
Three *Lavandula angustifolia* Mill. cultivars	To investigate at the lavender cultivars' genetic stability after clonal micropropagation.	RAPD (2 primers) and ISSR (5 primers)	Babanina et al., (2023)
L. angustifolia var. Hemus (F_2 segregating population)	Identification of QTLs and Genetic Linkage Map for Lavender Floral Volatile Accumulation ((Forty-three QTLs mapped)	SSR	Georgieva et al., (2025)
L. angustifolia var. Hemus	QTL identification governing the flowers' linalool to linalyl acetate ratio	SSR and SRAP	Rusanov et al., (2023)
Lavandula angustifolia Mill.	Development of SSR markers and construction of genetic linkage maps in lavender.	SSR and SRAP	Georgieva et al., (2025)

In lavender breeding, determining the identity of botanical and essential oil compounds of species is very important for parent selection to be used in breeding programs. In a study, genetic (DNA barcoding) and chemical analysis methods were combined and chemical compounds and genetic markers were used to differentiate eleven lavender species. As a result, it was reported that three chemical compounds, namely ferulic acid hexoside, coumarin acid hexoside and rosmarinic acid, and three genetic markers, namely trnH–psbA, RbcL and ITS, could be used for the differentiation of lavender species in a collection containing eleven lavender species (Philippe et al., 2022). In a different study, EST and SSR markers were developed using genomic resources obtained from essential oil-containing tissues of lavender. More than 250 SSRs (≥ 18 bp) and 31 EST-SSRs were validated from *L. angustifolia* and *L. x intermedia* ESTs, and twenty-four of these markers were observed to have strong discrimination power in donor plant species and transferability in related species (Adal, 2019). In another study, the heterozygous clone "Maillette" was used as a reference for DNA and RNA sequencing. Sixteen commercial lavender clones were tested within the scope of genetic distance analysis using SNP markers. As a result, 359 thousand polymorphic regions and a high level of heterozygosity were observed (Fopa Fomeju et al., 2020).

CONCLUSION

The cultivation of lavender (*Lavandula*) for essential oil production is a significant industry, with various products, including fresh flowers and dried extracts, being produced for food and other purposes. The essential oil obtained from the flowers of this plant is highly prized due to its versatility and is widely utilised in various industries, such as perfume, cosmetics, flavour, pharmaceuticals and detergents. The essential oils of lavender are characterised by their colourlessness or pale yellow hue, and they represent the primary active constituents of the flowers. Despite the implementation of breeding programmes aimed at cultivating lavender varieties capable of providing a consistent supply of plant raw materials, spanning the historical to the contemporary period, these endeavours may be inadequate. It is imperative for lavender producers to engage in breeding practices in order to facilitate rapid adaptation to environmental changes and market demands, thereby enhancing their competitiveness within the sector. The successful species obtained through lavender breeding will increase agricultural productivity and generate increased revenue in the industrial sector. Conventional breeding methods, such as hybridisation and selection, are being progressively enhanced in their efficacy and efficiency when employed in conjunction with genomic and molecular techniques. For instance, the utilisation of molecular markers has been demonstrated to facilitate the expeditious selection of genetic individuals that possess the desired traits. Moreover, an enhanced comprehension of genetic diversity facilitates the development of more targeted and efficient breeding programmes. In the context of lavender breeding, particularly in the realm of breeding studies, the objective is to ascertain the valuable parents and to determine the significant relationships between genotypes. This process has facilitated the acquisition of invaluable information pertaining to the provenance of lavender genetic resources. Although molecular and genomic studies on lavender plants are limited, it is thought that with the rapid development of marker technology, these studies will gain momentum and more successful results will be obtained in lavender breeding.

ETHICAL APPROVAL

The study, entitled " A Comprehensive Review of Lavender (*Lavandula* spp.): Taxonomy, Pollination Biology, Essential Oil Applications and Breeding Developments ", was conducted in accordance with the relevant scientific, ethical and citation rules. No falsification was made of the collected data, and this study has not been sent to any other academic media for evaluation. As it does not require ethics committee approval, it can be considered to be in accordance with the relevant ethical standards.

CONFLICT OF INTEREST

The authors declare no conflict of interest in this study.

AUTHOR CONTRIBUTION

All authors contributed equally.

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