

Article

Eco-Friendly Biotechnological Approaches to Enhance Germination Efficiency in *Lavandula angustifolia* Mill.

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Abstract

The improvement of *Lavandula angustifolia* Mill. seed germination represents a crucial step towards the development of eco-biotechnological solutions for the sustainable propagation of aromatic plants. This study evaluated the effects of four biostimulant formulations, namely Amino 16 (amino acid-based), Razormin (humic–fulvic complex), Germinoseed (phytoextract-based), and Atonik (nitrophenolate), together with a non-treated control, on the germination efficiency and early growth of nine *Lavandula* genotypes under controlled laboratory conditions. A factorial design (9×5) with four replications was applied, and multiple germination indices were calculated. Data were analysed using a two-way ANOVA with genotype and treatment as main factors. Results indicated significant genotype-dependent responses. Amino 16 and Razormin markedly increased germination percentage, speed of emergence, and seedling vigour, achieving up to 100% germination in responsive genotypes such as ‘Ellagance Snow’ and ‘Blue Spear’. Correlation and clustering analyses revealed strong links between seed size, germination rate, and seedling development, suggesting a possible synergistic role of amino and humic substances in stimulating metabolic activation during germination. These findings demonstrate that eco-friendly biostimulants function as effective biotechnological activators of seed physiology, supporting low-input propagation systems and the transition toward a circular green bioeconomy.

Keywords: *Lavandula angustifolia*; eco-biotechnology; sustainable germination; biostimulant activators; amino acids; humic substances; genotype-dependent response; circular bioeconomy



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1. Introduction

Lavender (*Lavandula angustifolia* Mill.) is one of the most valuable aromatic and medicinal plants cultivated worldwide, appreciated for its multiple economic and therapeutic uses. Its essential oil represents a cornerstone of the global perfume, cosmetic,

and pharmaceutical industries [1–5], while its dried flowers and derivatives are widely employed in herbal remedies [6,7], food flavourings [8–10], and ornamental horticulture [11–13]. The commercial importance of lavender has grown substantially in recent decades due to the increasing demand for natural and organic products, stimulating the expansion of lavender farms across Europe, Asia, and other continents [14,15]. France and Bulgaria remain leading producers, but cultivation has also increased significantly in Central and Eastern Europe, including Romania, where lavender farming supports rural economies and contributes to the diversification of sustainable agricultural systems [16–18]. Recent advances in eco-biotechnology have emphasised the potential of natural plant biostimulants as bioactive molecular agents capable of modulating seed metabolism and improving propagation efficiency in aromatic and medicinal crops. These approaches align with sustainable horticultural practices and the global transition toward bio-based agricultural inputs.

From a medicinal perspective, *L. angustifolia* has been known for centuries for its calming, antiseptic, and digestive properties [19,20]. Modern pharmacological research has confirmed the biological activity of its main components, linalool and linalyl acetate, which exhibit anxiolytic, sedative, anti-inflammatory, and antimicrobial effects. Numerous studies have highlighted its efficacy in alleviating anxiety, sleep disorders, and certain neurological and dermatological conditions [20–23]. This dual role, as a high-value aromatic crop and a medicinal resource, reinforces lavender's significance as a strategic plant for both economic development and public health [14,16]. However, the growing demand for high-quality plant material necessitates the improvement of its propagation techniques, particularly for seed germination, which remains challenging [24,25].

Propagation of lavender can be achieved through vegetative methods such as cuttings or division, but sexual propagation via seeds remains essential for breeding programmes, genetic improvement, and the development of new cultivars suited to different ecological conditions [26,27]. Despite its biological importance, seed propagation of lavender is often limited by low germination rates, non-uniform emergence, and prolonged dormancy. Physiological seed dormancy, caused primarily by an impermeable seed coat and embryo immaturity, prevents adequate water and oxygen uptake, delaying or even inhibiting germination [28]. These constraints are aggravated by environmental factors such as temperature, moisture, and light, resulting in inconsistent or weak seedling establishment [29]. The low and uneven germination of lavender seeds poses a major obstacle for breeding programmes and commercial propagation, especially in organic or low-input systems where the use of synthetic growth regulators is restricted.

From a biotechnological perspective, optimising lavender seed germination through the application of environmentally friendly activators represents a sustainable and science-based approach consistent with the principles of green innovation and circular bioeconomy. Such eco-biotechnological interventions aim to stimulate the intrinsic metabolic potential of seeds without the ecological drawbacks associated with synthetic growth regulators.

In recent years, scientific research has focused on various pre-germination treatments designed to overcome these limitations. Techniques such as mechanical or chemical scarification, cold stratification, and hormonal priming have been successfully applied to break dormancy and enhance germination rates [30,31]. Amongst these, the use of plant biostimulants has gained particular attention as a promising and environmentally friendly solution [32,33]. Biostimulants are natural or synthetic compounds, including amino acids, humic and fulvic acids, seaweed extracts, and microbial inoculants, that promote physiological processes in plants, improving germination, root development, and stress tolerance without directly providing nutrients [34]. These substances act as metabolic enhancers,

stimulating enzymatic activity, antioxidant defence systems, and hormonal balance during the early stages of plant development [35,36].

In aromatic and medicinal plants, biostimulants have demonstrated significant benefits in improving germination efficiency, seedling vigour, and uniformity [34]. They can accelerate water uptake and metabolic activation of the embryo, shorten the germination period, and increase the percentage of viable seedlings [37]. Moreover, they contribute to a more synchronised emergence, which is crucial for the uniform growth of seedlings in commercial nurseries [38]. Amino acid-based formulations, humic substances, and seaweed extracts are particularly effective in mitigating oxidative stress and enhancing the energy metabolism of seeds [39,40]. These advantages align with the principles of sustainable agriculture, offering eco-friendly alternatives to chemical seed treatments and supporting the transition towards low-input production systems [41,42].

Despite the recognised importance of lavender as a high-value crop, few systematic studies have examined the effects of different biostimulant formulations on its germination behaviour under controlled laboratory conditions. Most previous research has focused on major crops or ornamental species, leaving a gap in knowledge regarding aromatic plants with complex physiological responses. Understanding how various biostimulants influence germination parameters in *L. angustifolia* is therefore essential for optimising nursery production and enhancing the genetic and physiological quality of planting material.

The present study aims to evaluate the effect of different biostimulant treatments on the germination of nine *Lavandula* genotypes under laboratory conditions. The genotypes, representing both traditional and modern cultivars, were selected for their agronomic and ornamental importance, genetic diversity, and adaptability to temperate environments. The biostimulant formulations tested (Germinoseed, Amino 16, Razormin, and Atonik) were compared to a distilled water control to assess their influence on multiple germination indices. By combining quantitative measurements with comparative analyses amongst genotypes and treatments, this research seeks to identify the most effective combinations for enhancing seed germination performance. Moreover, the integration of biostimulant treatments into lavender propagation aligns with the goals of green innovation and circular bioeconomy, emphasising efficiency, ecological compatibility, and the valorisation of natural resources. In this context, the present research provides a biotechnological framework for the genotype-specific optimisation of germination processes in *Lavandula angustifolia*, supporting the integration of eco-friendly biostimulants into reproducible and scalable propagation systems suitable for sustainable plant biotechnology applications.

2. Materials and Methods

2.1. Plant Material

The study was carried out using seeds from nine genotypes of *Lavandula angustifolia* Mill., selected for their agronomic, ornamental, and genetic diversity. The genotypes included ‘Munstead’, ‘Hidcote’, ‘Ellagance Purple’ (abbreviated hereinafter sometimes as ‘El Purple’), ‘Ellagance Snow’ (abbreviated hereinafter sometimes as ‘El Snow’), ‘Vera’, ‘Sevtopolis’, ‘Avignon’, ‘Blue Spear’, and ‘Purple Deep’. These varieties represent a wide geographical and phenotypic spectrum, ranging from compact ornamental types to highly productive industrial cultivars used for essential oil extraction. All seeds were obtained from certified commercial suppliers. The provenance of each cultivar, including the seed company and country of origin, is provided in Table A1. The studies were conducted within the seed warranty period indicated by the supplier. Each genotype was chosen for its adaptability to Central and Eastern European conditions and its relevance to lavender cultivation and breeding programmes.

2.2. Biostimulant Treatments

Five pre-germination treatments were tested, including a control (distilled sterile water, used as an untreated reference) and four commercial biostimulants (Germinoseed, Amino 16, Razormin, and Atonik), each differing in chemical composition and physiological effect. The selected formulations are commonly used to enhance seed metabolic activation and early seedling growth through natural or low-toxicity compounds. All treatments were applied in liquid form, and the dilution of each biostimulant was carried out according to the manufacturer's specifications to ensure treatment comparability. Detailed information on the manufacturer, country of origin, and product reference is provided in Table A2.

Prior to sowing, seeds were soaked in each treatment solution for 12 h at room temperature. The control group was soaked in distilled sterile water under identical conditions. All solutions were freshly prepared to prevent degradation of active compounds and to ensure consistency between treatments.

2.3. Germination Conditions and Experimental Design

Germination tests were conducted under controlled laboratory conditions following ISTA rules [43], with four replicates of 100 seeds for each treatment, using a factorial design (9 genotypes $\times$ 5 treatments).

All experiments were carried out under controlled eco-biotechnological laboratory conditions, ensuring biosafety, reproducibility, and uniform environmental parameters. The setup minimised external variability, allowing precise assessment of genotype–treatment interactions and the biostimulant-driven modulation of germination physiology.

Sterilised Petri dishes (9 cm diameter) were used, each containing a double-layer filter paper moistened with 5 mL of the respective treatment solution. The incubation parameters were as follows: temperature: 22 ± 1 °C; relative humidity: 65–70%; photoperiod: 16 h light/8 h dark. Petri dishes were covered with transparent lids to prevent evaporation and contamination, and were inspected daily. The treatment solutions were reapplied every five days, uniformly to all germination samples, following the established protocol.

A seed was considered germinated when the radicle reached at least 2 mm in length. Germination counts were recorded daily by the same operator to ensure consistency and to reduce subjective variation. On day 21 after the start of germination, plant length, comprising both root (radicle) and stem length, was measured, and data from the four replications were collected and subsequently processed statistically.

Strict laboratory hygiene protocols were maintained throughout the experiment. All glassware and materials were sterilised before use, and seed batches were surface-disinfected in 1% sodium hypochlorite for 5 min, followed by multiple rinses in sterile distilled water.

2.4. Germination Indices and Data Collection

The daily germination data were used to evaluate the progression of seed germination in relation to cultivar and biostimulant treatment and to calculate various germination indices describing the rate and uniformity of the process. Therefore, to obtain a comprehensive overview of the germination process, the following indices were calculated: germination percentage (GP), germination index (GI), speed of emergence (SE), coefficient of velocity of germination (CVG), and seedling vigour index (SVI). The formulas and corresponding references used for these calculations [43–47] are provided in Table A3.

2.5. Statistical Analysis

Statistical analyses were performed using the analysis of variance (ANOVA) approach (PAST software, version 4.17), depending on the structure of each dataset. For seed mor-

phological traits (seed length), differences between cultivars were assessed using a one-way ANOVA, followed by Duncan's Multiple Range Test (MRT) for post hoc mean comparisons at $p < 0.05$. For germination parameters and seedling traits (root and stem length), a two-way factorial ANOVA was applied to evaluate the effects of genotype (G), treatment (T), and their interaction ($G \times T$). Significant effects were further separated using Duncan's MRT ($p < 0.05$). Results are expressed as mean values $\pm$ standard error (SEM). Prior to analysis, data were checked for normality and homogeneity of variances. Multivariate analyses were also performed to identify biotechnological response patterns across genotypes and treatments, revealing potential synergies between biostimulant composition and seed physiological behaviour. This integrative approach allowed a comprehensive interpretation of germination variability from a biotechnological perspective.

Before performing multivariate analyses, all variables were normalised (z-scores) to minimise scale effects among parameters and to ensure comparability across genotypes and treatments. Subsequently, hierarchical clustering (UPGMA) based on Euclidean distance and Pearson's correlation coefficients was computed using PAST software, version 4.17 [48].

3. Results

The mean seed length varied significantly within the nine *Lavandula* cultivars (Figure 1). The largest seeds were recorded for the cultivar 'Sevtopolis', which did not differ significantly from 'Ellagance Snow' according to Duncan's Multiple Range Test ($p < 0.05$). The remaining cultivars exhibited intermediate or smaller seed sizes, forming partially overlapping homogeneous groups. For example, 'Blue Spear' and 'Vera' generally showed above-average seed lengths, whereas 'Avignon', 'Munstead', and 'Purple Deep' tended towards lower mean values. The observed variation in seed size reflects the genetic and morphological diversity between cultivars, which may influence water uptake capacity, metabolic activation, and subsequent germination performance.

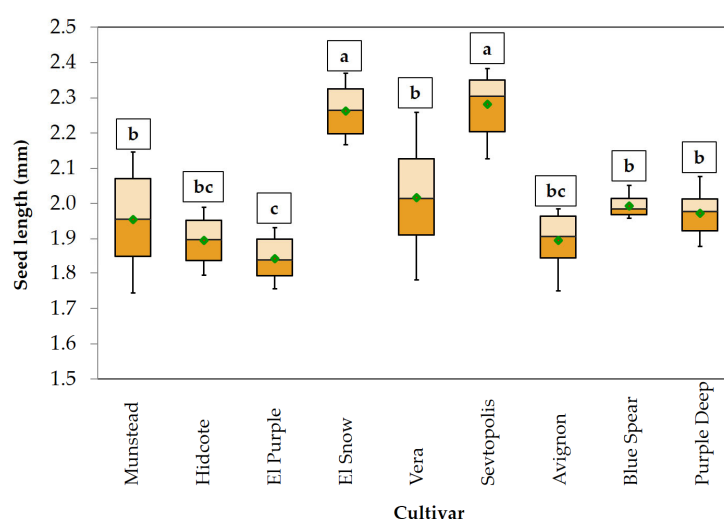


Figure 1. Boxplot of seed length (mm) for nine *Lavandula* cultivars. Significant differences ($p < 0.05$) between mean values (represented by green diamonds), as determined by Duncan's Multiple Range Test, are indicated by different letters.

The cumulative germination curves revealed distinct temporal dynamics for the nine *Lavandula* cultivars and across biostimulant treatments (Figure 2). In all genotypes, germination began within the first four days after sowing and reached a plateau between days 10 and 14. The control (distilled water) generally exhibited a slower onset and lower final germination percentages compared with the treated variants.

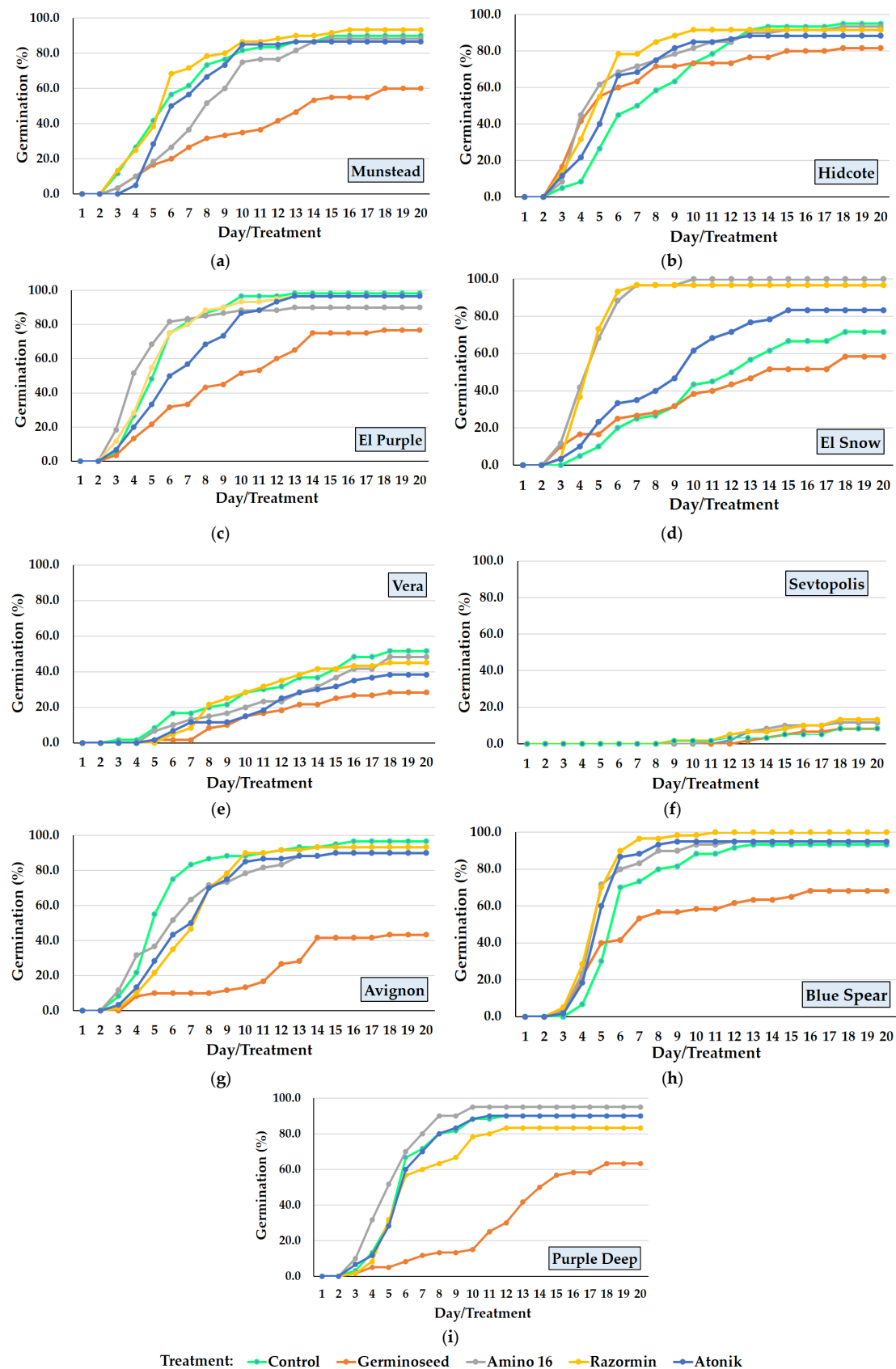


Figure 2. Germination dynamics in nine *Lavandula* cultivars under different biostimulant treatments compared to the control (distilled water): (a) 'Munstead', (b) 'Hidcote', (c) 'Ellagance Purple', (d) 'Ellagance Snow', (e) 'Vera', (f) 'Sevtopolis', (g) 'Avignon', (h) 'Blue Spear', and (i) 'Purple Deep'.

Amongst the tested formulations, Amino 16 and Razormin most effectively accelerated germination and increased final percentages in several cultivars, particularly in ‘Ellagance Snow’, ‘Ellagance Purple’, and ‘Blue Spear’. By contrast, the Germinoseed treatment generally tracked below the other curves (and often below the control), indicating a comparatively weaker stimulatory effect on seed metabolic activation, while Atonik mainly enhanced the early phase with limited effects on final percentages. The cultivar ‘Sevtopolis’ consistently maintained the lowest germination levels under all treatments, indicating a weaker physiological responsiveness. Notably, the Germinoseed treatment produced lower cumulative germination curves across most cultivars, indicating a comparatively weaker stimulatory effect on seed metabolic activation.

Overall, both genotype and biostimulant treatment significantly influenced the germination dynamics, with the eco-friendly formulations leading to faster and more synchronised seed emergence compared to the untreated control.

Significant variation in germination percentage was observed between cultivars, treatments, and their interaction (Table 1). The highest germination rates were recorded for ‘Ellagance Snow’, ‘Blue Spear’, and ‘El Purple’ when treated with Amino 16 or Razormin, where mean germination percentages approached or reached 100%. Similarly, high values were obtained in several cultivars, including ‘Hidcote’, ‘Munstead’, and ‘Avignon’, particularly under Amino 16 and Razormin.

Table 1. Germination percentage (%; mean $\pm$ SEM) of nine *Lavandula* cultivars under different biostimulant treatments. Means followed by different letters differ significantly at $p < 0.05$ (Duncan’s MRT).

No.	Cultivar	Treatment (Biostimulants)				
		Control	Germinoseed	Amino 16	Razormin	Atonik
1	‘Munstead’	90.0 $\pm$ 10.6 m–o	60.0 $\pm$ 8.4 gh	88.3 $\pm$ 8.5 l–n	93.3 $\pm$ 11.5 n–q	86.7 $\pm$ 8.5 k–m
2	‘Hidcote’	95.0 $\pm$ 11.8 o–r	81.7 $\pm$ 7.5 k	93.3 $\pm$ 9.8 n–q	91.7 $\pm$ 10.9 m–p	88.3 $\pm$ 8.8 l–n
3	‘El Purple’	98.3 $\pm$ 12.5 qr	76.7 $\pm$ 8.2 j	90.3 $\pm$ 10.7 m–o	96.7 $\pm$ 11.5 p–r	96.7 $\pm$ 12.1 p–r
4	‘El Snow’	71.7 $\pm$ 8.7 i	58.3 $\pm$ 6.7 g	100.0 $\pm$ 12.8 r	96.7 $\pm$ 10.2 p–r	83.3 $\pm$ 8.5 kl
5	‘Vera’	51.7 $\pm$ 8.5 f	28.3 $\pm$ 3.3 b	48.3 $\pm$ 6.7 ef	45.0 $\pm$ 5.6 de	38.3 $\pm$ 5.5 c
6	‘Sevtopolis’	11.7 $\pm$ 2.4 a	8.3 $\pm$ 2.9 a	11.7 $\pm$ 2.4 a	13.3 $\pm$ 4.2 a	8.3 $\pm$ 2.9 a
7	‘Avignon’	96.7 $\pm$ 10.9 p–r	43.3 $\pm$ 4.6 d	90.0 $\pm$ 10.8 m–o	93.3 $\pm$ 10.5 n–q	90.0 $\pm$ 9.3 m–o
8	‘Blue Spear’	93.3 $\pm$ 11.1 n–q	68.8 $\pm$ 8.6 i	95.0 $\pm$ 11.6 o–r	100.0 $\pm$ 12.1 r	95.0 $\pm$ 9.6 o–r
9	‘Purple Deep’	90.0 $\pm$ 10.4 m–o	63.3 $\pm$ 7.5 h	95.0 $\pm$ 10.4 o–r	83.3 $\pm$ 8.5 kl	90.0 $\pm$ 10.3 m–o

In contrast, ‘Sevtopolis’ exhibited very low germination in all treatments, remaining below 15%, while ‘Vera’ showed moderate but significantly reduced values compared with the other cultivars. Amongst the biostimulants tested, Amino 16 and Razormin resulted in the highest overall germination percentages across genotypes, followed by Atonik and Germinoseed, whereas the control consistently produced lower germination levels.

According to Duncan’s multiple range test, differences amongst cultivars and treatments were statistically significant, confirming that both genetic background and biostimulant formulation strongly influenced germination performance.

The analysis of the main effects (Figure 3a,b) revealed significant variation in germination percentage between cultivars and biostimulant treatments.

When averaged across treatments (Figure 3a), the cultivars ‘Ellagance Purple’, ‘Hidcote’, and ‘Blue Spear’ achieved the highest germination percentages, all exceeding 90%, and formed a statistically homogeneous group ($p < 0.05$). ‘Purple Deep’, ‘Munstead’, ‘Avignon’ and ‘Ellagance Snow’ displayed intermediate germination, while ‘Vera’ and particularly ‘Sevtopolis’ recorded the lowest mean values, confirming pronounced genotype-dependent variability in germination behaviour.

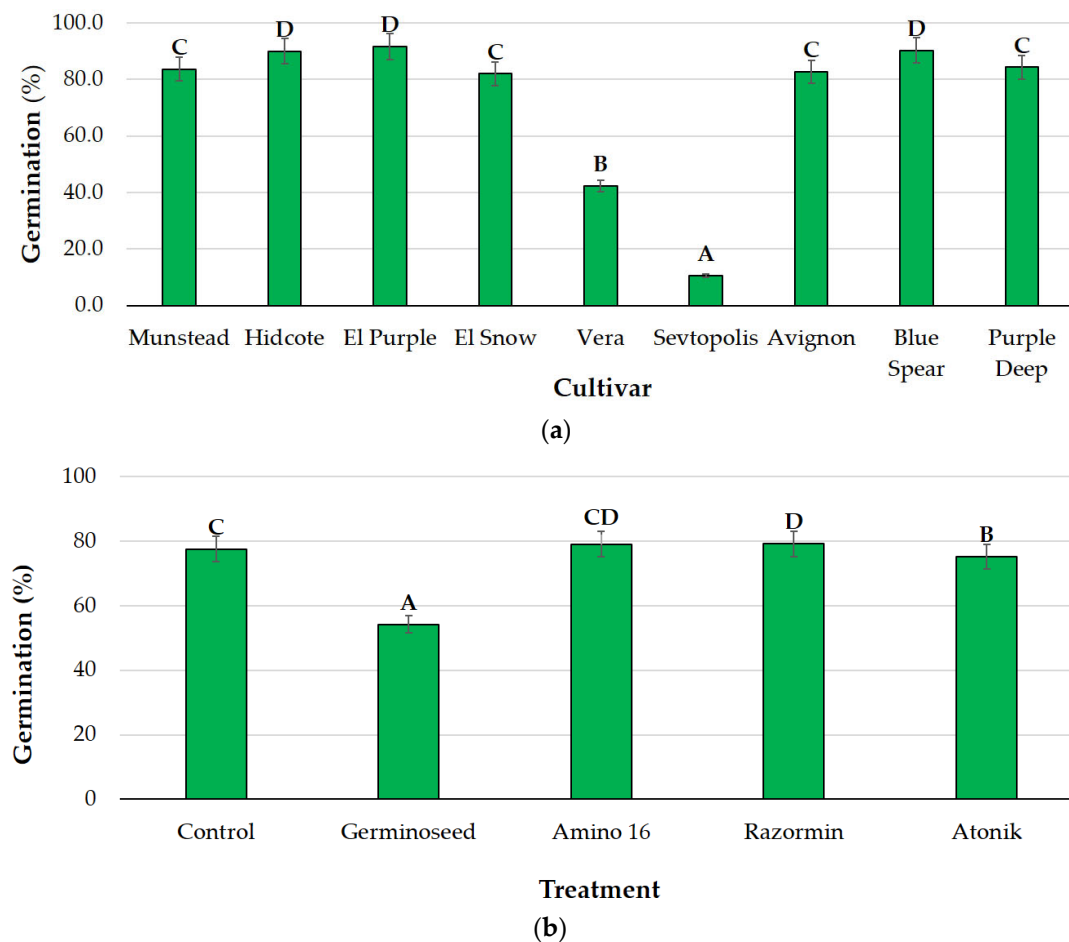


Figure 3. Main effects of *Lavandula* cultivar (a) and biostimulant treatment (b) on seed germination percentage (mean $\pm$ SEM). Different letters indicate significant differences at $p < 0.05$ (Duncan's MRT).

Across treatments (Figure 3b), Razormin produced the highest mean germination percentage, significantly exceeding the control and the other formulations, except Amino 16 ($p < 0.05$). Amino 16 showed a similar trend but did not differ significantly from the control according to Duncan's test. Atonik yielded intermediate values, while Germinoseed exhibited more variable effects depending on genotype.

These results demonstrate that both genetic background and biostimulant composition exerted significant and complementary influences on germination performance in *L. angustifolia*, reflecting the combined impact of intrinsic seed physiology and external metabolic stimulation.

The germination indices varied across cultivars and biostimulant treatments (Table 2), revealing coherent patterns with the percentage data. In several responsive cultivars, Amino 16 and Razormin were associated with higher GI and SE values relative to the control, indicating faster germination dynamics, whereas SVI generally mirrored these improvements at the seedling stage. By contrast, CVG values reflected differences in synchronisation, with more favourable (lower) variability aligning with treatments that also displayed higher GI and SE. Genotype effects remained evident across indices, with 'Sevtopolis' consistently at the lower end of the distributions and 'Ellagance Snow', 'Ellagance Purple', and 'Blue Spear' tending to rank amongst the better-performing groups under amino acid- and humic-based formulations. Overall, the index profiles support the conclusion that treatment efficacy is genotype-dependent and that improvements in germination dynamics are coupled with early seedling vigour.

Table 2. Main germination indices (GP, GI, SE, CVG, and SVI) of nine *Lavandula* cultivars under different biostimulant treatments.

No.	Treatment/ Provenance	Germination Indices				
		GP	GI	SE	CVG	SVI
Control (no treatment)						
1	‘Munstead’	90.0	10.1	2.7	6.4	12.0
2	‘Hidcote’	95.0	8.6	2.9	7.9	15.0
3	‘El Purple’	98.3	11.2	3.0	5.9	10.0
4	‘El Snow’	71.7	5.2	2.2	10.0	14.0
5	‘Vera’	51.7	3.7	1.6	10.5	15.0
6	‘Sevtopolis’	11.7	0.5	0.4	14.3	6.0
7	‘Avignon’	96.7	11.1	2.9	6.0	13.0
8	‘Blue Spear’	93.3	9.3	2.8	6.5	9.0
9	‘Purple Deep’	90.0	9.5	2.7	6.2	9.0
Germinoseed						
1	‘Munstead’	60.0	5.1	1.8	9.3	15.0
2	‘Hidcote’	81.7	10.5	2.5	5.8	15.0
3	‘El Purple’	76.7	6.7	2.3	8.6	15.0
4	‘El Snow’	58.3	5.6	1.8	8.9	15.0
5	‘Vera’	28.3	1.7	0.9	11.1	13.0
6	‘Sevtopolis’	8.3	0.3	0.3	15.2	5.0
7	‘Avignon’	43.3	3.1	1.3	10.8	14.0
8	‘Blue Spear’	68.3	7.5	2.1	6.6	13.0
9	‘Purple Deep’	63.3	3.9	1.9	11.8	15.0
Amino 16						
1	‘Munstead’	88.3	7.5	2.7	8.2	12.0
2	‘Hidcote’	93.3	11.3	2.8	6.1	15.0
3	‘El Purple’	90.0	12.6	2.7	4.8	10.0
4	‘El Snow’	100.0	13.0	3.0	5.0	7.0
5	‘Vera’	48.3	3.0	1.5	11.6	13.0
6	‘Sevtopolis’	11.7	0.5	0.4	13.6	7.0
7	‘Avignon’	90.0	10.0	2.7	6.6	12.0
8	‘Blue Spear’	95.0	11.4	2.9	5.4	9.0
9	‘Purple Deep’	95.0	11.4	2.9	5.5	7.0
Razormin						
1	‘Munstead’	93.3	10.6	2.8	6.3	13.0
2	‘Hidcote’	91.7	11.5	2.8	5.3	7.0
3	‘El Purple’	96.7	11.6	2.9	5.7	10.0
4	‘El Snow’	96.7	12.4	2.9	4.9	4.0
5	‘Vera’	45.0	3.0	1.4	9.9	12.0
6	‘Sevtopolis’	13.3	0.6	0.4	14.1	9.0
7	‘Avignon’	93.3	8.5	2.8	7.3	11.0
8	‘Blue Spear’	100.0	12.3	3.0	5.2	8.0
9	‘Purple Deep’	83.3	8.4	2.5	6.6	9.0
Atonik						
1	‘Munstead’	86.7	8.3	2.6	6.8	9.0
2	‘Hidcote’	88.3	10.2	2.7	6.0	10.0
3	‘El Purple’	96.7	9.7	2.9	7.0	10.0
4	‘El Snow’	83.3	7.2	2.5	8.4	12.0
5	‘Vera’	38.3	2.4	1.2	11.1	13.0
6	‘Sevtopolis’	8.3	0.4	0.3	14.4	9.0
7	‘Avignon’	90.0	8.7	2.7	7.0	12.0
8	‘Blue Spear’	95.0	11.1	2.9	5.3	6.0
9	‘Purple Deep’	90.0	9.5	2.7	6.2	8.0

GP—germination percentage, GI—germination index, SE—speed of emergence, CVG—coefficient of velocity of germination, SVI—seedling vigour index.

The mean root length of seedlings varied significantly depending on the applied treatment (Figure 4). Across all cultivars, the control exhibited the longest roots, averaging over 20 mm, followed by Amino 16 and Razormin, which produced roots of approximately 10 mm. In contrast, Germinoseed resulted in the shortest roots, averaging around 5 mm across most cultivars, while ‘Vera’ and ‘Sevtopolis’ consistently showed the lowest overall values regardless of treatment. According to Duncan’s multiple range test, differences among treatments were statistically significant ($p < 0.05$), confirming that the biostimulant formulation exerted a marked influence on root growth during the early germination phase.

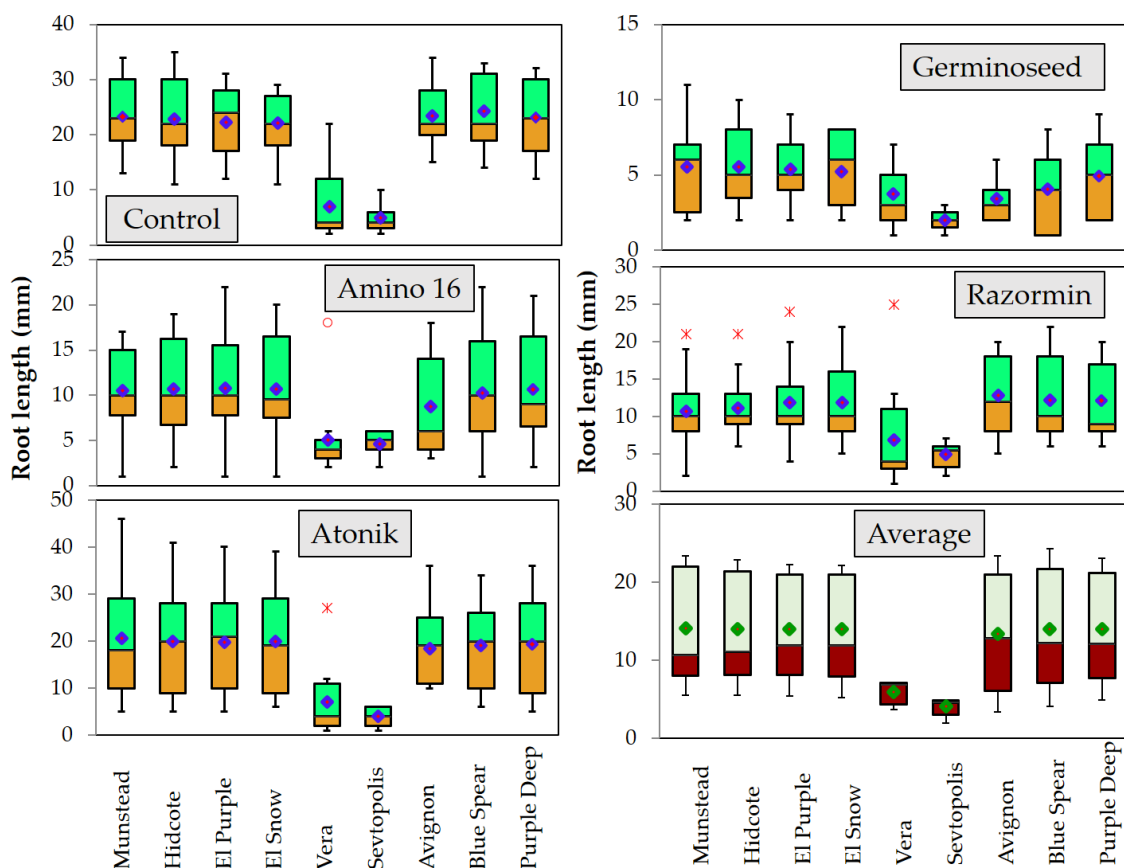


Figure 4. Average root length (mm) of *Lavandula* seedlings under control and biostimulant treatments (Germinoseed, Amino 16, Razormin, and Atonik). Box plots display the median (line), mean (♦), and outliers beyond $1.5 \times \text{IQR}$ represented by $\times$ and $\circ$ symbols.

The average stem length of lavender seedlings was significantly affected by the applied biostimulant treatments (Figure 5). Similar to root development, the formulations Amino 16 and Razormin induced the most pronounced increase in stem elongation compared to the control, with statistically significant differences at $p < 0.05$. Atonik also stimulated shoot growth, though to a lesser extent, while Germinoseed produced variable results depending on the cultivar.

Across genotypes, the cultivars ‘El Purple’, ‘El Snow’, and ‘Blue Spear’ exhibited the highest mean stem lengths under Amino 16 and Razormin treatments, whereas ‘Vera’ and ‘Sevtopolis’ maintained significantly shorter stems regardless of treatment. The control variant consistently resulted in reduced shoot elongation across all cultivars.

Duncan’s multiple range test confirmed significant differences amongst treatments ($p < 0.05$), demonstrating that biostimulant application markedly enhanced shoot growth during early seedling development.

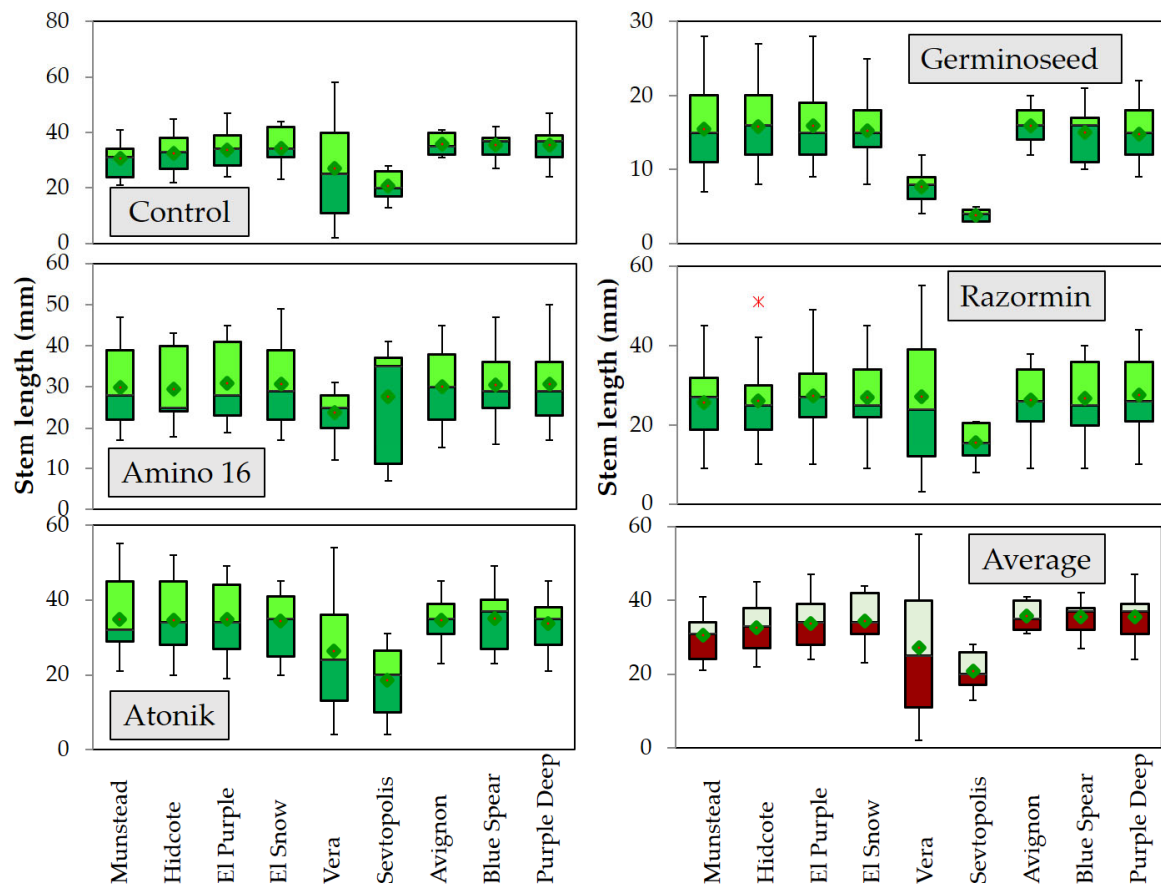


Figure 5. Average stem length (mm) of *Lavandula* seedlings under control and biostimulant treatments (Germinoseed, Amino 16, Razormin, and Atonik). Box plots display the median (line), mean (♦), and outlier beyond $1.5 \times \text{IQR}$ represented by $\times$ symbol.

The hierarchical clustering (UPGMA) clearly separated the nine cultivars into distinct groups (Figure 6a). The first division isolates ‘Vera’ and ‘Sevtopolis’ from all other genotypes. At higher resolution, ‘Vera’ and ‘Sevtopolis’ each form their own clusters, while ‘Ellagance Snow’ also appears as a separate group. The remaining cultivars are arranged into two clusters: (I) ‘Avignon’, ‘Blue Spear’, and ‘Purple Deep’; and (II) ‘Ellagance Purple’, ‘Hidcote’, and ‘Munstead’. This structure highlights reduced germination efficiency and seedling vigour in ‘Sevtopolis’ and ‘Vera’ compared with the other genotypes, with ‘Ellagance Snow’ occupying an intermediate position and the two multi-cultivar clusters showing relatively similar, higher-performing profiles under most treatments.

The comparative assessment of germination indices (GP, GI, SE, CVG, and SVI) across cultivars and biostimulant treatments (Figure 6b) confirmed the clustering trends observed in Figure 6a. Amino 16 and Razormin produced the highest overall values, indicating faster and more synchronised germination, whereas Germinoseed and Atonik displayed moderate or variable responses depending on genotype. The SVI values closely reflected these differences, confirming that improved germination translated into higher seedling vigour. Variation in CVG values corresponded to differences in synchronisation amongst treatments, with more favourable germination uniformity under the amino acid- and humic-based formulations. These results illustrate that treatment efficacy was strongly genotype-dependent, reinforcing the multivariate grouping patterns observed in the clustering analysis.

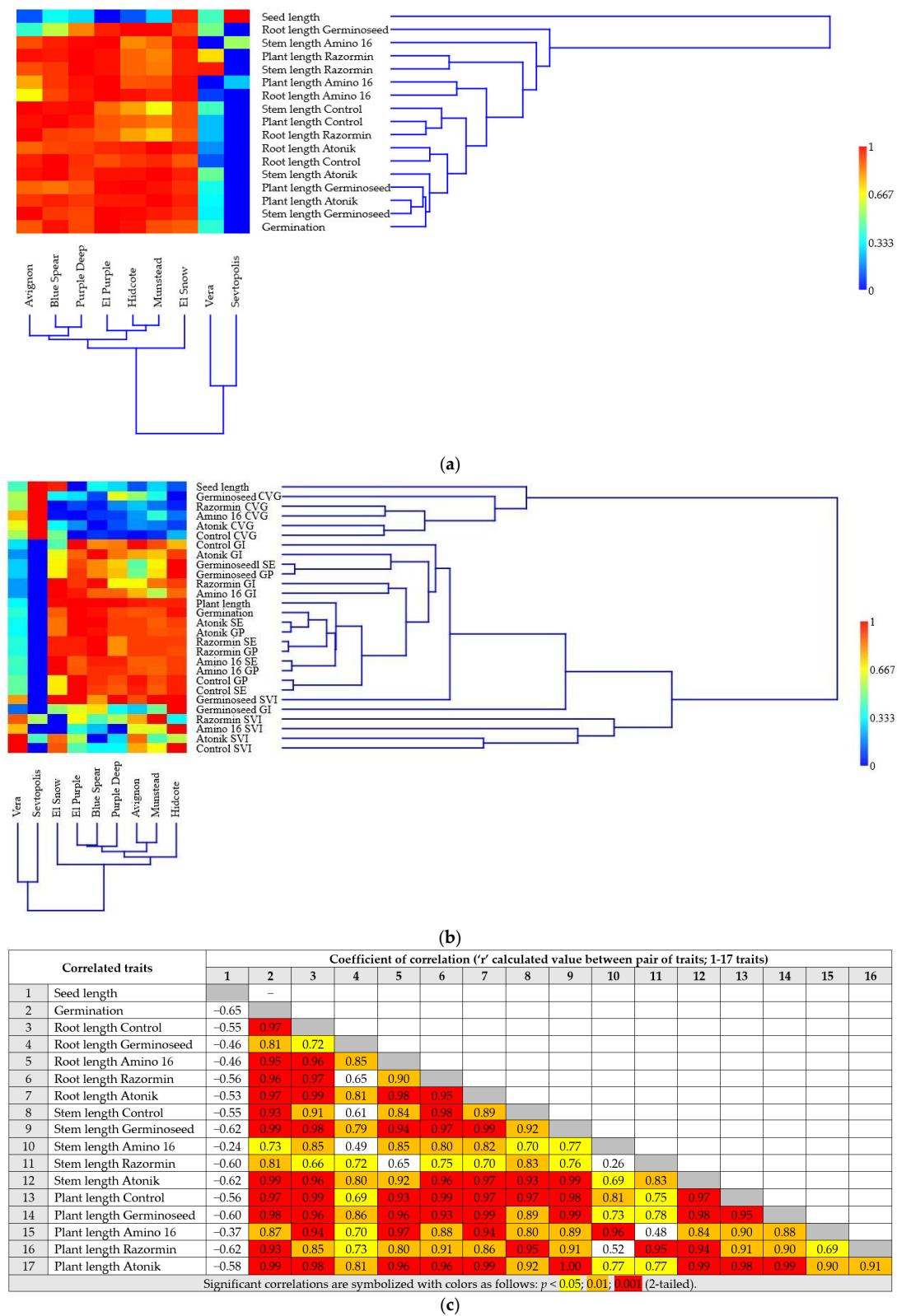


Figure 6. Hierarchical clustering (UPGMA) based on Euclidean similarity index of the nine *L. angustifolia* cultivars according to seed and seedling traits depending on: (a) biostimulant treatments; (b) germination indices due biostimulant treatments (GP—germination percentage; GI—germination index; SE—speed of emergence; CVG—coefficient of velocity of germination; SVI—seedling vigour index). (c) Relationships between seed morphology, germination success, and seedling growth under different treatments (Pearson’s phenotypic correlations, r) across nine cultivars.

The correlation matrix (Figure 6c) shows the relationships between seed morphology, germination success, and early seedling growth parameters across the nine *Lavandula* cultivars. Correlation analysis revealed a negative association between seed length, germination percentage, and seedling size, in some cases close to the threshold of statistical significance ($p \approx 0.05$). This pattern suggests that larger seeds tended to show lower germination efficiency and smaller seedlings during the early stage. By contrast, strong positive correlations were observed between germination percentage, root length, and stem length, suggesting that higher germination efficiency was directly associated with enhanced early growth. The colour scheme and label contrast ensure full readability of r -values across the entire matrix.

Overall, the multivariate patterns confirm that the effects of biostimulant treatments on germination and early growth are strongly shaped by the physiological characteristics of each genotype.

4. Discussion

The results of this study demonstrate that the germination performance of *Lavandula angustifolia* seeds is strongly influenced by both the genotype and the type of biostimulant applied. The observed differences amongst cultivars and treatments indicate complex genotype–treatment interactions, reflecting intrinsic physiological variability as well as the specific biochemical effects of the tested biostimulants. In general, the use of eco-friendly formulations such as Amino 16 and Razormin significantly enhanced germination parameters, root and shoot elongation, and overall seedling vigour compared with the untreated control. These findings confirm that the application of natural or low-toxicity biostimulants can effectively stimulate early plant development, consistent with previous studies reporting the benefits of amino acid and humic acid-based treatments on seed germination and vigour enhancement in medicinal and aromatic plants [49–51].

Amino acid-based products, such as Amino 16, likely exert their effect by improving nitrogen assimilation and protein synthesis during the initial stages of germination. Amino acids serve as metabolic precursors for enzymes and hormones that regulate cellular expansion, respiration, and energy transfer, accelerating radicle protrusion and uniform seedling emergence [52]. Humic and fulvic acids, the main constituents of Razormin, are known to activate membrane permeability, enhance nutrient uptake, and stimulate auxin-like activity, which collectively favour rapid cell elongation and root growth [50,53,54]. These physiological mechanisms may explain the consistently higher germination percentages and vigour indices observed under Amino 16 and Razormin treatments across most cultivars. Similar stimulatory effects have been documented in other aromatic species, confirming the broad efficacy of these substances in improving germination efficiency and early seedling establishment [37,55].

In contrast, the modest or inconsistent results obtained with Germinoseed and Atonik suggest that their biochemical modes of action were less suited to the specific metabolic requirements of *Lavandula* seeds. This stands in contrast to the mode of action of nitrophenolate-based biostimulants (e.g., Atonik), which act as metabolic accelerators with often transient effects that are highly dependent on precise concentration and timing of application [56,57]. Similarly, the phytohormone-rich extract in Germinoseed may have triggered unbalanced hormonal responses that did not uniformly enhance germination across all genotypes. These results highlight the importance of adjusting biostimulant composition and dosage to the physiological characteristics of the target species, particularly in plants exhibiting variable dormancy and slow metabolic activation [58].

The hierarchical clustering analysis provided an integrative view of cultivar relationships based on multiple germination and seedling traits. The grouping of ‘Ellagance Purple’, ‘Ellagance Snow’, and ‘Blue Spear’ into the same cluster reflects their shared

high responsiveness to amino acid- and humic-based formulations, suggesting similar metabolic regulation pathways during germination. The intermediate cluster containing ‘Munstead’, ‘Hidcote’, and ‘Avignon’ indicates stable but moderate adaptability to biostimulant treatments, consistent with their traditional selection for field hardiness rather than rapid seedling emergence. Conversely, the distinct separation of ‘Vera’ and especially ‘Sevtopolis’ corresponds to their persistently low germination percentages and vigour indices, pointing to limited enzymatic activity or stronger dormancy barriers that were not sufficiently alleviated by the tested treatments. These genotype-dependent responses are consistent with earlier observations that germination is controlled by both genetic and environmental factors, including seed coat structure, endogenous inhibitors, and differences in membrane permeability [59–65].

From a physiological perspective, the improved germination rates under Amino 16 and Razormin may be attributed to enhanced activation of hydrolytic enzymes such as amylases and proteases, increased oxygen diffusion, and accelerated mobilisation of storage reserves [66–68]. The resulting improvement in seedling vigour likely reflects a higher rate of cell division and elongation, as indicated by the greater root and shoot lengths recorded in these treatments. The strong correlation observed between germination indices and seedling length parameters further supports the hypothesis that biostimulant-induced metabolic activation during the early germination phase translates directly into improved seedling performance [69–71].

Beyond their physiological effects, the present results have practical implications for lavender propagation and breeding. The use of biostimulant treatments represents an environmentally safe alternative to synthetic plant growth regulators, aligning with the goals of sustainable and organic agriculture [40,72–74]. By improving germination uniformity and vigour, these formulations can facilitate more efficient seedling production in nurseries and reduce the need for vegetative propagation [35,41,75]. Moreover, the identification of cultivars with high responsiveness to specific biostimulants, such as ‘El Purple’ and ‘El Snow’, can guide future selection programmes aimed at developing genotypes better adapted to eco-friendly cultivation systems [73,76,77].

Overall, the results of the multivariate and clustering analyses confirm that eco-friendly biostimulant treatments can substantially improve the germination efficiency of *L. angustifolia* while revealing clear genotype-specific patterns of responsiveness. These findings emphasise the need for tailored biostimulant strategies based on cultivar physiology and biochemical compatibility. In a broader context, this research contributes to understanding how natural growth-promoting substances can enhance the early developmental stages of aromatic plants, providing a foundation for future studies on biochemical mechanisms, seed metabolomics, and gene expression associated with germination enhancement.

5. Conclusions

This study provides experimental evidence that eco-friendly biostimulant formulations can significantly enhance the germination efficiency and early seedling growth of *Lavandula angustifolia* under controlled conditions. Amongst the tested treatments, Amino 16 and Razormin consistently produced the most favourable results across multiple germination indices, reflecting their ability to activate physiological and biochemical processes essential for rapid and uniform germination. The observed variation amongst cultivars highlights a clear genotype-dependent response, suggesting that biostimulant efficacy is strongly influenced by genetic background and metabolic adaptability.

The integration of biostimulant treatments into lavender propagation protocols represents a sustainable and biotechnology-oriented approach that reduces the need for synthetic growth regulators while improving propagation success in organic or low-input systems.

The clustering analysis further supports the potential for genotype-specific optimisation of biostimulant use, offering practical insights for breeding and nursery management.

From a broader biotechnological perspective, these results underscore the value of natural stimulants as regulators of seed metabolism and early morphogenesis, pointing to their role as eco-compatible bioactivators in aromatic plant cultivation. Future studies combining physiological assays with transcriptomic or metabolomic profiling could elucidate the molecular pathways through which amino acid- and humic acid-based biostimulants modulate germination and early seedling development in *Lavandula* and related species.

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Appendix A

Table A1. List of cultivars and seed sources used in the germination tests.

No.	Cultivar	Country of Origin	Seed Company	Example of Seeds Used in the Study, Purchased from Retail Sources
1	‘Munstead’	Germany	Benary	
2	‘Hidcote’	Germany	Benary	
3	‘El Purple’	Netherlands	PanAmerican Seed	
4	‘El Snow’	Netherlands	PanAmerican Seed	
5	‘Vera’	Netherlands	PanAmerican Seed	
6	‘Sevtopolis’	Netherlands	PanAmerican Seed	
7	‘Avignon’	Netherlands	PanAmerican Seed	
8	‘Blue Spear’	Netherlands	PanAmerican Seed	
9	‘Purple Deep’	Netherlands	PanAmerican Seed	

Table A2. Biostimulants and their sources used in the germination tests.

No.	Commercial Name	Main Active Ingredients/Composition	Formulation Type	Manufacturer	Country	Dilution Rate/Application
1	Germinoseed	Plant extracts rich in natural phytohormones and amino acids	Liquid	Norofert Group	Romania	As per manufacturer's specifications
2	Amino 16	16 free and combined amino acids (13.7% total amino acids)	Liquid	EVYP Crop Biostimulation Technologies	Greece	
3	Razormin	Humic and fulvic acids, macro- and microelements, plant extracts	Liquid	Atlántica Agrícola	Spain	
4	Atonik	Sodium para-nitrophenolate, sodium ortho-nitrophenolate	Liquid	Asahi Chemical Co., Ltd.	Japan	

Table A3. List of germination indices used in the germination tests: formulas and reference.

Index Name (Abbreviation)	Formula and Explanation	Reference
Final Germination Percentage (GP)	$GP = \frac{N_f}{N_t}$ where N_f is the final number of germinated seeds and N_t is the total number of seeds tested.	ISTA, 2022 [43]
Germination Index (GI)	$GI = \sum \frac{G_t}{D_t}$ where G_t is the number of seeds germinated on day t , and D_t is the number of days from sowing.	Maguire, 1962 [45]
Speed of Emergence (SE)	$SE = \frac{N_1}{1} + \frac{N_2}{2} + \frac{N_3}{3} + \dots$ where $N_1, N_2, N_3, \dots$ are the numbers of seeds that emerged on day 1, 2, 3, ... respectively. This is conceptually identical to the Germination Index but is often used specifically for seedling emergence tests.	Maguire, 1962 [45]
Coefficient of Velocity of Germination (CVG)	$CVG = \frac{\sum N_n}{\sum (D_n \times N_n)} \times 100$ where N_n is the number of seeds germinated on day D_n .	Ruan et al., 2002 [46]
Seedling Vigour Index (SVI)	$SVI = GP \times S_l$ where GP is the Final Germination Percentage (i.e., as a decimal, could be 0.9 for 90%) and S_l is the mean seedling length (root + shoot) or mean seedling dry weight.	Abdul-Baki and Anderson, 1973 [47]

References

- Lim, T.K. *Lavandula angustifolia*. In *Edible Medicinal and Non Medicinal Plants: Volume 8, Flowers*; Lim, T.K., Ed.; Springer: Dordrecht, The Netherlands, 2014; pp. 156–185.
- Betlej, I.; Andres, B.; Cebulak, T.; Kapusta, I.; Balawejder, M.; Jaworski, S.; Lange, A.; Kutwin, M.; Pisulewska, E.; Kidacka, A.; et al. Antimicrobial Properties and Assessment of the Content of Bioactive Compounds *Lavandula angustifolia* Mill. Cultivated in Southern Poland. *Molecules* **2023**, *28*, 6416. [\[CrossRef\]](#)
- Aprotosoiaie, A.C.; Gille, E.; Trifan, A.; Luca, V.S.; Miron, A. Essential oils of *Lavandula* genus: A systematic review of their chemistry. *Phytochem. Rev.* **2017**, *16*, 761–799. [\[CrossRef\]](#)
- Woronuk, G.; Demissie, Z.; Rheault, M.; Mahmoud, S. Biosynthesis and therapeutic properties of *Lavandula* essential oil constituents. *Planta Medica* **2011**, *77*, 7–15. [\[CrossRef\]](#)
- Wells, R.; Truong, F.; Adal, A.M.; Sarker, L.S.; Mahmoud, S.S. *Lavandula* Essential Oils: A Current Review of Applications in Medicinal, Food, and Cosmetic Industries of Lavender. *Nat. Prod. Commun.* **2018**, *13*, 1403–1417. [\[CrossRef\]](#)
- Salehi, B.; Mnayer, D.; Özçelik, B.; Altin, G.; Kasapoğlu, K.N.; Daskaya-Dikmen, C.; Sharifi-Rad, M.; Selamoglu, Z.; Acharya, K.; Sen, S.; et al. Plants of the Genus *Lavandula*: From Farm to Pharmacy. *Nat. Prod. Commun.* **2018**, *13*, 1385–1402. [\[CrossRef\]](#)
- Prusinowska, R.; Smigielski, K.B. Composition, biological properties and therapeutic effects of lavender (*Lavandula angustifolia* L.). A review. *Herba Pol.* **2014**, *60*, 56–66. [\[CrossRef\]](#)
- Da Porto, C.; Decorti, D.; Kikic, I. Flavour compounds of *Lavandula angustifolia* L. to use in food manufacturing: Comparison of three different extraction methods. *Food Chem.* **2009**, *112*, 1072–1078. [\[CrossRef\]](#)
- Erland, L.A.E.; Mahmoud, S.S. Chapter 57—Lavender (*Lavandula angustifolia*) Oils. In *Essential Oils in Food Preservation, Flavor and Safety*; Preedy, V.R., Ed.; Academic Press: San Diego, CA, USA, 2016; pp. 501–508.
- Petruț, G.; Muste, S.; Mureșan, C.; Mureșan, A.E.; Vlaic, R.; Chiș, S.; Sturza, A.; Pop, A. Flavour Compounds of *Lavandula angustifolia* L. to Use in Food Preservation. *Hop Med. Plants* **2017**, *25*, 38–46. [\[CrossRef\]](#)
- Demasi, S.; Caser, M.; Lonati, M.; Gaiino, W.; Scariot, V. Ornamental traits of *Lavandula angustifolia* Mill. are affected by geographical origin and cultivation substrate composition. *Acta Hort.* **2021**, *1331*, 49–56. [\[CrossRef\]](#)
- Van Oost, E.; Leus, L.; De Rybel, B.; Van Laere, K. Determination of Genetic Distance, Genome Size and Chromosome Numbers to Support Breeding in Ornamental *Lavandula* Species. *Agronomy* **2021**, *11*, 2173. [\[CrossRef\]](#)
- Szekely-Varga, Z.; Hitter, T.; Cantor, M. The Healing Power and the Uses in Landscape Design of Lavender (*Lavandula angustifolia* L.). *Hop Med. Plants* **2017**, *25*, 47–55. [\[CrossRef\]](#)
- Khan, S.U.; Hamza, B.; Mir, R.H.; Fatima, K.; Malik, F. Lavender Plant: Farming and Health Benefits. *Curr. Mol. Med.* **2024**, *24*, 702–711. [\[CrossRef\]](#)

15. Kiprovski, B.; Zeremski, T.; Varga, A.; Čabarkapa, I.; Filipović, J.; Lončar, B.; Aćimović, M. Essential Oil Quality of Lavender Grown Outside Its Native Distribution Range: A Study from Serbia. *Horticulturae* **2023**, *9*, 816. [\[CrossRef\]](#)
16. Crișan, I.; Ona, A.; Vârban, D.; Muntean, L.; Vârban, R.; Stoie, A.; Mihăiescu, T.; Morea, A. Current Trends for Lavender (*Lavandula angustifolia* Mill.) Crops and Products with Emphasis on Essential Oil Quality. *Plants* **2023**, *12*, 357. [\[CrossRef\]](#)
17. Giray, F.H. An Analysis of World Lavender Oil Markets and Lessons for Turkey. *J. Essent. Oil Bear. Plants* **2018**, *21*, 1612–1623. [\[CrossRef\]](#)
18. Vijulie, I.; Lequeux-Dincă, A.-I.; Preda, M.; Mareci, A.; Matei, E. Could Lavender Farming Go from a Niche Crop to a Suitable Solution for Romanian Small Farms? *Land* **2022**, *11*, 662. [\[CrossRef\]](#)
19. Manzoor, S.; Rakha, A.; Rasheed, H.; Bhat, Z.F.; Khan, M.S.A.; Abdi, G.; Aadil, R.M. A Comprehensive Review on Anxiolytic Effect of *Lavandula angustifolia* Mill. in Clinical Studies. *Food Sci. Nutr.* **2025**, *13*, e70993. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Batiha, G.E.-S.; Teibo, J.O.; Wasef, L.; Shaheen, H.M.; Akomolafe, A.P.; Teibo, T.K.A.; Al-kuraishy, H.M.; Al-Garbeeb, A.I.; Alexiou, A.; Papadakis, M. A review of the bioactive components and pharmacological properties of *Lavandula* species. *Naunyn-Schmiedeberg's Arch. Pharmacol.* **2023**, *396*, 877–900. [\[CrossRef\]](#) [\[PubMed\]](#)
21. Miastkowska, M.; Kantyka, T.; Bielecka, E.; Kałucka, U.; Kamińska, M.; Kucharska, M.; Kilanowicz, A.; Cudzik, D.; Cudzik, K. Enhanced Biological Activity of a Novel Preparation of *Lavandula angustifolia* Essential Oil. *Molecules* **2021**, *26*, 2458. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Dobros, N.; Zawada, K.D.; Paradowska, K. Phytochemical Profiling, Antioxidant and Anti-Inflammatory Activity of Plants Belonging to the *Lavandula* Genus. *Molecules* **2023**, *28*, 256. [\[CrossRef\]](#)
23. Nasiri Lari, Z.; Hajimonfarednejad, M.; Riasatian, M.; Abolhassanzadeh, Z.; Iraj, A.; Vojoud, M.; Heydari, M.; Shams, M. Efficacy of inhaled *Lavandula angustifolia* Mill. Essential oil on sleep quality, quality of life and metabolic control in patients with diabetes mellitus type II and insomnia. *J. Ethnopharmacol.* **2020**, *251*, 112560. [\[CrossRef\]](#)
24. Chaimae, S.; Hakima, S.; Chaimae, R.; Wafae, S.; Lazraq, A.; Lahsen, E.G.; Saadia, B.; Ghizlane, E. Improvement of germination rate and in vitro multiplication of *Lavandula angustifolia*. *J. Appl. Biol. Biotechnol.* **2020**, *8*, 52–57. [\[CrossRef\]](#)
25. Demirkaya, M.; Aydın, B.; Şekerci, A.D.; Gülşen, O. Effects of osmotic conditioning treatments of lavender (*Lavandula angustifolia*) seeds on mean germination time and germination rate. *Int. J. Second. Metab.* **2017**, *4*, 418–422. [\[CrossRef\]](#)
26. Sharan, H.; Pandey, P.; Singh, S. Genetic Resources and Breeding Strategies for Lavender (*Lavandula angustifolia* Mill.). In *Ethnopharmacology and OMICS Advances in Medicinal Plants Volume 2: Revealing the Secrets of Medicinal Plants*; Nandave, M., Joshi, R., Upadhyay, J., Eds.; Springer Nature: Singapore, 2024; pp. 33–54.
27. Stanev, S.; Zagorcheva, T.; Atanasov, I. Lavender Cultivation in Bulgaria-21st Century Developments, Breeding Challenges and Opportunities. *Bulg. J. Agric. Sci.* **2016**, *22*, 584–590.
28. Adel Al-Tai, A.; Mohammed, A. Germination of lavender (*Lavandula angustifolia*) plant seeds and production of its seedlings callus cultures. *Malays. J. Microbiol.* **2024**, *20*, 36–39. [\[CrossRef\]](#)
29. Kryuchkova, V.; Evtyukhova, A.; Avdeev, S.; Donskih, V.; Shelepova, O.; Ladyzhenskaya, O.; Gorbunov, Y. Lavender Breeding for Winter Hardiness in a Temperate Climate. *Horticulturae* **2025**, *11*, 139. [\[CrossRef\]](#)
30. Labbafi, M.; Khalaj, H.; Delfani, M.; Qavami, N. Evaluation of different hormonal and temperature treatments on dormancy breaking of Lavender (*Lavandula angustifolia*) seed. *Iranian J. Seed Res.* **2022**, *9*, 10. [\[CrossRef\]](#)
31. Dobrowolska, A.; Zawadzińska, A. The influence of stratification on seedling emergence and growth of narrow-leaved lavender and its cultivars. *Int. J. Plant Soil Sci.* **2014**, *3*, 948–958. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Kobets, O.; Derevianko, N.; Zavorodnii, M.; Berezovska, M. Prospects for the use of growth regulators in vegetative propagation technology of *Lavandula angustifolia*. *Regul. Mech. Biosyst.* **2024**, *15*, 198–206. [\[CrossRef\]](#)
33. Carvalho, R.d.S.; Silva, M.A.d.; Borges, M.T.M.R.; Forti, V.A.J.C.R. Plant extracts in agriculture and their applications in the treatment of seeds. *Cienc. Rural* **2022**, *52*, e20210245. [\[CrossRef\]](#)
34. du Jardin, P. Plant biostimulants: Definition, concept, main categories and regulation. *Sci. Hortic.* **2015**, *196*, 3–14. [\[CrossRef\]](#)
35. Kisvarga, S.; Farkas, D.; Boronkay, G.; Neményi, A.; Orlóci, L. Effects of Biostimulants in Horticulture, with Emphasis on Ornamental Plant Production. *Agronomy* **2022**, *12*, 1043. [\[CrossRef\]](#)
36. Gupta, S.; Doležal, K.; Kulkarni, M.G.; Balázs, E.; Van Staden, J. Role of non-microbial biostimulants in regulation of seed germination and seedling establishment. *Plant Growth Regul.* **2022**, *97*, 271–313. [\[CrossRef\]](#)
37. Bulgari, R.; Franzoni, G.; Ferrante, A. Biostimulants Application in Horticultural Crops under Abiotic Stress Conditions. *Agronomy* **2019**, *9*, 306. [\[CrossRef\]](#)
38. Farruggia, D. Sustainable Approach to Improve the Production Performance of Medicinal and Aromatic Plants by Application of Various Types of Biostimulants in an Organic Agricultural System. Ph.D. Thesis, Università degli Studi di Palermo, Palermo, Italy, 2024.
39. Shahrajabian, M.H.; Sun, W. Sustainable approaches to boost yield and chemical constituents of aromatic and medicinal plants by application of biostimulants. *Recent Adv. Food Nutr. Agric.* **2022**, *13*, 72–92. [\[CrossRef\]](#) [\[PubMed\]](#)
40. Rouphael, Y.; Colla, G. Synergistic Biostimulatory Action: Designing the Next Generation of Plant Biostimulants for Sustainable Agriculture. *Front. Plant Sci.* **2018**, *9*, 1655. [\[CrossRef\]](#) [\[PubMed\]](#)

41. Rosa, A.C.R.; Verly, L.B.; Miranda, G.S.; Marques, C.F.P.M.; Vieira, G.F.A.; Carvalho, G.A.; Perin, I.L.B.; Caprini, H.O.G.; da Silva, C.R.; Andrade, J.V.; et al. Natural Bio-stimulants for Seed Growth and Development. In *Advances in Seed Quality Evaluation and Improvement*; Roy, B., Shukla, G., Dunna, V., Sharma, P., Shukla, P.S., Eds.; Springer Nature: Singapore, 2025; pp. 105–126.
42. Gavrić, T.; Gadžo, D.; Erhatic, R.; Hafner-Vuk, K. The effect of the use of biostimulant on the yield and quality of lavandin and lavender. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2024**, *52*, 13967. [\[CrossRef\]](#)
43. ISTA. *International Seed Testing Association. International Rules for Seed Testing*; ISTA: Zurich, Switzerland, 2022.
44. Roman, A.M.; Truta, A.M.; Morar, I.M.; Viman, O.; Dan, C.; Sestras, A.F.; Holonec, L.; Boscaiu, M.; Sestras, R.E. From Seed to Seedling: Influence of Seed Geographic Provenance and Germination Treatments on Reproductive Material Represented by Seedlings of *Robinia pseudoacacia*. *Sustainability* **2022**, *14*, 5654. [\[CrossRef\]](#)
45. Maguire, J.D. Speed of Germination—Aid In Selection And Evaluation for Seedling Emergence And Vigor. *Crop Sci.* **1962**, *2*, 176–177. [\[CrossRef\]](#)
46. Ruan, S.; Xue, Q.; Tylkowska, K. The influence of priming on germination of rice (*Oryza sativa* L.) seeds and seedling emergence and performance in flooded soil. *Seed Sci. Technol.* **2002**, *30*, 61–67.
47. Abdul-Baki, A.A.; Anderson, J.D. Vigor Determination in Soybean Seed by Multiple Criteria. *Crop Sci.* **1973**, *13*, 630–633. [\[CrossRef\]](#)
48. Hammer, Ø.; Harper, D.A.T.; Ryan, P.D. PAST: Paleontological statistics software package for education and data analysis. *Palaeontol. Electron.* **2001**, *4*, 4–9.
49. Trevisan, S.; Francioso, O.; Quaggiotti, S.; Nardi, S. Humic substances biological activity at the plant-soil interface. *Plant Signal. Behav.* **2010**, *5*, 635–643. [\[CrossRef\]](#)
50. Canellas, L.P.; Olivares, F.L.; Aguiar, N.O.; Jones, D.L.; Nebbioso, A.; Mazzei, P.; Piccolo, A. Humic and fulvic acids as biostimulants in horticulture. *Sci. Hortic.* **2015**, *196*, 15–27. [\[CrossRef\]](#)
51. Colla, G.; Nardi, S.; Cardarelli, M.; Ertani, A.; Lucini, L.; Canaguier, R.; Roupahel, Y. Protein hydrolysates as biostimulants in horticulture. *Sci. Hortic.* **2015**, *196*, 28–38. [\[CrossRef\]](#)
52. Teixeira, W.F.; Fagan, E.B.; Soares, L.H.; Umburanas, R.C.; Reichardt, K.; Neto, D.D. Foliar and seed application of amino acids affects the antioxidant metabolism of the soybean crop. *Front. Plant Sci.* **2017**, *8*, 327. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Nardi, S.; Pizzeghello, D.; Schiavon, M.; Ertani, A. Plant biostimulants: Physiological responses induced by protein hydrolyzed-based products and humic substances in plant metabolism. *Sci. Agric.* **2016**, *73*, 18–23. [\[CrossRef\]](#)
54. Zandonadi, D.; Santos, M.; Busato, J.; Eustáquio, L.; Peres, P.; Façanha, A. Plant physiology as affected by humified organic matter. *Theor. Exp. Plant Physiol.* **2013**, *25*, 12–25. [\[CrossRef\]](#)
55. Gruszecki, R.; Stawiarz, A. Biostimulants containing amino acids in vegetable crop production. *Acta Sci. Pol. Hortorum Cultus* **2021**, *20*, 45–57. [\[CrossRef\]](#)
56. Calvo, P.; Nelson, L.; Kloepper, J.W. Agricultural uses of plant biostimulants. *Plant Soil* **2014**, *383*, 3–41. [\[CrossRef\]](#)
57. Przybysz, A.; Gawrońska, H.; Gajc-Wolska, J. Biological mode of action of a nitrophenolates-based biostimulant: Case study. *Front. Plant Sci.* **2014**, *5*, 713. [\[CrossRef\]](#)
58. Yakhin, O.; Lubyantsev, A.; Yakhin, I.; Brown, P. Biostimulants in Plant Science: A Global Perspective. *Front. Plant Sci.* **2017**, *7*, 2049. [\[CrossRef\]](#)
59. Grassmann, J.; Hippeli, S.; Elstner, E.F. Plant's defence and its benefits for animals and medicine: Role of phenolics and terpenoids in avoiding oxygen stress. *Plant Physiol. Biochem.* **2002**, *40*, 471–478. [\[CrossRef\]](#)
60. Wahid, A.; Ghazanfar, A. Possible involvement of some secondary metabolites in salt tolerance of sugarcane. *J. Plant Physiol.* **2006**, *163*, 723–730. [\[CrossRef\]](#)
61. Stoian-Dod, R.L.; Dan, C.; Morar, I.M.; Sestras, A.F.; Truta, A.M.; Roman, G.; Sestras, R.E. Seed Germination within Genus *Rosa*: The Complexity of the Process and Influencing Factors. *Horticulturae* **2023**, *9*, 914. [\[CrossRef\]](#)
62. Bhattacharya, A. Effect of Low-Temperature Stress on Germination, Growth, and Phenology of Plants: A Review. In *Physiological Processes in Plants Under Low Temperature Stress*; Bhattacharya, A., Ed.; Springer: Singapore, 2022; pp. 1–106.
63. Barua, D.; Butler, C.; Tisdale, T.E.; Donohue, K. Natural variation in germination responses of *Arabidopsis* to seasonal cues and their associated physiological mechanisms. *Ann. Bot.* **2011**, *109*, 209–226. [\[CrossRef\]](#)
64. Malovichko, Y.V.; Shikov, A.E.; Nizhnikov, A.A.; Antonets, K.S. Temporal Control of Seed Development in Dicots: Molecular Bases, Ecological Impact and Possible Evolutionary Ramifications. *Int. J. Mol. Sci.* **2021**, *22*, 9252. [\[CrossRef\]](#)
65. Macovei, A.; Pagano, A.; Leonetti, P.; Carbonera, D.; Balestrazzi, A.; Araújo, S.S. Systems biology and genome-wide approaches to unveil the molecular players involved in the pre-germinative metabolism: Implications on seed technology traits. *Plant Cell Rep.* **2017**, *36*, 669–688. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Guzmán-Ortiz, F.A.; Castro-Rosas, J.; Gómez-Aldapa, C.A.; Mora-Escobedo, R.; Rojas-León, A.; Rodríguez-Marín, M.L.; Falfán-Cortés, R.N.; Román-Gutiérrez, A.D. Enzyme activity during germination of different cereals: A review. *Food Rev. Int.* **2019**, *35*, 177–200. [\[CrossRef\]](#)

67. Bewley, J.D.; Bradford, K.J.; Hilhorst, H.W.M.; Nonogaki, H. Mobilization of Stored Reserves. In *Seeds: Physiology of Development, Germination and Dormancy*, 3rd ed.; Bewley, J.D., Bradford, K.J., Hilhorst, H.W.M., Nonogaki, H., Eds.; Springer: New York, NY, USA, 2013; pp. 183–246.
68. Joshi, R. Role of enzymes in seed germination. *Int. J. Creat. Res. Thoughts* **2018**, *6*, 1481–1485.
69. Bhatla, S.C.; Kathpalia, R. Seed Dormancy and Germination. In *Plant Physiology, Development and Metabolism*; Bhatla, S.C., Lal, M.A., Eds.; Springer Nature: Singapore, 2023; pp. 625–640.
70. Nephali, L.; Piater, L.A.; Dubery, I.A.; Patterson, V.; Huyser, J.; Burgess, K.; Tugizimana, F. Biostimulants for Plant Growth and Mitigation of Abiotic Stresses: A Metabolomics Perspective. *Metabolites* **2020**, *10*, 505. [[CrossRef](#)]
71. Johnson, R.; Joel, J.M.; Puthur, J.T. Biostimulants: The Futuristic Sustainable Approach for Alleviating Crop Productivity and Abiotic Stress Tolerance. *J. Plant Growth Regul.* **2024**, *43*, 659–674. [[CrossRef](#)]
72. Roupael, Y.; Colla, G. Toward a Sustainable Agriculture Through Plant Biostimulants: From Experimental Data to Practical Applications. *Agronomy* **2020**, *10*, 1461. [[CrossRef](#)]
73. Malik, A.; Mor, V.S.; Tokas, J.; Punia, H.; Malik, S.; Malik, K.; Sangwan, S.; Tomar, S.; Singh, P.; Singh, N.; et al. Biostimulant-Treated Seedlings under Sustainable Agriculture: A Global Perspective Facing Climate Change. *Agronomy* **2021**, *11*, 14. [[CrossRef](#)]
74. Sani, M.N.H.; Yong, J.W.H. Harnessing Synergistic Biostimulatory Processes: A Plausible Approach for Enhanced Crop Growth and Resilience in Organic Farming. *Biology* **2022**, *11*, 41. [[CrossRef](#)] [[PubMed](#)]
75. Parađiković, N.; Teklić, T.; Zeljković, S.; Lisjak, M.; Špoljarević, M. Biostimulants research in some horticultural plant species—A review. *Food Energy Secur.* **2019**, *8*, e00162. [[CrossRef](#)]
76. Lau, S.-E.; Lucas, W.; Hamdan, M.; Chan, C.; Saidi, N.; Ong-Abdullah, J.; Tan, B. Enhancing plant resilience to abiotic stress: The power of biostimulants. *Phyton* **2025**, *94*, 1–31. [[CrossRef](#)]
77. Rai, N.; Rai, S.P.; Sarma, B.K. Prospects for abiotic stress tolerance in crops utilizing phyto-and bio-stimulants. *Front. Sustain. Food Syst.* **2021**, *5*, 754853. [[CrossRef](#)]

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