



Article

Cold Plasma-Assisted Lavender Essential-Oil Pilot Production: Impact on Oil Yield, Isolation Kinetics and Chemical Parameters

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Abstract

This study investigated the influence of filamentary cold plasma (FCP) pretreatment on the isolation kinetics, yield and quality of lavender essential oil obtained by hydrodistillation (HD) and steam distillation (SD) at pilot scale. Lavender flowers were processed with or without FCP treatment under identical HD and SD conditions. FCP promoted tissue electroporation and the formation of additional mass transfer pathways in the calyx, shortening isolation time and increasing essential-oil yield from 2.46% to 2.65% for HD and from 2.33% to 2.65% for SD. In the SD process, FCP reduced process time from 240 ± 5.8 min to 95.3 ± 6.1 min to obtain an equal oil yield volume and decreased the specific energy consumption from 0.35 to 0.14 kWh mL⁻¹ of essential oil. GC–MS analysis confirmed that FCP did not deteriorate the volatile profile; linalool and linalyl acetate were the dominant constituents, with the relative contribution of other compounds depending on the distillation method. The combined linalool and linalyl acetate fraction increased from 65.9% to 68.2% after HD and from 63.49% to 68.11% after SD, indicating partial conversion of bound essential oil into a more extractable form. These results demonstrate that conveyor-based FCP pretreatment can intensify lavender oil production while preserving oil quality and provide practical parameters for assessing industrial-scale implementation.

Keywords: isolation; pilot plant; lavender inflorescence; essential oil; filamentary cold plasma; electroporation; steam distillation; oil quality

1. Introduction

Essential and vegetable oils are widely used because of their nutritional, sensory and therapeutic properties. High-quality and efficient isolation of these oils is therefore a fundamental operation in the manufacturing sector [1]. The conventional method for isolating volatile compounds from lavender flowers (*Lavandula angustifolia* Mill.) is distillation [2]. During distillation, aromatic plant material is exposed to boiling water or steam, which releases essential oils from the plant matrix. Several distillation approaches have been developed for laboratory- and industrial-scale lavender oil production [3].

In lavender, essential oil is localized mainly in the flowers, and its content varies from approximately 0.8% to 3.5% depending on whether the raw material is derived from a local population or a selected variety [4]. Essential oils are synthesized and stored in specialized glands that may be located on the surface or within internal plant structures. Most of the lavender essential oil is contained in glands on the calyx in a free form and can be readily removed by solid–steam mass transfer [5]. However, a fraction of the oil remains in internal calyx and stem structures, where diffusion from the internal tissue to the



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material surface becomes the rate-limiting step. Therefore, methods capable of modifying the capillary-porous structure of the raw material are required to intensify oil release.

Water distillation is energy- and time-intensive, with water heating accounting for a substantial proportion of total process energy. In the context of rising energy prices and the need to reduce CO₂ emissions, innovative technologies for accelerating essential-oil isolation are of increasing interest. Promising alternatives include instant controlled pressure drop (DIC) technology, supercritical fluid extraction (SFE), microwave- and ultrasound-assisted extraction, enzyme-assisted extraction and solvent-based extraction using media such as n-hexane, petroleum ether, dichloromethane, ethanol or diethyl ether [6]. These approaches can increase essential-oil yield and extraction rate; however, their broader industrial application is often limited by scale-up challenges, requirements for a liquid conductive phase or the risk of local overheating of thermolabile compounds.

Ultrasound pretreatment and ultrasound-assisted extraction have been widely investigated for intensifying the processing of essential-oil-bearing plant materials [7]. The main mechanism is cavitation, which occurs under low-frequency ultrasound. The collapse of cavitation bubbles in the bulk medium and near plant surfaces generates pressure gradients and microjets with velocities that can reach several hundred kilometers per hour. These effects can disrupt cell membranes or increase their porosity, thereby facilitating mass transfer from the intracellular region [8]. Nevertheless, ultrasound-assisted processes may be difficult to scale and typically require a liquid phase with suitable properties for stable cavitation.

Microwave-assisted extraction can also intensify essential-oil recovery without adding organic solvents. Heating of intracellular water promotes cell expansion and rupture of essential-oil glands, allowing the oil to evaporate together with water. This method can provide results comparable with those of hydrodistillation [9]. Intermittent solvent-free microwave extraction was applied to citrus peel and reduced extraction time from 240 min to 15 min [10]. However, microwave processing also faces limitations related to scale-up and nonuniform heating of plant material.

Pulsed electric field (PEF) technology is another established intensification approach for oil extraction. Several studies have reported enhanced essential-oil extraction by combining PEF pretreatment with hydrodistillation: 4 kV cm⁻¹ was applied to *Rosa alba* L. during a 30–250 min extraction [11]; 2 kV cm⁻¹ with a specific energy of approximately 10 kJ kg⁻¹ was applied to eucalyptus, rosemary and thyme leaves during a 120 min extraction [12]; 1 kV cm⁻¹ and 55 pulses were applied to coriander seeds during a 240 min extraction [13]; and 20 kV cm⁻¹ was applied to Damask rose flowers during a 120 min extraction [14]. These studies demonstrate that electrical pretreatments can increase EO yield when processing parameters are optimized [15].

Among emerging intensification methods, cold plasma is a promising scalable technology for improving extraction yield and extraction rate from essential-oil-bearing raw materials [16,17]. However, only a limited number of studies have examined this application. Different cold-plasma-assisted extraction processes have been reviewed by Xi et al. [18]. Cold plasma treatment for 1–5 min was shown to affect the EO content and composition of lemon verbena leaves [19]. In betel leaf powder, a maximum EO yield of 3.33 ± 1.2% was achieved using microwave plasma treatment at 738 W for 98 s followed by a 104 min extraction [20]. Rezaei et al. [16] applied cold plasma pretreatment before hydrodistillation of fennel seeds and spearmint leaves, obtaining essential-oil yields of 1.83% and 1.81%, respectively, at an applied voltage of 19 kV. The same authors emphasized the potential advantages of cold plasma for raw materials containing bound essential oil in internal tissues. Conversely, negative effects of cold plasma pretreatment have been reported for hyssop [21] and lemon verbena [19], which may be related to the plasma type, partial oil evaporation during treatment or chemical degradation by reactive plasma species.

To the best of the authors' knowledge, all reported research based on cold plasma application involves only surface treatment of the product. No previous reports were found regarding the feasibility of straight-through microplasma treatment technology to enhance the essential-oil isolation process.

Despite the potential of FCP pretreatment to increase EO isolation and reduce distillation time, the number of published studies and plant matrices investigated remains limited [6,7,10,12,16,19–21]. Therefore, the present study was designed to evaluate filamentary cold plasma pretreatment combined with hydrodistillation and steam distillation at the pilot scale. The effects on extraction efficiency, isolation kinetics, extraction rate, essential-oil yield and chemical quality parameters were systematically examined.

2. Materials and Methods

2.1. Materials

Lavender flowers (*Lavandula angustifolia*) harvested in Crimea, Russia, in July 2025 were used in the current experiments. The initial moisture content of the lavender flowers was $58.2 \pm 0.4\%$, as determined using a moisture analyzer (Evlas-2M, Sibagropribor, Novosibirsk, Russia). A schematic flow of the experimental program is shown in Figure 1, including procurement of lavender flower samples, FCP pretreatment combined with hydrodistillation (HD) and steam distillation (SD), and analytical procedures for extraction efficiency and quality assessment. The study was designed to evaluate whether FCP pretreatment combined with HD or SD could preserve the quality attributes of lavender essential oil while improving isolation efficiency. Analytical measurements were performed in at least two independent repetitions using different samples.

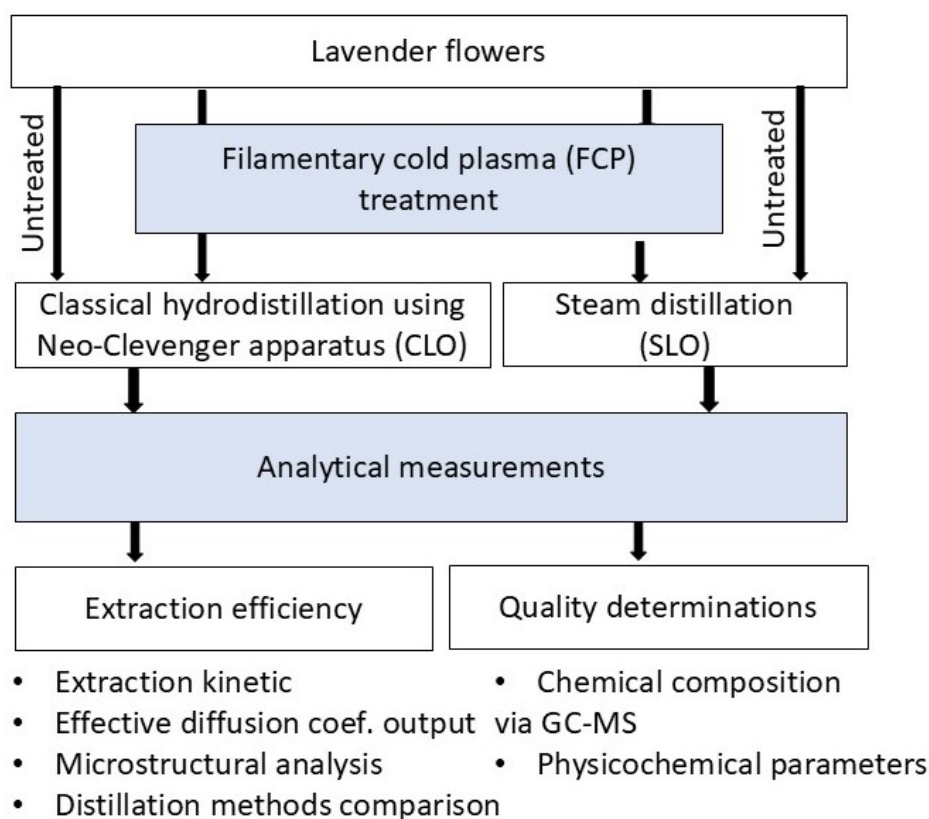


Figure 1. Experimental workflow for evaluating filamentary cold plasma (FCP) pretreatment before lavender essential-oil isolation by hydrodistillation (HD/CLO) and steam distillation (SD/SLO), followed by extraction-efficiency and quality analyses.

2.2. Filamentary Cold Plasma-Assisted Lavender Essential-Oil Pilot Production

A pilot filamentary cold plasma system with a tray-conveyor treatment chamber was used for the lavender essential-oil production process. The pilot FCP system with the tray-conveyor chamber is presented in Figure 2. The experimental line consisted of two main units: (1) a pilot FCP system (PulseTech, Shellrice Inc., Krasnodar, Russia), including the tray conveyor and FCP treatment chamber, and (2) a semi-industrial steam distillation setup. The pilot FCP system was based on a 20 kV Matsusada pulse generator (Matsusada Precision Inc., Kusatsu, Japan) that produces adjustable bipolar or monopolar rectangular pulses with a width of 30–100 μ s. In this study, a point-plane chamber with a movable cathode and a static anode was used for tray-conveyor treatment of essential-oil-bearing raw material. A low-current spark discharge mode was applied in all experiments [22], and the treatment procedure was the same as previously reported [23].

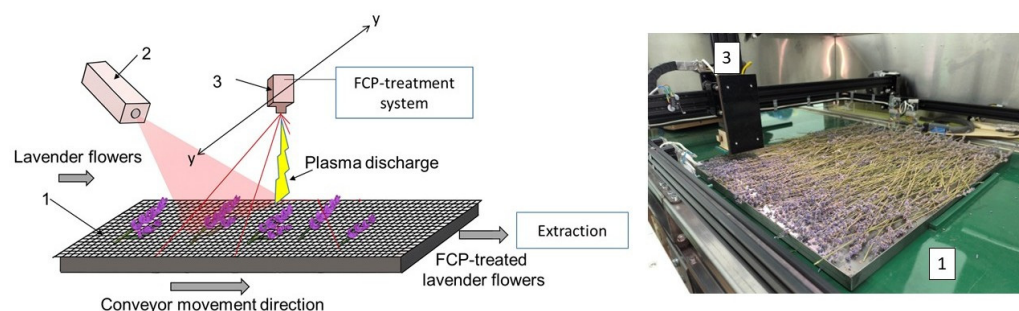


Figure 2. Pilot filamentary cold plasma (FCP) treatment system with a tray conveyor for lavender flowers: schematic representation of the scanning discharge zone and picture of the pilot treatment unit. 1—tray conveyor with lavender flowers; 2—monitoring camera; 3—movable FCP discharge unit.

Lavender flowers were treated in the tray-conveyor mode. In brief, 1500 g of lavender flowers were transported in a stainless-steel tray through the FCP treatment unit. Conveyor speed was set to 10 cm/s. The total residence time in the treatment zone was 120 s. The entire surface of the lavender sample was treated by the cathode through scanning movements. Discharge current (lower than 20 mA) and voltage (up to 15 kV) were recorded using a Tektronix DPO 2004B (Tektronix, Inc., Beaverton, OR, USA) oscilloscope equipped with a high-voltage probe (P6015A $\times$ 1000) (Tektronix, Inc., Beaverton, OR, USA). In all experiments, the gap between electrodes was set to 3 cm, and the pulse frequency was set to 1.5 kHz. After treatment, lavender flowers were extracted using semi-industrial steam distillation and lab-scale hydrodistillation.

2.3. Essential-Oil Isolation After FCP Treatment

Lavender essential oil was obtained using both HD and SD. The experimental isolation setups are shown in Figure 3. The SD process was carried out using a 25 L pilot setup, and the extraction time was set to 240 min. The HD process was carried out using a lab-scale Clevenger apparatus with a 1000 mL round-bottom flask. Process kinetics were evaluated by measuring the cumulative volume of essential oil collected in a graduated burette equipped with a drain tap at selected process-time intervals. The volume of the separated essential-oil layer was read using a cathetometer (KM-6, Moscow, Russia) without interrupting the distillation process. Thus, the kinetic curves were obtained from the time-dependent accumulation of essential oil in the receiver rather than from separate experiments stopped at different process times. The distillation rate was 60 drops min^{-1} , as previously reported [24].

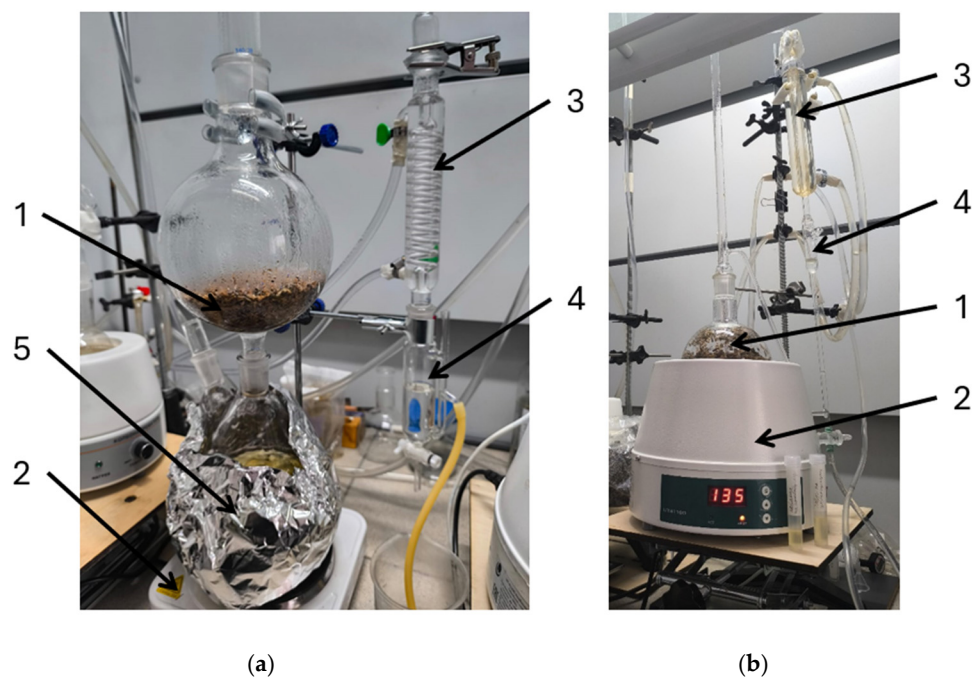


Figure 3. Devices for obtaining essential oils: (a) steam distillation and (b) hydrodistillation. 1—lavender flowers; 2—heater; 3—condenser; 4—essential-oil receiver; 5—flask with water.

The oil yield was measured and reported as w/w percentage according to the following equation:

$$EO = \frac{V \cdot \rho \cdot 100}{M} \quad (1)$$

where V is the volume of decanted oil, cm^3 ; ρ is the density of essential oil, g cm^{-3} ; and M is the mass of the lavender flower sample on an as-received basis, g.

For kinetic analysis, the same calculation was applied to the cumulative oil volume measured at each process-time interval. Thus, the current amount of isolated essential oil was calculated from the measured oil volume, while the final amount of isolated oil after 240 min was used as the reference value for calculating C/C_m and EO . The essential oil was collected, dried over anhydrous sodium sulfate and weighed, and then stored at 4°C .

2.4. Isolation Kinetics

During lavender essential-oil isolation, extractable compounds diffuse from the surface and the internal solid porous structure into the external liquid or vapor phase. The solid material frame is assumed to remain unchanged. Therefore, extractable compounds must overcome both intraparticle and external diffusion resistance: the former is associated with diffusion from pores to the material surface, whereas the latter is associated with diffusion from the surface through the boundary layer into the external phase. The extraction kinetic model for lavender flowers was developed according to the theory proposed by several authors [25,26]. In general, the isolation kinetics, assuming an unchanged solid structure, can be described by a modified model of Fickian diffusion [27]:

$$EO = \frac{C_0 - C}{C_0 - C_m} = \frac{1}{1 + \beta} - \sum_{n=1}^{\infty} A_n \exp\left(-\mu_n^2 Fo_g\right) \quad (2)$$

Here, EO is the essential-oil concentration simplex; C_0 and C are the initial and current concentrations of extractives, expressed as essential-oil-related concentration terms in the pore volume, kg m^{-3} ; C_m is the extractives' concentration in the external distillation phase, kg m^{-3} ; $\beta = (1 - \epsilon)/\epsilon$ is the dimensionless micropore-to-external-phase volume ratio;

ε is layer porosity; A_n and μ_n are the roots of the characteristic equation, which depend on the Biot criterion; and Fo_g is the Fourier number:

$$Fo_g = \frac{D \cdot t}{R^2} \quad (3)$$

D is the effective diffusion coefficient, $\text{m}^2 \text{s}^{-1}$; R is the equivalent geometrical parameter of the lavender flower particle, m ; and t is current time, s . In the present model, lavender flowers were approximated as plate-like particles according to the extraction kinetic approach used for plant materials [25–27]. Therefore, R was taken as one-half of the average thickness of the lavender flower/calyx fragment participating in internal diffusion. Based on the measured average particle thickness of approximately 1.0 mm, R was set to $5.0 \times 10^{-4} \text{ m}$ for all kinetic calculations.

In the experimental procedure, C , C_m and EO were not measured directly as independent chemical concentrations. According to the extraction kinetic approach used for plant materials [25–27], these parameters were calculated from the cumulative volume of essential oil collected in the receiver at selected process-time intervals. The C/C_m ratio was calculated by normalizing the current cumulative amount of isolated essential oil to the final amount isolated after 240 min. Since oil density and sample mass were constant within each experiment, this normalization was equivalent to using the ratio between the current cumulative oil volume and the final oil volume.

Equation (2) for a sufficiently long isolation time ($t \rightarrow \infty$) can be simplified to

$$E = A - B \exp(-kt) \quad (4)$$

where $A = 1/(1 + \beta)$, B is a dimensionless fitting parameter, and k is the kinetic coefficient of the regular extraction period, s^{-1} . The concentration simplex EO was calculated from the same cumulative oil-volume data according to the extraction kinetic model [25–27]. At each process time, EO represented the relative remaining extractable fraction of essential oil in the plant matrix, while the final amount of isolated oil after 240 min was used as the reference value. The dependence of $\ln(EO)$ on process time was then used to determine B and k during the regular extraction period.

For the regular extraction step, roots of the characteristic equation can be defined for the plate-like particle geometry of lavender flowers by the equation

$$\mu_1^2 = \frac{2 - B\beta(1 + \beta)}{B} \quad (5)$$

In Equation (3), the real material geometry is reduced to a one-dimensional equivalent. The effective diffusion coefficient can be determined by the equation

$$D = k \frac{R^2}{\mu_1^2} \quad (6)$$

where k is the kinetic coefficient of the regular extraction equation, s^{-1} , determined from the slope of the $\ln(EO)$ versus process time plot. The absolute value of k was used for calculating the effective diffusion coefficient D .

Nonlinear regression analysis of Equation (3) was applied to fit all experimental data on essential-oil extraction from FCP-treated and untreated lavender flowers using SigmaPlot 11.0 (Systat Software, Inc., San Jose, CA, USA).

2.5. Chemical Analysis of General Essential-Oil Quality Parameters

The essential oils were analyzed by gas chromatography coupled to mass spectrometry (GC–MS) using a Khromatek-Crystall 5000 (ZAO SKB Khromatek, Yoshkar-Ola, Russia) gas chromatograph equipped with a mass spectrometric detector (ZAO SKB Khromatek, Yoshkar-Ola, Russia) and a CR-5ms capillary column (30 m × 0.25 mm i.d.; film thickness 0.25 µm). GC–MS analysis was performed under the following conditions: helium carrier gas; flow rate, 1 mL min^{−1}; injector temperature, 250 °C; oven temperature program, 75–240 °C at 4 °C min^{−1}; ionization mode and electron impact at 70 eV. Components were identified by their linear retention indices on the column, determined using a homologous series of C₈–C₂₂ n-alkanes, and by comparing their mass-spectral fragmentation patterns with those stored in the Wiley/NBS library.

Physicochemical parameters of the oil were assessed by measuring the pH using a pH meter (Anion 4100, NPP Infraspak-Analit LLC, Novosibirsk, Russia), as well as by evaluating oil density and color.

2.6. Filamentary Cold Plasma and Specific Energy Consumption

The amount of energy consumed by FCP treatment W was determined from the data of the current and voltage oscillogram in accordance with the formula

$$W = n \cdot \int U(t) \cdot I(t) \cdot dt \quad (7)$$

where n is the number of discharges per processing, $U(t)$ is the value of the discharge voltage [V], and $I(t)$ is the discharge current passing through the sample [A].

The energy consumption of the FCP-treatment was calculated per mass of isolated lavender essential oil m_{EO} [mL] as

$$W_{FCP} = W / m_{EO} \quad (8)$$

The total specific energy consumption (W_{spec}) was calculated as a ratio of the energy consumed to the total mass of isolated lavender essential oil from lavender flowers during the isolation process:

$$W_{spec} = \frac{N_{dist} \cdot \tau}{m_{EO}} + W_{FCP} \quad (9)$$

where N_{dist} is power consumption of HD or SD [kW], and τ is time of isolation [h].

2.7. Microstructural Analysis

The microstructure of the internal tissues and the surface of lavender flowers was examined using a scanning electron microscope EVO HD 15 (Zeiss, Cambridge, UK/Oberkochen, Germany). Measurement conditions were set at: electron beam energy, 10 keV, and magnification, ×30–×100.

2.8. Statistical Analysis

Each experimental treatment, including untreated HD, FCP-treated HD, untreated SD and FCP-treated SD, was repeated three times using independent lavender flower samples ($n = 3$). The results are presented as mean ± standard deviation (SD). Statistical differences between untreated and FCP-treated samples were evaluated separately for each distillation method using one-way analysis of variance (ANOVA), followed by Tukey's post hoc test at a significance level of $p < 0.05$. Different superscript letters within the same row indicate statistically significant differences. Statistical analysis was performed using Design-Expert version 13.0.5.0 (Stat-Ease, Inc., Minneapolis, MN, USA).

3. Results

3.1. Effect of Filamentary Cold Plasma Treatment on the Microstructure of Lavender Flowers

Lavender essential oil is localized primarily in external storage structures, namely glandular trichomes, consisting of a one- or two-celled head situated on a one- or two-celled stalk. Figure 4a shows the surface microstructure of lavender flower trichomes and an essential-oil globule with an approximate diameter of 45 μm . During extraction, this oil is transferred from the plant tissue by contact with solvent or steam.

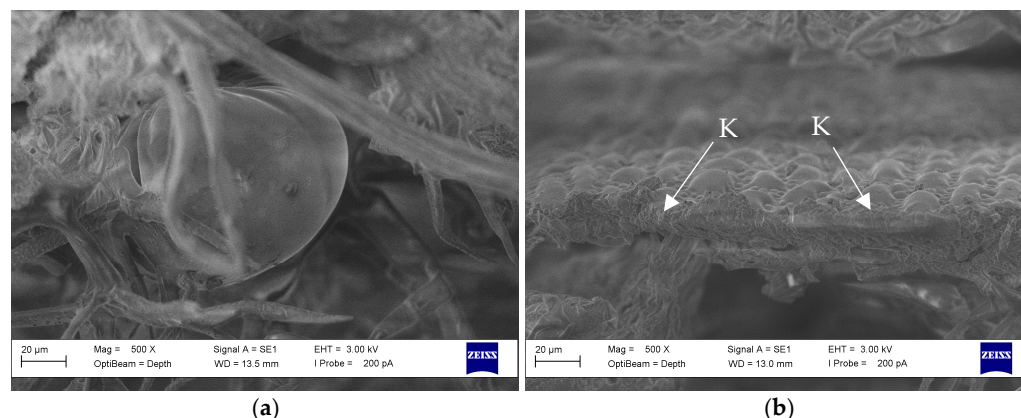


Figure 4. SEM micrographs of lavender flowers: (a) surface microstructure with a glandular trichome and an essential-oil globule; (b) cross-section of internal tissue after FCP treatment, showing crater-like channels (K).

Figure 4b demonstrates microstructural changes in the internal diffusive-barrier tissue of lavender flowers in cross-section. The image shows crater-like depressions and channel formations that most likely resulted from localized effects of FCP treatment. These changes may contribute to rupture of cell walls and facilitate subsequent essential-oil release during extraction. Similar studies on plasma-treated betel leaves and lemon peel reported cracks, fissures and cellular damage on the raw-material surface, resulting in enhanced diffusion of essential oil from oil-bearing secretory structures compared with untreated controls [20,28].

In contrast, Molina et al. [29] reported that dielectric barrier discharge treatment of *Lavandin Grosso* did not change the surface roughness of glandular trichomes even under prolonged exposure, indicating that surface alterations occurred predominantly at the nanometer scale. The difference between these observations and the present results may be explained by the use of different plasma-discharge configurations. The key feature of the FCP approach appears to be its ability to affect internal oil-cell membranes rather than only the external surface layers.

Overall, FCP treatment produced additional microchannels in the internal tissues of lavender inflorescences, thereby facilitating release of bound essential oil. Tree-like structures formed under FCP treatment have also been reported in other plant matrices [22,30], supporting the proposed mechanism of plasma-assisted mass transfer intensification.

3.2. Impact of FCP Treatment on Essential-Oil Isolation

Figure 5 presents the kinetics of essential-oil isolation over 240 min during hydrodistillation and steam distillation. The curves show a more rapid approach to the plateau for the FCP-treated samples in both HD and SD, especially during the first 30 min of isolation, followed by stabilization of the yield curve. Based on the yield values reported for the process, FCP increased essential-oil yield from 2.46% to 2.65% for HD (+7.7%) and from 2.33% to 2.65% for SD (+13.7%). The obtained EO yields (2.33–2.65%) are consistent with previously reported values for lavender oil, including 2.13% [31], 1.5% [32] and 2.2% [33].

Differences among studies may be related to cultivar, geographical origin, climate and harvesting conditions. A similar increase in essential-oil yield after electrical pretreatment was reported for *Marrubium vulgare* [34].

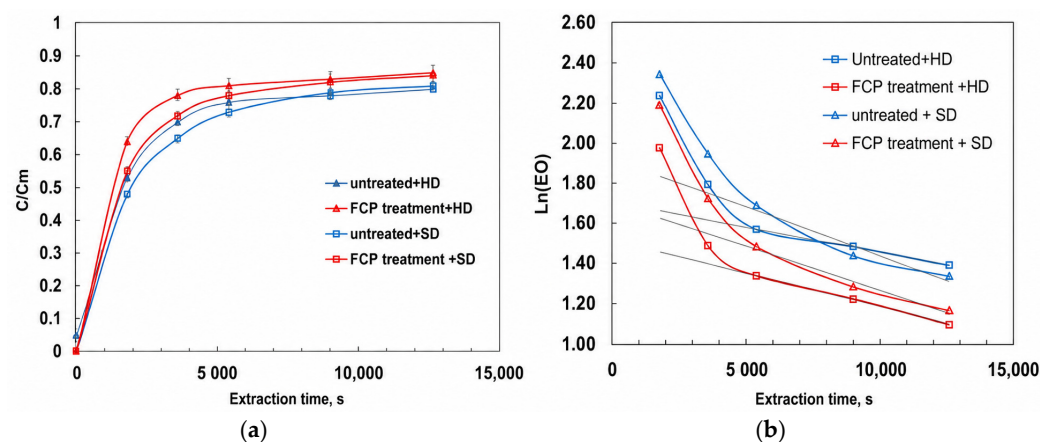


Figure 5. (a) Essential-oil isolation kinetics expressed as C/C_m during hydrodistillation and steam distillation; (b) logarithmic transformation of the calculated essential-oil concentration simplex, $\ln(EO)$, used for determining kinetic parameters. The grey lines represent linear fits used to determine the kinetic parameters during the regular extraction period.

The kinetic curves indicate that FCP pretreatment increased the distillation rate. This acceleration is attributable to a reduction in diffusion barriers that hinder oil release from the internal tissues of lavender flowers. The data also suggest that an optimum treatment intensity may exist, beyond which further increases in distillation rate become negligible.

FCP treatment was superior to the untreated SD control in terms of rapidity, reducing process time from 240 ± 5.8 min to 95.3 ± 6.1 min to obtain equal oil yield volume. The increase in essential-oil yield, depending on the distillation method, ranged from 0.19 to 0.32 percentage points, confirming the effectiveness of FCP as a raw-material preparation step. Experimental data highlighting the regular-regime region of lavender oil isolation after FCP treatment are shown in Figure 5. The experimental points in Figure 5a were calculated from the cumulative volume of essential oil measured at selected process-time intervals and expressed as C/C_m . To determine the kinetic parameters, the concentration simplex EO was calculated from the same cumulative oil-volume data according to the model described in Section 2.4, and the dependence of $\ln(EO)$ on process time was plotted. Coefficient B was determined from the intercept of the fitted linear function, whereas kinetic coefficient k was determined from its slope. The effective diffusion coefficient D was calculated from the absolute value of k using Equation (5). The calculated values of μ_1 , β and D are presented in Table 1. FCP treatment increased the diffusion coefficient from 6.22×10^{-12} to $9.29 \times 10^{-12} \text{ m}^2 \text{ s}^{-1}$ for hydrodistillation and from 1.13×10^{-11} to $1.84 \times 10^{-11} \text{ m}^2 \text{ s}^{-1}$ for steam distillation. This confirms the hypothesis that FCP pretreatment increases the proportion of essential oil that is in a free and readily extractable state.

Table 1. General extraction kinetic parameters.

FCP Treatment + SD	Untreated + SD	FCP Treatment + HD	Untreated + HD	Parameter
1.924	1.706	1.706	1.514	Coefficient B
-4.88×10^{-5}	-4.42×10^{-5}	-2.53×10^{-5}	-3.283×10^{-5}	Kinetic coefficient k, s^{-1}
0.19	0.16	0.20	0.15	Micropore-to-external-phase volume ratio, β (dimensionless)
0.813	0.986	0.931	1.147	Characteristic equation root, μ_1
1.84×10^{-11}	1.13×10^{-11}	9.29×10^{-12}	6.22×10^{-12}	Diffusion coefficient, $D (\text{m}^2 \text{ s}^{-1})$

Total energy consumption for FCP treatment and isolation was calculated using Equation (9) with a previously described method [35]. For FCP + SD, the total consumed energy was 0.14 kWh mL^{-1} of essential oil, compared with 0.35 kWh mL^{-1} for the untreated control. Thus, FCP treatment enhanced both total essential-oil yield and extraction rate while reducing specific energy consumption.

3.3. Influence of FCP Treatment on the Chemical Composition and Quality of Essential Oil

The effect of FCP treatment on essential-oil quality indicators is summarized in Table 2. According to Turek and Stintzing [36], important essential-oil quality indicators include pH and color. Density at 20°C (g cm^{-3}) was also included because it is an indirect indicator of oil purity and naturalness and may reflect quantitative variation in specific components. FCP treatment did not markedly affect the physicochemical parameters of lavender oil. All essential-oil samples were transparent, light-yellow liquids with a fresh, sweet and floral aroma and distinct herbaceous and slightly camphoraceous undertones.

Table 2. Physicochemical parameters of lavender essential oil.

FCP Treatment + SD	Untreated + SD	FCP Treatment + HD	Untreated + HD	Parameter
Transparent liquid	Transparent liquid	Transparent liquid	Transparent liquid	Appearance
Light yellow	Light yellow	Light yellow	Light yellow	Color
4.74 ± 0.12	4.42 ± 0.14	4.82 ± 0.103	4.76 ± 0.144	pH
0.882	0.881	0.876	0.88	Density at 20°C , g cm^{-3}

Quantitative determination of volatile terpenes was performed by gas–liquid chromatography, and the results are presented in Table 3. The quality of lavender essential oil for perfumery applications is mainly determined by its content of monoterpene alcohols and esters. The main components of the oil obtained by classical hydrodistillation were linalool (51.7%), linalyl acetate (14.2%), terpinen-4-ol (4.09%), lavandulol (3.28%) and borneol (1.19%). After FCP treatment, the corresponding values for HD were linalool (53.0%), linalyl acetate (15.2%), terpinen-4-ol (4.21%), lavandulol (3.26%) and borneol (1.10%). For SD, the main identified compounds included linalool (50.84–53.64%), linalyl acetate (12.65–14.47%), caryophyllene oxide (4.54–5.13%) and 1,8-cineole + limonene + β -phellandrene (3.39–3.48%). Literature data on lavender essential-oil composition report similar major components, supporting the high purity of the oil obtained in the present study [2,37,38]. Comparative evaluation indicates that FCP treatment promoted deeper extraction from lavender flowers, increasing the combined linalool and linalyl acetate fraction from 65.9% to 68.2% for HD and from 63.49% to 68.11% for SD.

Table 3. Relative peak area (%) of volatile compounds identified in lavender essential-oil samples obtained by hydrodistillation (HD) and steam distillation (SD).

FCP Treatment + SD	Untreated + SD	FCP Treatment + HD	Untreated + HD	Compound Name	No.
0.21	0.17	0.06	0.07	α -Pinene	1
0.26	0.25	0.10	0.12	Camphene	2
—	—	0.16	0.20	β -Pinene	3
0.13	—	0.45	0.46	3-Octanone	4
0.20	0.15	0.67	0.81	Myrcene	5
—	0.68	0.13	0.14	Hexyl acetate	6
3.48	3.39	0.29	0.29	1,8-Cineole + limonene + β -phellandrene	7
—	—	0.78	1.38	(Z)- β -Ocimene	8

Table 3. Cont.

FCP Treatment + SD	Untreated + SD	FCP Treatment + HD	Untreated + HD	Compound Name	No.
—	—	1.39	1.55	(E)- β -Ocimene	9
0.76	—	—	—	3-Carene	10
—	0.54	—	—	Benzene, 1-methyl-3-(1-methylethyl)-	11
0.57	—	—	—	Benzene, 1-methyl-4-(1-methylethyl)-	12
3.32	3.40	—	—	α -Methyl- α -[4-methyl-3-pentenyl]oxiranemethanol	13
0.12	—	—	—	Cyclopropane, 2-(1,1-dimethyl-2-propenyl)-1,1-dimethyl-	14
53.64	50.84	53.0	51.7	Linalool	15
0.09	0.01	0.05	0.05	Oct-1-en-3-yl acetate/octen-1-ol acetate	16
—	—	0.12	0.11	Camphor	17
—	—	0.05	0.05	Hexyl isobutyrate	18
0.23	0.18	—	—	Propanoic acid, 2-methyl-, hexyl ester	19
0.27	0.28	—	—	Bicyclo[2.2.1]heptan-2-one, 1,7,7-trimethyl-, (1R)-	20
1.94	1.52	—	—	3-Cyclohexen-1-ol, 4-methyl-1-(1-methylethyl)-, (R)-	21
0.27	0.25	—	—	Butanoic acid, butyl ester	22
1.36	1.03	—	—	Butanoic acid, hexyl ester	23
0.15	—	—	—	Butanoic acid, 2-methyl-, hexyl ester	24
1.25	1.09	—	—	2-Cyclohexen-1-one, 4-(1-methylethyl)-	25
—	0.14	—	—	Bornyl acetate	26
0.34	0.26	—	—	Benzaldehyde, 4-(1-methylethyl)-	27
0.15	0.14	—	—	2-Cyclohexen-1-one, 2-methyl-5-(1-methylethenyl)-, (S)-	28
—	—	1.10	1.19	Borneol	29
14.47	12.65	15.2	14.2	Linalyl acetate	30
—	—	—	—	1,6-Octadien-3-ol, 3,7-dimethyl-, 2-aminobenzoate	31
2.00	1.84	—	—	4-Hexen-1-ol, 5-methyl-2-(1-methylethenyl)-, acetate	32
0.12	0.12	—	—	Bicyclo [2.2.1]heptan-2-ol, 1,7,7-trimethyl-, acetate, (1S-endo)-	33
0.08	—	—	—	Bicyclo[3.1.1]heptane, 6,6-dimethyl-2-methylene-, (1S)-	34
0.09	—	—	—	Bicyclo[3.1.0]hex-2-ene, 2-methyl-5-(1-methylethyl)-	35
0.06	—	—	—	Hexane, 1-methoxy-	36
0.24	—	—	—	Cyclohexanol, 2,2-dimethyl-, acetate	37
0.08	—	—	—	2,6-Octadienal, 3,7-dimethyl-	38
0.10	—	—	—	1-Cyclohexene-1-carboxaldehyde, 4-(1-methylethyl)-	39
0.08	—	—	—	Bicyclo[3.1.1]hept-2-en-6-one, 2,7,7-trimethyl-	40
0.11	—	—	—	Cyclobutanecarboxylic acid, hexyl ester	41
—	—	3.26	3.28	Lavandulol	42
—	—	4.21	4.09	Terpinen-4-ol	43
—	—	0.30	0.29	α -Terpineol	44
—	—	0.12	0.11	Hexyl butyrate	45
—	—	0.97	0.94	Lavandulyl acetate	46
1.93	1.54	—	—	3-Nonanol, 1,2	47
0.20	—	—	—	Isopentyl hexanoate	48
0.48	0.48	—	—	2,6-Octadien-1-ol, 3,7-dimethyl-, acetate, (Z)-	49
0.81	0.40	—	—	2,6-Octadien-1-ol, 3,7-dimethyl-, acetate, (E)-	50
0.10	—	—	—	Copaene	51
0.07	—	—	—	1,3-Cyclohexadiene, 5-(1,5-dimethyl-4-hexenyl)-2-methyl-, [S-(R,S)]-	52

Table 3. Cont.

FCP Treatment + SD	Untreated + SD	FCP Treatment + HD	Untreated + HD	Compound Name	No.
0.60	0.48	—	—	Bicyclo[3.1.1]hept-2-ene, 2,6-dimethyl-6-(4-methyl-3-pentenyl)-	53
1.68	1.48	—	—	Tricyclo[2.2.1.0(2,6)]heptane, 1,7-dimethyl-7-(4-methyl-3-pentenyl)-, (-)-	54
1.51	0.88	—	—	Bicyclo[7.2.0]undec-4-ene, 4,11,11-trimethyl-8-methylene-	55
0.17	—	—	—	2H-1-Benzopyran-2-one	56
0.14	—	—	—	Bicyclo[7.2.0]undec-4-ene, 4,11,11-trimethyl-8-methylene-, [1R-(1R,4Z,9S)]-	57
1.81	0.89	—	—	1,6,10-Dodecatriene, 7,11-dimethyl-3-methylene-, (E)-	58
0.39	0.26	—	—	Cyclohexene, 3-(1,5-dimethyl-4-hexenyl)-6-methylene-, [S-(R,S)]-	59
0.07	—	—	—	Cyclohexene, 1-methyl-4-(5-methyl-1-methylene-4-hexenyl)-, (S)-	60
0.07	—	—	—	Naphthalene, 1,2,3,4,4a,5,6,8a-octahydro-7-methyl-4-methylene-1-(1-methylethyl)-, (1 α ,4 α ,8 α)	61
0.06	—	—	—	α -Santalol	62
—	—	1.32	1.11	β -Caryophyllene	63
5.13	4.54	—	—	Caryophyllene oxide	64
0.14	—	—	—	Furan, 3-(4,8-dimethyl-3,7-nonadienyl)-, (E)-	65
0.23	0.12	—	—	2-Pentadecanone, 6,10,14-trimethyl-	66
0.08	—	—	—	2-Butenal, 2-methyl-4-(2,6,6-trimethyl-1-cyclohexen-1-yl)-	67
0.18	1.17	—	—	Heneicosane	68
0.38	0.22	—	—	Benzene, 1-(1,5-dimethyl-4-hexenyl)-4-methyl-	69
—	—	17.10	16.87	Unidentified minor peaks (individual peak area < 1.00%)	70
100.00	100.00	100.00	100.00	Total	

4. Discussion

The results support the working hypothesis that FCP pretreatment improves lavender essential-oil isolation primarily by modifying internal mass transfer pathways. SEM observations showed channel-like defects in internal tissues, while kinetic modeling demonstrated higher effective diffusion coefficients for both hydrodistillation and steam distillation. These mutually consistent structural and kinetic data indicate that FCP can convert part of the bound oil fraction into a more accessible form, thereby reducing the time required to reach the regular extraction regime. The direct correlation between plasma-induced plant tissue micropore change and effective diffusion coefficient was evident (Table 1, parameters β and D). Similar results were reported by applying arc discharge for mass transfer acceleration for grapes [39].

From a mass transfer mechanism point of view an internal essential-oil diffusion is limited by mass transfer resistance including oil globules, membranes and pores [40]. In the HD process lavender flowers were submerged in water, and water molecules diffuse into the internal structure more slowly than during the SD process. In the SD process, steam provides a transport medium for the distillate, and FCP pretreatment promotes improved mass transfer. Such behavior is consistent with a modified structure of lavender essential-oil globules [41]. It was expected that steam distillation would have the longest extraction time, because this method's setup required more glassware than the hydrodistillation methods and because the steam must travel farther before reaching the condenser. FCP treatment decreased the mass transfer resistance and accelerated essential-oil extraction (diffusion coefficient increased >50% for both methods). When comparing hydrodistillation with steam distillation, the results suggested that the FCP pretreatment step results in the oil containing more main identified compounds than if there was no pretreatment step.

From a process-engineering perspective, the most practically relevant outcome was obtained for the FCP + SD configuration. The combination of a shorter isolation time, an increased diffusion coefficient and a decrease in specific energy consumption from 0.35 to 0.14 kWh mL⁻¹ suggests that conveyor-based FCP pretreatment may be suitable for continuous or semi-continuous industrial implementation. The energy-consumption values are comparable with those reported for ohmic-accelerated steam distillation [42], while FCP has the additional advantage of treating the raw material before distillation without requiring immersion in a conductive liquid phase.

In lavender essential-oil production, processing time is a major factor because of seasonality and raw-material harvesting requirements [43]. Totally, it reaches up to 4 h of essential-oil recovery process time. Taking into account this general basis and according to the results presented in this study, FCP-assisted lavender essential extraction could potentially reduce 61.3% of the process time. In a large-scale lavender essential-oil mill processing 2 tons/day of lavender flowers, filamentary cold plasma technology could potentially increase daily raw-material throughput by approximately 2.6-fold under comparable operating conditions. This improvement may increase production efficiency and support the payback of FCP equipment investment. Probable technical challenges during full industrial scale-up, including uneven plasma penetration on thick material beds and conveyor speed adjustment optimization for large-batch production, require detailed study.

The chemical composition of essential oil obtained after FCP treatment indicates that this approach preserved the valuable volatile profile and did not induce detectable deterioration of key aroma-active constituents. Similar conclusions have been reported for pulsed electric field-assisted extraction of essential oils [1,44]. However, excessive cold-plasma exposure has been associated with decreased EO yield and reduced percentages of several monoterpenes [45,46]. Therefore, the treatment intensity and residence time must be optimized to maximize membrane permeabilization while avoiding oxidative or plasma-induced degradation. Further research should examine quantifying the optimal FCP treatment duration targeting different lavender cultivars as well as the potential of combining FCP with other emerging pretreatments such as ultrasonic-, pulsed electric field- or microwave-assisted processing.

5. Conclusions

This study demonstrates that filamentary cold plasma pretreatment is an effective emerging technology for intensifying lavender essential-oil production. In the conveyor-flow treatment mode, FCP accelerated SD isolation approximately 2.2-fold, indicating potential for improving the productivity and profitability of essential-oil mills. For equal isolation time, FCP pretreatment increased total oil yield by up to 13.7%.

The treatment chamber equipped with a moving FCP jet unit provided distributed plasma exposure and promoted the formation of additional internal pathways for mass transfer. Comparative analysis of the isolation processes showed that the diffusion coefficient followed the order FCP treatment + SD > untreated + SD and FCP treatment + HD > untreated + HD. FCP increased the micropore-to-external-phase volume ratio from $\beta = 0.15$ to $\beta_{\text{FCP}} = 0.20$ and increased the diffusion coefficient 1.62-fold during steam distillation, from 1.13×10^{-11} to 1.84×10^{-11} m² s⁻¹. A similar enhancement was observed during hydrodistillation, with the diffusion coefficient increasing from 6.22×10^{-12} to 9.29×10^{-12} m² s⁻¹. GC-MS analysis confirmed that FCP treatment preserved the chemical quality of lavender essential oil and increased the combined linalool and linalyl acetate fraction from 65.9% to 68.2% after HD and from 63.49% to 68.11% after SD. Further studies should focus on quantifying the optimal FCP treatment duration targeting different lavender cultivars, technical challenges during full indus-

trial scale-up including scalability, stability and plasma penetration factors in combinations with other intensification technologies to support the scale-up of FCP-assisted essential-oil recovery.

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Abbreviations

The following abbreviations are used in this manuscript:

FCP	Filamentary cold plasma
EO	Essential oil
HD	Hydrodistillation
SD	Steam distillation
GC–MS	Gas chromatography–mass spectrometry
SEM	Scanning electron microscopy
PEF	Pulsed electric field
DBD	Dielectric barrier discharge
DIC	Instant controlled pressure drop
SFE	Supercritical fluid extraction
CLO	Classical hydrodistillation using a Neo-Clevenger apparatus
SLO	Steam distillation

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