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Recent advances in cold plasma treatment for essential oil extraction

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Abstract:
The substitution of imported supplements and flavorings with domestic products is the key to food security in Russia and Belarus. Essential oils are used in a variety of sectors, including medicine, cosmetics, perfumery, food, and confectionery. The depth and rate of their extraction determine the efficiency of the essential oil industry. Cold plasma treatment increases the rate of extraction by 15–20%. The use of this treatment can make Russian producers more competitive in the domestic market, as well as give them a competitive advantage internationally by ensuring high quality.

This review examines the use of cold plasma treatment in preparation for essential oil extraction, briefly describing its mechanism of action, as well as process and equipment. The scientific papers published between 2010 and 2025 were subjected to retrospective analysis.

Essential oil materials were classified and their essential oil receptacles were examined structurally to determine the type of cold plasma treatment to be used. We analyzed the surface and penetrating cold plasma effects on the morphology and microstructure of material tissues. Cold plasma generation methods were classified and their applications were presented for materials with external and internal essential oil receptacles. We described factors that affect the efficiency of essential oil extraction. Finally, potential applications were outlined for cold plasma technology in essential oil extraction and production of high-quality target products.

This review demonstrates the critical importance of developing innovative electrophysical technologies for the food and essential oil industries. Cold plasma treatment of freshly harvested essential oil materials is a promising approach to ensure high extraction efficiency and high quality of the resulting products.

Keywords: Essential oil materials, extraction, food flavoring, electrophysical technologies, cold plasma, dietary supplement

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INTRODUCTION

The choice of essential oil extraction method depends on the properties of plant material, the type of tissue that contains essential oil, the composition of oil and the properties of its components, as well as the nature of bond between essential oil and material. If essential oil is in a bound state, the material is fermented before or during extraction. A properly selected method for preparing and processing plant material ensures the highest yield and the best quality of the product [1]. Many plant materials are rich not only in essential oils but also in other bioactive substances. Therefore, an integrated technology should be applied to ensure the maximum extraction of all components. Essential oil can be extracted by the following physicochemical and mechanical methods [2, 3]: steam distillation; extraction with volatile organic solvents; extraction with non-volatile solvents (maceration); water extraction; extraction with liquefied gases; sorption with various sorbents (enfleurage and dynamic sorption); and mechanical pressing.

Extraction is one of the primary methods for processing essential oil materials. Its products include essential oils, fragrant resinous substances, waxes, and wax-like substances. The cosmetic industry uses mixtures of essential oil, resins, and waxes extracted with volatile hydrocarbon solvents [4]. The food industry produces hydroalcoholic, hydroalcoholic glycerin, and oil extracts from essential oil materials [5]. These extracts contain bioactive substances such as carotenoids, tocopherols, flavonoids, etc. The efficiency of the essential oil industry is determined by the depth and rate of extraction.

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According to the Russian Ministry of Energy, high energy intensity is a pressing issue in essential oil production, which significantly limits its competitiveness [6].

The shortage of local essential oil materials and their extracts forces the producers to spend millions of dollars annually on importing them [7, 8]. Currently, as part of import substitution policy, the industry is seeking to restore domestic essential oil production, its technology and equipment [6].

Improving essential oil extraction technology to increase extract yield and maintain extract quality is an important step in intensifying mass transfer processes. Figure 1 shows what methods of essential oil extraction are available today.

Extraction can be intensified by both thermomechanical methods (grinding, flattening, wet-heat treatment, fermentation) and modern "green" technologies [9] which make use of high-precision instruments and equipment. Today, the food industry usually uses solvents to extract target components from essential oil plant materials [10]. In solid-liquid extraction, a solid sample is immersed in a solvent, and the extracted component begins to separate due to the difference in concentrations at the phase boundary. Extraction efficiency can be increased by using external methods such as microwave heating [11, 12], ultrasound [13], intense electric fields, and discharge technologies [14, 15]. These methods offer unique advantages for extraction under specific temperatures. However, microwave heating is not widely applied in essential oil extraction due to difficulties controlling the process and possible overheating. Ultrasonic vibrations demonstrate good efficiency, but have a narrow operating range, necessitating the use of a large number of ultrasonic sensors in large-scale production.

A promising way of increasing extraction efficiency is to develop a surface structure by cold plasma treatment at atmospheric pressure. Such preparation can help predict the process's direction, which is important for its control. However, intensive extraction using cold plasma treatment is in need of scientific support, since the estimated relationships available are, in most cases, empirical and have a limited scope of application. This is primarily due to a lack of understanding of the morphological and structural changes that occur during cold plasma treatment, or the chemical reactions that take place when reactive plasma particles interact with essential oil material tissue.

Of interest are some studies that show changes in the structure of a colloidal capillary-porous body, describing the presence of additional channels formed by cold plasma treatment [16, 17]. This new continuum results from a unique relaxation transfer process caused by a change in the shape of the moisture or oil bond [18–20].

STUDY OBJECTS AND METHODS

This review examines the use of cold plasma treatment in preparation for essential oil extraction, briefly describing its mechanism of action, as well as process and equipment. The keywords "essential oil material", "cold plasma", and "assisted extraction" were used to search the Scopus, Web of Science, and eLIBRARY.RU databases. The scientific papers published between 2010 and 2025 were subjected to retrospective analysis.

Classification of essential oil materials. Essential oil-bearing plant materials can be classified by the part of a plant used industrially and by the type of interaction between essential oil components and other substances such as carbohydrates. According to the plant part, plant materials are classified into five groups [3, 21]:

– grains and fruits: coriander, anise, fennel, caraway, dill;
– leaves, stems, and branches: mint, rose geranium, patchouli, eucalyptus, sweet bay, wormwood, catnip, sweet violet, rosemary, grindelia, dill, lemon, conifers, tobacco, mock orange, fennel, anise, etc.;

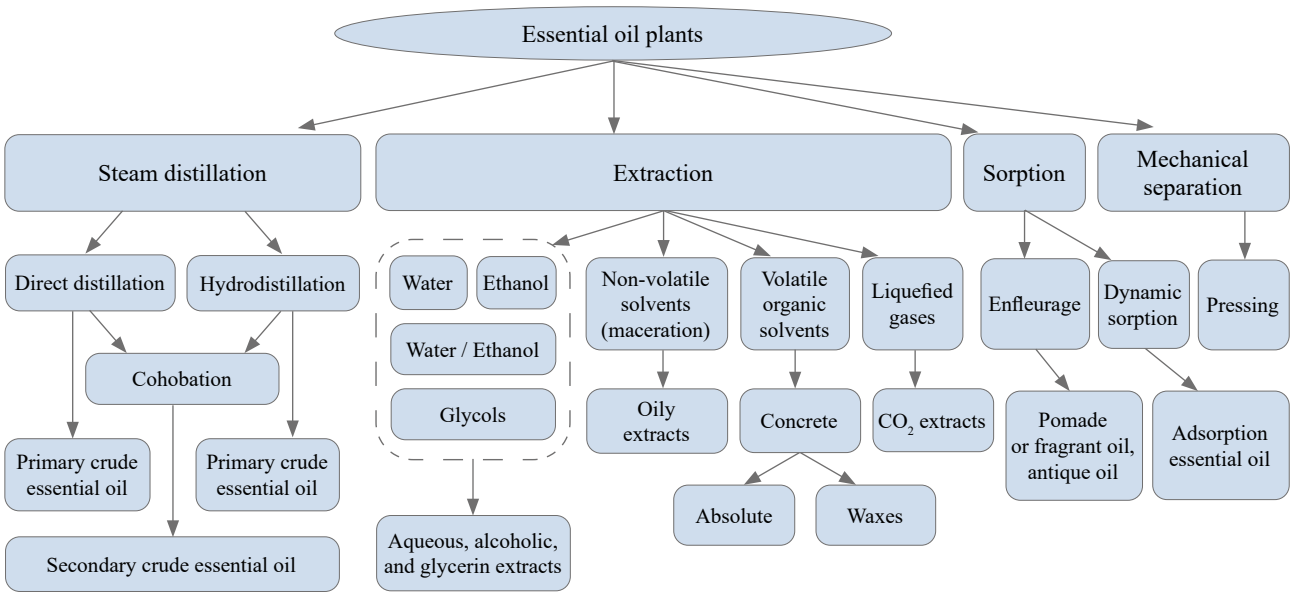


Figure 1 Methods of essential oil extraction

– flowers and flower buds: azalea, rose, clary sage, lavender, lavandin, Spanish jasmine, tobacco, white lily, regal lily, lilac, false acacia, silver-green wattle acacia, chamomile, yarrow, mock orange, iris, clove tree (buds), etc.;
– roots and rhizomes: calamus, vetiver, iris; and
– materials for obtaining fixatives: lichen – oak moss and cistus.

Each essential oil plant is usually a source of one type of material and one type of essential oil. This is typical for plants in which essential oil is found in only one organ or has similar compositions in different organs (e.g., coriander seeds, mint leaves and flowers, basil, and laurel branches). Some plants can be a source of two types of material and a single type of essential oil. Exceptions include citrus fruits, whose young branches yield petitgrain essential oil (bergamot-like aroma due to linalyl acetate), whose flowers yield neroli oil (citrus blossom aroma due to methyl anthranilate), and whose fruits yield lemon oil, orange oil, and other essential oils (characteristic aroma due to citral, limonene, and other compounds).

Essential oils in plants exist in both free and bound forms. If the oil is bound, this plant material does not have a scent characteristic of any particular essential oil, as its components are in the form of glycosides. The oil can be released only after hydrolysis or enzymatic cleavage of the glycosides.

Localization of essential oils in plant materials. Bound essential oils are usually distributed evenly throughout the plant tissues and are not strictly localized. Free essential oils and resinous substances are found in special excretory structures, or essential oil receptacles, on the surface or within plant tissues (Fig. 2).

Waxy substances can be found on the surface of all plant organs, in the cell membranes of the skin (epidermis), in the cuticle, and on its surface. In the outer walls of the epidermal cell membranes, they form cuticular layers alternating with cellulose. The cuticle, which covers the epidermis, is primarily composed of these layers. Waxes, which come in the form of small grains, thin rods, or solid crusts, form a waxy coating above the cuticle. The thickness of the cuticle and waxy coating varies among different plants, their organs and parts [22, 23].

RESULTS AND DISCUSSION

Composition and application of essential oils. Essential oils are widely used in the food industry as flavoring agents (plant extracts), as well as in the pharmaceutical and cosmetic industries (Fig. 3). An essential oil is a plant-based complex of mostly fragrant volatile

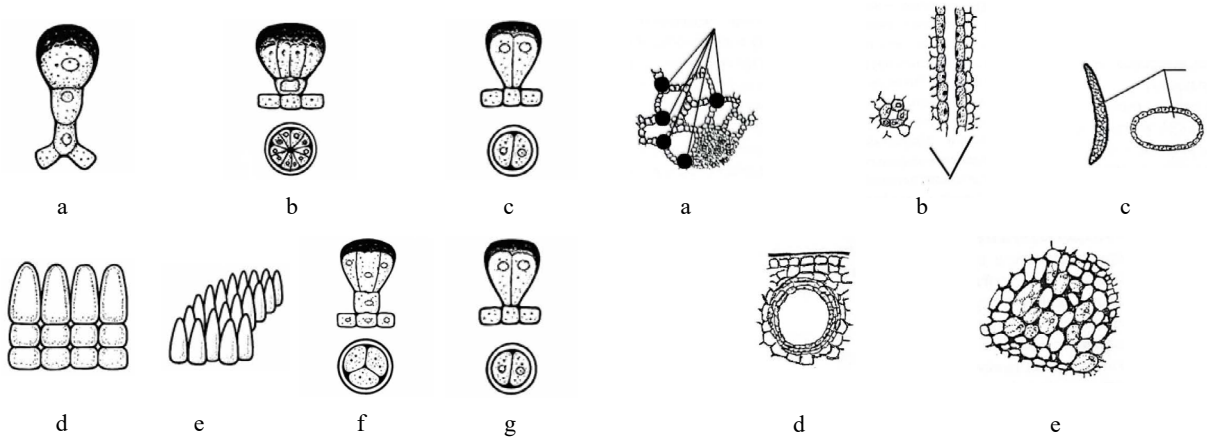


Figure 2 Essential oil receptacles
External oil receptacles (left): (a) geranium hair; (b) rosemary gland; (c) patchouli hair; (d) papillary hairs of rose petal; (e) upper epidermis of rose petal; (f) peppermint hair; and (g) eugenol basil gland;
Internal oil receptacles (right): (a) idioblasts of calamus rhizomes; (b) resin duct (channel); (c) essential oil channel of coriander fruit; (d) eucalyptus leaf gland; (e) water-bearing idioblasts of geranium with essential oil in a finely dispersed state

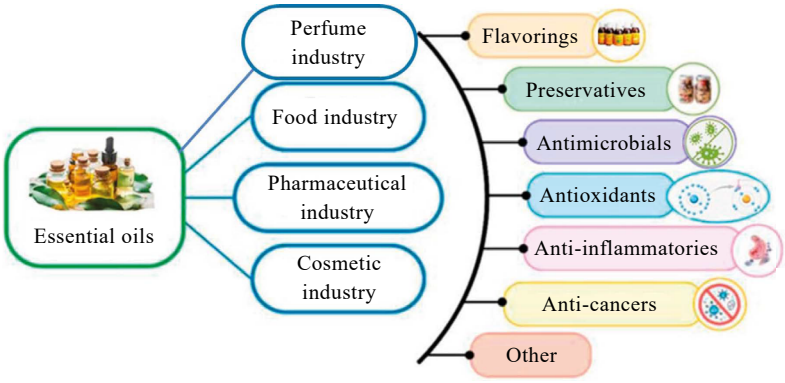


Figure 3 Essential oil applications

terpene compounds, which are responsible for the plant's scent [24]. Physicochemically, essential oils are usually transparent, or sometimes yellowish, optically active liquids. Some oils are exceptions and have rich colors: dark brown (cinnamon oil), green (bergamot oil), blue or greenish-blue (wormwood, chamomile, and yarrow oils), or red (thyme oil). Almost all essential oils have a relative density of less than 1 g/cm^3 (except for clove, basil, and cinnamon oils), as well as unique taste and aroma [25].

Terpene compounds in essential oils are primarily members of the mono- and sesquiterpene classes, as well as their oxygen-containing derivatives (ketones, alcohols, aldehydes, acids, esters, lactones, etc.) known as terpenoids. These compounds are systems of conjugated double bonds, making them extremely reactive during metabolic processes within plant cells. Terpenes are also essential components of natural balsams and resins [26]. In addition to terpenes, essential oils contain aromatic hydrocarbons, organic sulfides, amines, as well as phenolic and heterocyclic compounds. Typically, a predominant terpene or terpenoid (or a mixture of both) determines the specific scent of oil, as well as its pharmacological properties.

In the food industry, essential oils are used as flavoring agents in soft drinks (kvass), confectionery (gingerbread, lollipops, caramel, chewing gum, fruit desserts), tea, meat dishes, cheeses, and liqueurs. They are also added to enrich the flavor of various spices, seasonings, sauces, table salt, sugar, and table vinegar. Their introduction into food products in the form of food essences or flavorings is regulated by State Standard 10-237-99 "Food Flavorings. Specifications" [27]. Since essential oils mainly consist of bioactive terpene compounds, they can be used in parapharmaceutical dietary supplements. These supplements are taken as part of preventative and adjuvant therapy, as well as to support the functional activity of organs and systems within physiological limits. However, they cannot be used to correct the chemical composition of human food, unlike nutraceuticals [2].

According to some studies [28], the active components of essential oils improve digestion and normalize the cardiovascular system, as well as have powerful effects on the genitourinary system and nervous tissue. All of this provides grounds for developing dietary supplements based on essential oils. As noted in a study of Baser and Bonello, the demand for plant extracts of essential oils is expected to grow due to a global trend toward replacing synthetic components in food products with natural ones [29]. In this regard, essential oils are a natural alternative to synthetic flavors and food preservatives, and they can be used to improve food safety and extend shelf life.

Essential oils have potential as additives for increasing the shelf life of food products. Patrignani *et. al.* [30] refer to many studies that used essential oils in pure form or as part of preparations and observed a significant increase in the shelf life of food products stored in containers made of cardboard, tin, glass, polyethylene, or natural fabrics. Furthermore, one of the studies found that some components of essential oil, such as citral, citronellol, eugenol, farnesol, and nerol, can protect chili seeds and fruits from fungal infection for six months. The authors also reported that the essential oil isolated from *Ageratum conyzoides* L. increased the shelf life of mandarins by 30 days by fighting against blue mold rotting. In other studies, the essential oils of lemongrass (*Cymbopogon nardus* (L.) Rendle) and basil (*Ocimum basilicum* L.) controlled the development of anthracnose on bananas, increasing their shelf life by 21 days. Thus, essential oils are promising biocontrol agents acting against fungal and bacterial pathogens. Some researchers are exploring their use for integrating pathogens into food containers. For example, some oils can be used as fumigants in containers made of natural fabric, cardboard, and even wooden planks. They can also be introduced as fumigant sprays into the product itself [31].

Extraction of essential oils pre-treated with cold plasma. ***Cold plasma characteristics.*** The term "plasma", which was introduced by Irving Langmuir in 1927, was based on an analogy between its complex composition and that of blood plasma [32]. In the 1970s, plasma technologies were commercially used mainly in the electronics and polymer industries [33]. Over the past 5 years, however, cold plasma has been actively applied to food processes and technologies. Cold plasma is formed through the ionization of a gas by an electric discharge using various media (air, argon, oxygen, etc.). A cold plasma jet generates cations, anions, free and excited electrons, and a number of volatile atoms and molecules [34], which can be divided into reactive oxygen species and reactive nitrogen species. Its interaction with food products causes complex physical and chemical reactions to occur. Their effects include sterilization, enzyme inactivation, impact on the anatomical integrity of plant cells, and surface changes [35, 36]. The diversity of active cold plasma particles indicates high chemical activity, which is used for various purposes, including the bactericidal treatment of food products [37, 38].

As cold plasma technology developed, it began to be used to modify the surface and capillary-porous structure of food materials due to a so-called "etching" effect [39].

Cold plasma generation methods. Cold plasma can be generated in various ways (Fig. 4): a dielectric barrier discharge (two oppositely charged plates), an arc discharge [40], a microplasma jet [41], a corona discharge, and a microplasma jet supported by thermionic emission. The processes of cold plasma treatment are shown in Fig. 4.

Thermionic emission-supported cold plasma can form a thin cord of charged particles with a directed energy effect on the object treated. Furthermore, due to thermionic emission, electric field strengths are in the range of 6–8 kV/cm, compared to the typical range of 15–20 kV/cm for other cold plasma generation methods [35]. This reduces overall energy consumption and creates a controlled plasma combustion and treatment. With this type of electrophysical action, the material remains unheated, and the process can be scaled up in the flow [20, 42].

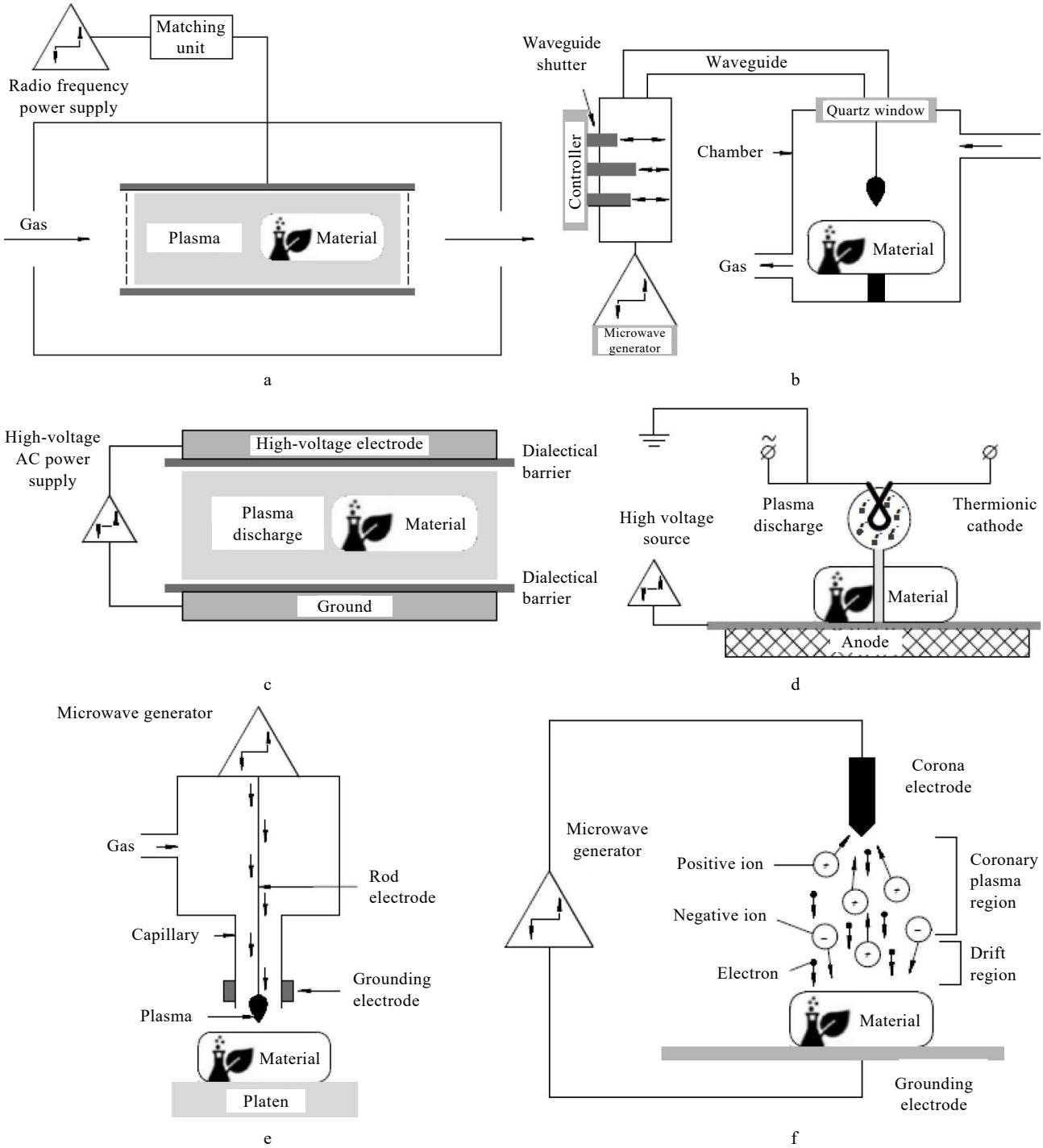


Figure 4 Cold plasma treatment schemes: (a) radio frequency discharge; (b) microwave discharge; (c) dielectric barrier discharge; (d) microplasma discharge; (e) glow discharge flow; and (f) corona discharge

With a corona discharge, cold plasma generation requires a system of point-on-plane electrodes spaced at 3–10 cm from each other. Although low energy consumption is an advantage of cold plasma, the corona discharge only has an "etching" effect on the surface of the material without penetrating its internal structure.

A cold plasma jet with pressurized gas supply is used most widely for cold plasma generation. The intensity of cold plasma treatment can be controlled by the generator power, treatment time, distance, and working gas flow rate [43]. Compared to other methods, a plasma jet is more flexible and is not limited by the space between the electrodes. Its major drawback, however, is a limited surface area and low penetration into the material structure, similarly to a corona discharge.

For a dielectric barrier discharge, the object under treatment is positioned between metal electrodes coated with a dialectic material. To cover a larger area, two plane-parallel electrodes are used, with at least one of them coated with a dielectric material [44]. To ensure

discharge stability, the distance between the two electrodes is limited to a few millimeters. A discharge at atmospheric pressure requires a sinusoidal or pulsed high-voltage power source. The main advantage is that food materials can be treated with cold plasma in dielectric packaging, such as polyethylene film. However, given the treatment area of several millimeters, this method can be used primarily for powdered materials.

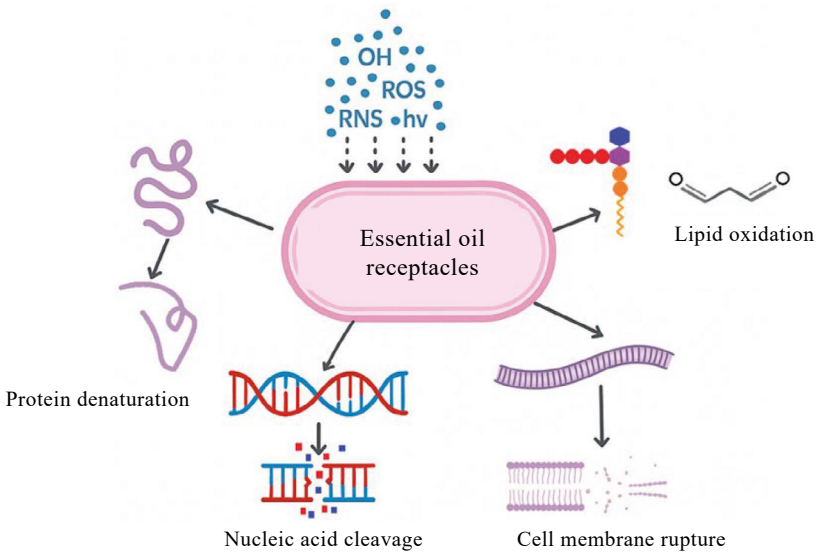
A Jacob's Ladder can be used to demonstrate an arc discharge in the air. For this, two or more electrodes are positioned perpendicularly to the plane. An arc is first ignited in the narrowest gap between the two electrodes and then slides in the direction of the injected gas, lengthening [45]. The sliding arc discharge has high energy and gas consumption, and most of the energy is used to stimulate chemical reactions rather than to heat the gas. Furthermore, compared to other plasma-generating devices, the sliding arc discharge can have a uniform effect over a large area, which enables its use in heat and mass transfer processes [40, 46].

Surface-type cold plasma treatment of essential oil materials. Figure 5 shows the principle that explains the mechanism of cold plasma action on the surface of plant materials. Particles of reactive oxygen species and reactive nitrogen species bombard and interact with the surface of the plant material in the form of a shell and a covering layer. This interaction between reactive particles and plant tissue components can be explained by lipid oxidation processes, membrane electroporation, protein denaturation, and nucleic acid cleavage [47]. Most studies describe it through the "etching" effect, which is associated with the decomposition of the wax shell [35] and the disintegration of plant cell membranes [48, 49]. Other approaches require high-precision equipment and a full spectrum of analyses, from the data on reactive plasma particles to the parameters of bioactive compounds.

Essential oil materials, with their target component in the internal structure, have a wax shell which acts a "diffusion barrier" for mass transfer [50]. Cold plasma treatment of the surface layer and the capillary-porous structure of the material reduces this barrier. Macedo *et al.* [51] studied the effect of cold plasma on the surface morphology of kapok fibers. The treatment parameters were: an electric current of 0.09–0.12 A, a voltage of 400–500 V, a sample's temperature of 72°C, an oxygen flow rate of 10 cm^3/min, and a working distance of 4.0 cm. The authors analyzed changes in fiber roughness and absorption characteristics caused by the treatment. Karunanithi *et al.* [52] reported the effect of dielectric barrier plasma on the morphology of betel leaf fibers. The authors found significant structural changes, the presence of damaged cells, and an etching effect. The impact of reactive particles on the integrity of oil globules affected the yield of subsequent extraction.

Khudyakov *et al.* [53] treated tobacco leaves (*Nicotiana tabacum* L. var. *virginia*) with cold plasma. The authors varied the discharge current and observed two main results. At low discharge currents (5 mA), the cellular structure acquired a darker color due to the interaction between reactive particles and tobacco leaf tissue. The resulting oxidation indicated the intense action of oxygen-containing reactive particles in cold plasma. Increasing the discharge current caused through holes to form on the surface of the tobacco leaf plate (Fig. 6).

The change in color can be explained by the degradation of chlorophyll. Ahmadian *et al.* [54] reported chlorophyll degradation and changes in phenolic components of peppermint, stinging nettle, and Schisandra leaves after cold plasma treatment using a dielectric barrier discharge. However, the specific mechanism of interaction between cold plasma particles and bioactive components of the plant materials remains unknown.



ROS – reactive oxygen species; RNS – reactive nitrogen species

Figure 5 Interaction between cold plasma and plant cell surface

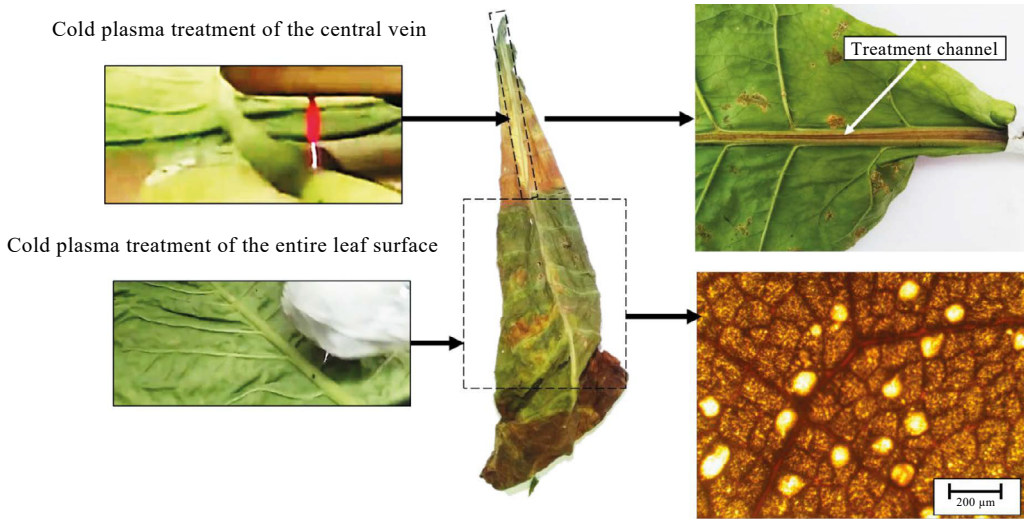


Figure 6 The effect of cold plasma on the plate and vein of a tobacco leaf

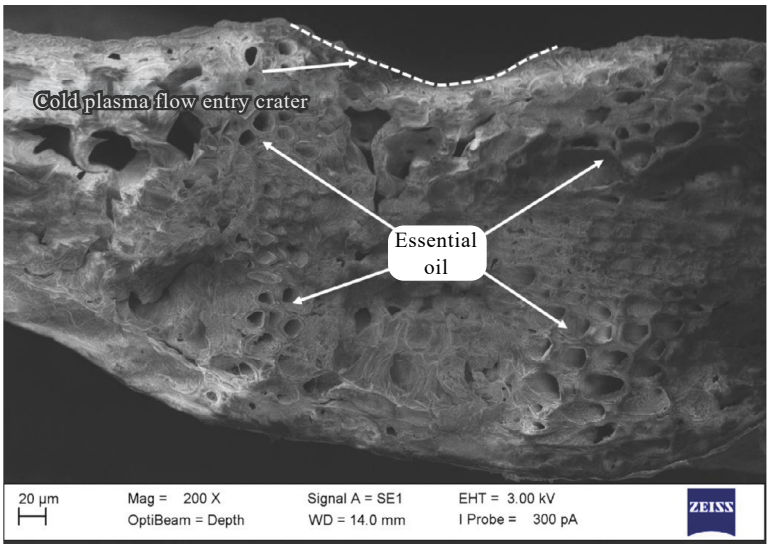


Figure 7 A section of a laurel leaf with internal essential oil receptacles (scanning electron microscope image) [57]

Noteworthily, Baser and Bonello reported that the temporary pores formed as a result of cold plasma treatment changed their size over time [29]. Pore size is known to directly affect the efficiency of extracting the target component from essential oil receptacles. Therefore, further research is needed to maximize the effect of cold plasma. In a study by Bunse *et al*. [28], an apple disc treated with cold plasma had a pore diameter of 100 µm. These electrically induced pores accelerated mass transfer by 15–20%. It should be noted that pores and channels can form on the surface of herbaceous plants as well. For example, positive effects were observed when treating the stem of hyssop (*Hyssopus officinalis* L.) with cold plasma [54, 56].

The effectiveness of the "etching" effect of cold plasma treatment depends on the thickness of the material layers and the presence of air gaps. Consequently, longer treatment and higher moisture of the material can significantly increase the number of micropores and cracks on the treated surface, which affects the duration of the drying process [20, 49].

Penetrating cold plasma treatment of essential oil materials. As noted above, the surface effects caused by cold plasma can accelerate the removal of the diffusion barrier in the material. However, cold plasma can also affect the internal structure of the material. Since essential oil receptacles can be located in its thickness, removing the diffusion barrier of the wax shell is only the first part of deep processing. The next barrier to effective mass transfer during essential oil extraction lies in plant cell membranes and internal tissue structures. It was not until recently that researchers began to examine the use of cold plasma to improve essential oil extraction by modifying the internal structure of the material. Spark discharge or thermionic emission methods (Fig. 4) are typically used for penetrating effects.

As shown in Fig. 7, essential oil receptacles are located in the thickness of a laurel (*Laurus nobilis* L.) leaf,

which requires penetrating cold plasma exposure. The discharge passed through the structure of the material, creating a developed structure on the surface of essential oil receptacles. Khudyakov *et al*. [57] observed similar effects of a low-current spark discharge on the tissues of lavender inflorescences.

Auguste *et al*. [58] reported the effects of cold plasma treatment on the physical and biochemical properties of basil leaves. The highest concentration of estragole was found in the leaves, while linalool dominated in the flowers, followed by estragole, eugenol, eucalyptol, and methyl cinnamate. Overall, cold plasma treatment increased the yield of antioxidant components in the essential oil extracts.

Cold plasma treatment had a penetrating effect on tobacco leaves, forming through holes of 40–50 μm in the leaf blade [53]. Keshavarzi *et al*. [59] studied the effects of cold plasma on the components of *Camellia sinensis* (L.) Kuntze leaves. Pectin and cellulose are the main components of a plant cell wall. Based on the data obtained by Cao *et al*. [60], we can assume that pectin molecules may be ruptured by the cleavage of the C_4–O covalent bond, resulting from oxidation caused by cold plasma exposure. Consequently, cold plasma treatment can promote the rupture of covalent bonds in the cell wall, thereby increasing the rate of water diffusion.

Despite the complexity of cold plasma impact on multicomponent food products, only the "etching" effect and the electroporation of plant cell membranes have been confirmed for most of the studied materials. However, important factors include the depth of cold plasma penetration into the material structure, the nature of its propagation in the cross-section of the material, and the size of pores and channels forming in the thickness of the material. Various research groups are working on these problems in Europe, China, America, and the Middle East [40, 61, 62].

Efficiency factors of essential oil extraction using cold plasma treatment. There has been limited research into the effects of cold plasma on essential oil extraction. This is primarily due to high demands placed on experimental design and lack of high-tech equipment. These studies mainly focus on increasing the yield of essential oil. However, their results are quite contradictory. Some studies demonstrated a negative effect of cold plasma on essential oil yield. For example, Jangi *et al*. [63] reported a decrease in the yield of essential oil from hyssop (*H. officinalis*) leaves treated with cold plasma. Similar results were observed by Ebadi *et al*. [64] for lemon verbena (*Aloysia citrodora* L.) extracts exposed to prolonged cold plasma treatment. A positive effect of cold plasma treatment was reported for betel leaves (*Piper betle* L.) [52], mint leaves (*Mentha spicata* L.) [65], thyme leaves (*Thymus vulgaris* L.) [66], black pepper (*Piper nigrum* L.) [67], and cumin seeds (*Cuminum cyminum* L.) [68]. The extraction efficiency was analyzed against such parameters as the power level and duration of cold plasma treatment, the plant type (matrix structure, type of cutting), and the use of concomitant extraction methods (Table 1).

The use of surface plasma treatment required high energy consumption and long exposure times, with a relatively small increase in essential oil yield [66]. However, the use of a combined approach (e.g., cold plasma and microwave exposure) shortened the extraction time or reduced the amount of energy consumption, increasing the yield of essential oil [52].

As noted above, cold plasma treatment improves extraction primarily by changing the microstructure of the material surface (e.g., creating micro-holes in plant cell walls), thereby accelerating mass transfer [69]. In addition, reactive plasma particles destroy non-covalent bonds in the polymer bonds that make up the cell walls, reducing their stability and promoting the formation of additional intercellular spaces and cavities [70]. Namjoo *et al*. [69] also reported changes in the physicomechanical properties of the materials. Jangi *et al.* [63] suggested that cold plasma destroys glandular trichomes –

Table 1 Parameters and efficiency of cold plasma treatment

Material and method of treatment	Treatment efficiency	Reference
Hyssop leaves (*Hyssopus officinalis* L.) Barrier discharge	Decrease in essential oil yield by 33–56%	[63]
Lemon verbena (*Aloysia citrodora* L.) Microwave plasma in a low-pressure gas environment	Decrease in essential oil yield by 36.7%	[64]
Betel leaves (*Piper betle* L.) Microwave plasma	Increase in essential oil yield by 3.33 ± 1.2%	[52]
Mint leaves (*Mentha spicata* L.) Barrier discharge	Increase in essential oil yield by 1.81%	[65]
Thyme leaves (*Thymus vulgaris* L.) Barrier discharge	Increase in essential oil yield by 20%	[66]
Lavandin inflorescences (*Lavandula hybrid* var. *grosso*) Barrier discharge	Increase in essential oil yield by 0.25% after treatment for 1 min and decrease by 0.12% after treatment for 10 min	[16]
Black peppercorns (*Piper nigrum* L.) Sliding discharge	Increase in essential oil yield by 27.6%	[67]
Cumin seeds (*Cuminum cyminum* L.) Argon plasma	Increase in essential oil yield by 44% compared to control	[68]

epidermal structures found in 30% of all plants. These structures are responsible for the production and storage of eosinophils. Low exposure to cold plasma can increase the yield of eosinophils.

Shokoohi *et al.* found that pretreatment with cold plasma can affect not only the yield of essential oil in the extract, but also its composition [66]. Although some researchers observed no such effects [66, 68], most studies emphasized the duration and intensity of plasma treatment as having the key effect on the quality of essential oil. Jangi *et al.* reported a significant decrease in the contents of major compounds in hyssop leaves treated with cold plasma for longer times at all intensity levels [63]. At high intensity and the longest treatment time, the contents of trans-pinocamphone, *β*-pinene, and *cis*-pinocamphone decreased by 17, 21.3, and 28.6%, respectively. However, at low and medium intensity and a relatively short time (1 and 5 min), cold plasma treatment had a positive effect on the composition of essential oils.

In general, oxygenated compounds are not as important for the quality of essential oils as monoterpene hydrocarbons, which have a more pronounced scent. The above studies found a direct relationship between the duration of cold plasma treatment and its intensity, as well as the contents of oxygenated compounds and monoterpene hydrocarbons. Short treatments of 1–3 min increased the conversion of monoterpene hydrocarbons over time. Longer treatments of over 3 min had the opposite effect – an increased amount of monoterpene hydrocarbons caused by the decomposition of oxygenated monoterpenes [64].

A combined use of cold plasma and ultrasound had a positive effect on the composition of essential oils [71], increasing the amount of oxygenated compounds. Combining cold plasma with microwave treatment resulted in a yield of 3.33% compared to the control at 2.87% [72]. This was because oxygenated molecules with higher dipole moments interacted vigorously with microwaves compared to monoterpene hydrocarbons with lower dipole moments, resulting in a smaller thermal and hydrolytic effect [73]. Other factors that influence the final composition of essential oils include the type of cold plasma working gas, the type of essential oil material, the location of essential oil receptacles, and the composition of bioactive components [74].

Although the studies show that cold plasma treatment is used to accelerate extraction, we still do not know how it affects the solid phase of the capillary-porous body of essential oil material. It is still unclear whether the plasma treatment modifies its structure creating new channels, or whether the essential oil undergoes a transition from a bound to a free form. To address this, we need to develop a method for evaluating extraction kinetic curves that describes the bond form of the essential oil.

Industrial application of cold plasma technology for essential oil extraction. Industrial belt-type units have been created to prepare plant materials for extraction [42]. Figure 8 shows one of such units developed by the Kuban State University of Technology in partnership with Shelris Company. This unit can treat up to one ton of material per hour, followed by its transfer for extraction or steam distillation.



Figure 8 Industrial belt-type unit for cold plasma treatment created by Kuban State University of Technology and Shelris Company

The past year saw a steady increase in the number of patents related to the use of cold plasma in the food industry. For examples, Pańka *et al.* [75] presented a pilot system based on a belt conveyor for using cold plasma to sterilize food product surfaces. This system could potentially be adapted for preparing essential oil materials for extraction.

Technological challenges of using cold plasma for essential oil extraction. The implementation of innovative solutions in the food and essential oil industries requires combined efforts of scientists from various fields, as well as manufacturers and agricultural suppliers. Cold plasma treatment offers a number of advantages. In particular, cold plasma can: reduce the diffusion barrier in the essential oil material by having an etching effect that can improve subsequent extraction; increase the yield of essential oil extraction (although quality assessment is vital at every stage); and be generated by a variety of highly efficient and scalable methods.

Below are several directions for the intensive implementation of cold plasma in essential oil extraction processes.

The current equipment for cold plasma treatment is expensive and needs to be adapted for each type of plant material. Commercial units are being developed for generating cold plasma for extraction, but mostly on a small scale. Therefore, the limited facilities that are available today have to be tried out on a wide range of plant materials, which, in turn, have to be adapted to industrial conditions. This process can be facilitated by expanding and advancing research and development in this area.

One of the limitations of cold plasma is its low penetration into thick materials. This can reduce the efficiency

of the equipment, making it inapplicable on a large scale, and lower the quality of the treatment. Therefore, better technical organization of the process and special preparation (e.g., unifying thickness and fill rate) are needed to ensure high-quality cold plasma treatment.

Promising research directions. Food Industry 5.0 requires the use of alternative, less energy-intensive approaches to extracting essential oils. This process can be made more efficient and cost-effective by incorporating modern electrophysical technologies into traditional processes and using smart systems at all stages of the food supply chain [88]. Furthermore, these technologies need to be green and ensure high quality of the resulting essential oils. Therefore, a promising direction could be a symbiosis of advanced electrophysical technologies in the overall food production chain (Fig. 9). This approach can have a multiple synergistic effect, enabling the production of high-quality essential oils in sufficient quantities.

The analysis of innovative physical methods in essential oil production revealed a number of technological barriers for cold plasma treatment. To overcome them, we need to:

– identify reactions and mechanisms of interaction between reactive plasma particles and individual components of food matrices (lipids, proteins, carbohydrates, etc.). Our systematic review of experimental studies showed a lack of data on the effects of cold plasma treatment on individual food components, including wax shells, pectin, cellulose, and others. This requires an in-depth analysis of reactive cold plasma particles and component compositions of materials under treatment;

– optimize cold plasma generation methods and ensure a continuous material flow to reduce overall energy costs. For example, atmospheric cold plasma treatment takes place under ambient conditions without the use of vacuum equipment. In addition, there is a need for a standardized methodology for calculating energy indicators of cold plasma treatment;

– analyze the effect of cold plasma treatment on the size of electrically induced pores and channels, as well as determine the effect of the pore size on the chemical composition of the resulting essential oil, which is an important quality indicator; and

– determine the electrical and dielectric characteristics of essential oil materials, essential oils, and by-products. The dielectric properties of essential oils are understudied, although the use of electrophysical treatment requires a thorough understanding of the mechanism by which electromagnetic fields affect plant materials, as well as their response.

CONCLUSION

This review presented the latest advances in the application of cold plasma treatment in essential oil extraction. Cold plasma treatment significantly increases the depth of extraction and accelerates the rate of essential oil recovery by 15–20%. Various modes of cold plasma treatment create an “etching” effect on surface tissues and cause electroporation of essential oil globule membranes. These effects contribute to a developed capillary-porous structure in essential oil materials.

One of the downsides to cold plasma treatment is insufficient penetration of reactive plasma particles into the plant material structure, limiting the disruption of essential oil globule membranes. Further research is needed to identify optimal modes of cold plasma treatment for essential oil materials with varying thickness. Localized overheating from cold plasma can affect the quality of the resulting essential oil and therefore must be avoided.

A methodology for assessing the form of essential oil binding to the capillary-porous structure needs to be developed to better understand the mechanism by which cold plasma affects essential oil extraction. This methodology will describe the physical model of essential oil transfer and lay the foundation for developing a mathematical model for extracting essential oils pre-treated with cold plasma.

The existing studies use a limited range of essential oil materials to explore the potential of cold plasma for

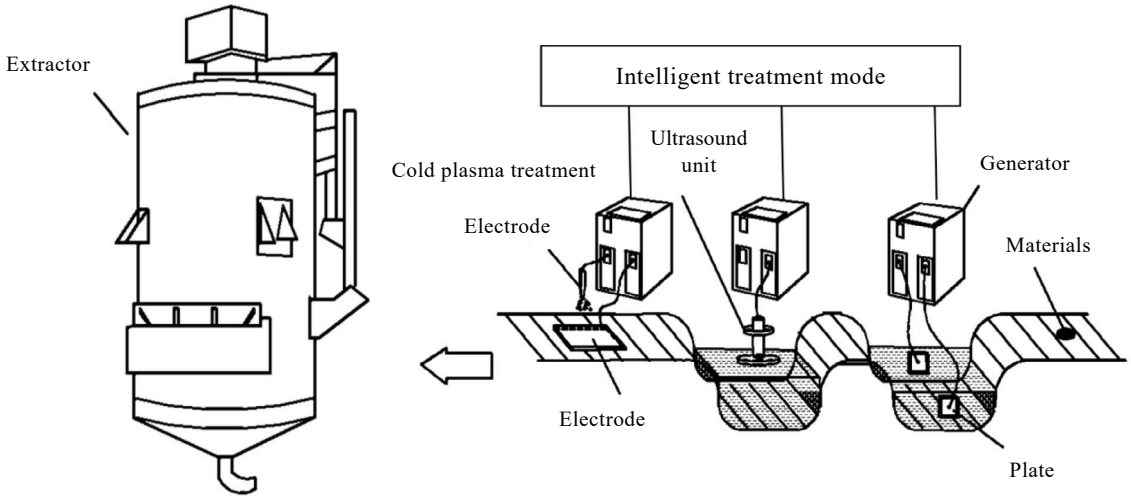


Figure 9 Preparation of food materials for extraction (based on Industry 5.0)

extraction. Therefore, the range of plant materials needs to be expanded to test the technology of cold plasma treatment and adjust it to industrial processes and scales.

CONTRIBUTION

A.G. Sherstyukov and O.I. Andreeva were responsible for information retrieval and graphic design. V.E. Tarasov and I.A. Shorstkii were involved in information retrieval and supervised the writing process.

CONFLICT OF INTEREST

The authors declared no potential conflict of interest regarding the research, authorship, and/or publication of this article.

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