Review

Encapsulation of Essential Oils via Spray Drying: Recent Developments in Wall Materials, Emulsion Technologies, and Food Applications

Simić Pavle[1], Poklar Nataša Ulrih[1,*]

1. University of Ljubljana, Biotechnical faculty, Ljubljana, Slovenia
* Correspondence: natasa.poklar@bf.uni-lj.si

Citation: Simić P, Poklar Ulrih N. Encapsulation of Essential Oils via Spray Drying: Recent De-velopments in Wall Materials, Emulsion Technologies, and Food Applications. Proceedings of Socratic Lectures. **2025**, 13, 62-69. https://doi.org/10.55295/PSL.13.2025.8

Publisher's Note: UL ZF stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Abstract:
The encapsulation of essential oils represents a promising strategy to overcome their inherent volatility, chemical instability and limited water solubility, which limit their wider application in food and nutraceutical products. This review provides a comprehensive examination of recent advances in wall materials and emulsion technologies used for the microencapsulation of essential oils by spray drying. Traditional wall materials such as maltodextrin, gum arabic and whey protein isolates have been extensively studied; however, novel biopolymers have proven to be effective alternatives that allow for improved encapsulation efficiency and controlled release. Improved emulsion stability can be achieved by high pressure homogenisation and ultrasonic treatment. They have facilitated the production of stable emulsions with a uniform droplet size distribution, which is crucial for efficient encapsulation. Nanoemulsions and Pickering emulsions have great potential to produce very stable microcapsules with essential oils compared to conventional emulsions. Advances in spray drying technology, such as electrostatic spray drying and nanospray drying, have further improved the bioavailability of essential oils and optimised the release kinetics. The applications of spray-dried essential oils have shown significant potential for extending shelf life, reducing synthetic additives and improving flavour in various foods, as well as for the development of functional food supplements. Future research should focus on process optimisation, scalability and evaluation of release behaviour under real storage and consumption conditions.

Keywords: Essential oil, Spray drying, Encapsulation, Wall material, Emulsion

1. Introduction

Essential oils (EOs) represent a diverse group of secondary metabolites derived from various parts of aromatic plants (S. Sharma et al., 2021). These oils are characterized by their complex composition, including low molecular weight lipophilic compounds such as aliphatic hydrocarbons, phenyl propanoids, terpenoids, and phenolic constituents. Additionally, EOs contain a variety of oxygenated compounds like aldehydes, ketones, esters, oxides, and alcohols. Despite their strong lipophilic and volatile nature, which renders them almost insoluble in water, EOs are widely utilized for their antioxidant, anti-inflammatory and antimicrobial properties (Amorati et al., 2013; Chouhan et al., 2017; Miguel, 2010). However, due to their instability and lipophilicity, only a limited number of EOs are commercially viable, with approximately 300 types being used out of the 3000 known varieties (Dima & Dima, 2015).

EOs are volatile and heat-sensitive compounds that can degrade when exposed to light, air, and moisture. This susceptibility to oxidation and environmental factors limits their practical applications. To address these challenges, encapsulation is employed as a strategy to enhance the stability of EOs. This technique involves encasing the oils in a protective coating, which helps to maintain their integrity during handling, processing, and storage (Veiga et al., 2019).

Spray drying is indeed the most used encapsulation technique in the food industry. This method involves converting liquid mixtures into dry powders by rapidly drying them with a hot gas. It is highly effective for encapsulating active ingredients, including essential oils, as it helps to preserve their stability and extend their shelf life (Piñón-Balderrama et al., 2020).

This review focuses on exploring different wall materials, including novel and emerging options, as well as novel emulsion techniques used for encapsulating essential oils. It also discusses new spray drying technologies, recent scientific advancements, future perspectives, and how spray-dried essential oils are applied in the food industry.

2. Wall Materials for Spray Drying of Essential Oils

2.1. Selection Criteria for Wall Materials

The selection of suitable wall materials for the encapsulation of essential oils in the food industry is based on several decisive criteria. Firstly, the chemical compatibility between the wall material and the core substance is crucial to avoid undesirable interactions that could affect product stability. The wall material must provide effective protection of the active ingredient against environmental influences such as light, heat, oxygen and moisture, which can lead to degradation. Controlled release behaviour is also an important prerequisite to enable a targeted and sustained release of the encapsulated active ingredient under certain physiological conditions such as pH changes or enzymatic activity (Weisany et al., 2022).

Good solubility and dispersibility of the wall material are crucial to achieve homogeneous distribution of the active ingredient and to maintain emulsion stability during processing. The rheological properties of the material must support efficient microencapsulation, especially in spray drying, where viscosity and flow behaviour influence droplet formation and drying performance (Tavares et al., 2022). Sensory neutrality in terms of odour, taste and colour is important to ensure that the wall material does not alter the organoleptic properties of the final food product. Finally, the selected material should be food safe, comply with regulatory standards (e.g. GRAS status), be economically viable for industrial production and be both biodegradable and bioavailable to ensure sustainability and effective delivery of the encapsulated compound (Shishir et al., 2018).

2.2 Common and Novel Wall Materials

Various carrier materials are used for the encapsulation of essential oils (**Figure 1**), which are selected according to compatibility with the encapsulation methods, target applications and stability requirements. Natural polysaccharides — such as maltodextrin, gum arabic, chitosan, alginate and pectin — are commonly used due to their biodegradability, low toxicity and good thermal stability (Fernandes et al., 2014). Proteins such as whey protein, casein, gelatine and zein also serve as efficient carriers as they are biocompatible and can be released in a controlled manner, although they are pH and temperature dependent

(Chen et al., 2015; Laina et al., 2024). Lipid-based carriers, both solid and liquid offer high encapsulation efficiency and prolonged release profiles (Yammine et al., 2024).

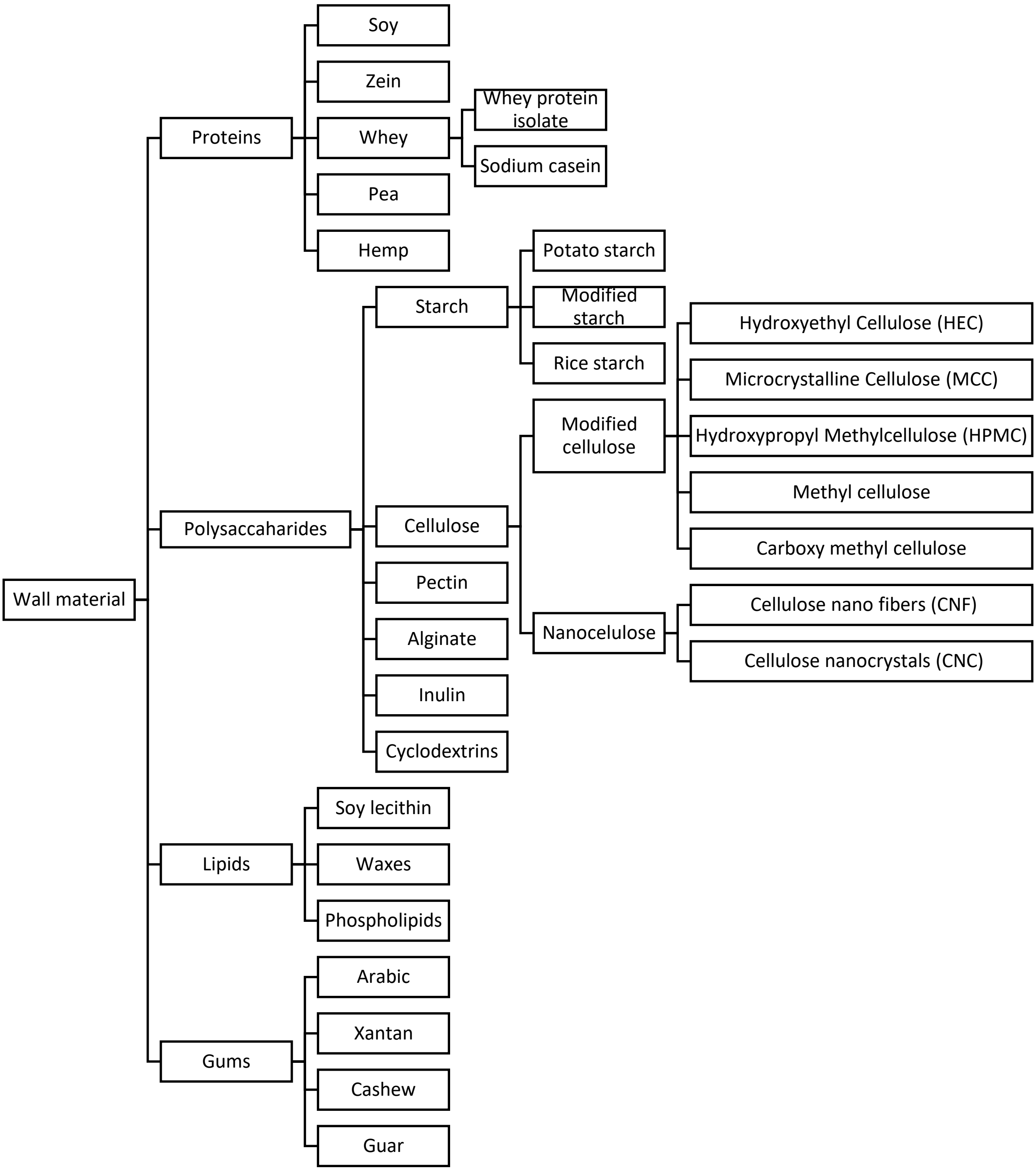

Figure 1. Wall materials used for encapsulation od essential oils

In recent years, novel wall materials have been investigated. The study by Kurek and Singh (2020) reports that among the various carrier materials investigated — combinations of maltodextrin with hemp, pea and rice proteins — the highest encapsulation efficiency was achieved with rice protein in combination with maltodextrin. This formulation outperformed the formulations with hemp and pea proteins, suggesting that rice protein maltodextrin is the most effective wall material for spray-dried encapsulation of hemp seed oil. Also, in another comparison study on spray-drying orange essential oil, it was concluded that formulations containing more than 50% chemically and thermo-mechanically modified rice starch as the primary wall material achieved the highest encapsulation efficiency

versus those using native rice starch, maltodextrin, or protein (Márquez-Gómez et al., 2018). Recently, novel material such as chachafruto flour have been explored for essential oil encapsulation due to their natural emulsifying properties (Daza et al., 2025). At concentrations of 3% and 4%, chachafruto flour significantly improved emulsion stability over 168 hours at room temperature, attributed to its starch and 20.5% protein content.
Overall, the choice of wall materials has a significant impact on the physicochemical properties, release mechanisms and functional performance of EO-loaded particles. Biocompatibility, biodegradability, regulatory status and economic feasibility are key criteria in optimising the selection of wall materials for food applications.

3. Emulsion Design for Improved Encapsulation

Emulsions are critical to the efficiency and stability of essential oil microparticles produced by encapsulation processes such as spray drying. Key physicochemical parameters—including droplet size, zeta potential, surface tension, rheological behaviour, and microstructure—are commonly evaluated to predict emulsion stability (Campelo et al., 2017). Maintaining emulsion stability from homogenization through to drying is essential to ensure the quality and performance of the resulting microcapsules, particularly in food and pharmaceutical applications.
High-speed homogenisation is generally used to produce coarse emulsions by mechanically reducing the droplet size. High pressure homogenisation (HPH) further refines the droplet size and improves the uniformity and stability of the emulsion. Another method for producing fine emulsions is ultrasonic treatment, which is particularly suitable for heat-sensitive essential oils due to its lower heat load (Lakshmayya et al., 2023). A study by Campelo et al. (2016) found that homogenisation followed by ultrasonic treatment was more efficient in emulsion formation than the homogenisation process alone.

3.1. Nanoemulsions & Pickering emulsions

Nanoemulsions and emulsions are colloidal dispersions consisting of two immiscible liquids and are often used in food systems. A key distinguishing feature is the droplet size, with emulsions having a droplet diameter of more than 200 nm, while nanoemulsions are characterised by droplets smaller than 200 nm (McClements, 2011). Nanoemulsions significantly enhance the properties of essential oils by increasing their stability, bioavailability and antimicrobial efficacy (K. Sharma et al., 2022). Due to their small droplet size, nanoemulsions provide a larger surface area that allows better interaction with microbial cell membranes, thereby improving their antimicrobial activity. They also protect essential oils from environmental factors such as temperature, light and oxygen that can degrade their active ingredients, ensuring their functionality over a longer period of time. In addition, nanoemulsions enable a more controlled and sustained release of essential oils, prolonging their antimicrobial effect in food. Compared to conventional emulsions, nanoemulsions are optically transparent and thermodynamically unstable, but their small droplet size provides greater stability against phase separation and creaming. In addition, nanoemulsions improve the dispersibility and solubility of essential oils in aqueous food systems, which is a challenge with conventional emulsions (Pathania et al., 2018). They also help to improve the sensory properties of foods by minimising the strong flavours and odours associated with essential oils due to better encapsulation and lower volatility. Overall, nanoemulsions are superior to standard emulsions when it comes to effectively and efficiently utilising the bioactive properties of essential oils in food and pharmaceutical applications. There is still scepticism in the food industry about the use of nanoparticles, which requires a thorough investigation of their uptake, entry into the food chain and distribution under both in vitro and in vivo conditions (Maurya et al., 2021). Such comprehensive assessments are essential to ensure the safe and effective use of essential oil–based nanoemulsions in food systems.
Pickering emulsions are a class of emulsions stabilised by solid particles that irreversibly adsorb at the oil–water interface and represent an alternative to conventional surfactant-based systems (Ming et al., 2023). They enhance the stability of essential oils by preventing droplet coalescence through electrostatic and steric mechanisms, reducing droplet size and

are usually produced by high-energy processes such as homogenisation or ultrasonic treatment (Souza et al., 2021). The solid particles at the interface of Pickering emulsions improve the resistance of oil droplets to coalescence and degradation during high-temperature spray drying. This stabilization contributes to the formation of more uniform and structurally robust microparticles after drying. Moreover, Pickering-based systems offer better encapsulation efficiency and protection of sensitive bioactives, such as essential oils, compared to conventional emulsions (Meng et al., 2024). Therefore, integrating Pickering emulsions into spray-drying encapsulation strategies presents a promising approach for improving the stability and functionality of the final powdered products.

4. Emerging Spraying Techniques

Electrospraying, nano spray drying and electrostatic spray drying are emerging encapsulation and drying techniques that utilise electrical forces to process sensitive bioactive compounds such as essential oils (Jayaprakash et al., 2023). In electrospraying, a high voltage is applied to a liquid fed through a nozzle, creating an electric field that atomises the liquid into fine droplets. These droplets dry quickly on their way to a grounded collector, forming micro- or nano-sized particles with high encapsulation efficiency without the need for high temperatures. Oregano essential oil was encapsulated into thermally stable chitosan nanoparticles using the electrospraying technique, achieving high encapsulation efficiency and monodisperse particles (Yilmaz et al., 2019). Electrospraying significantly enhanced the antifungal and fungistatic activity of the essential oil against *Alternaria alternata*, suggesting electrospraying as a promising method for controlled-release antimicrobial applications in food industry.

Nano spray drying, on the other hand, uses a modified spray drying setup with a vibrating mesh and an electrostatic particle collector. Nano-sized particles (less than 100 nm) are produced by forcing the liquid through laser-drilled holes in a vibrating mesh, while an electrostatic collector captures the ultra-fine particles and ensures a narrow size distribution (Jafari et al., 2021). Plati et al. (2021) used a nano-spray drying technique to encapsulate oregano essential oil in whey protein isolate–maltodextrin matrices. The resulting nanoparticles showed significantly improved antibacterial activity against both *Escherichia coli* and *Staphylococcus aureus* compared to the pure essential oil, emphasising their promising potential for food preservation.

In electrostatic spray drying, a pre-charged nozzle is used to atomise the material into droplets and then an electrostatic field is applied in a drying chamber to aid drying and collection. The principle is to create an electrostatic force that repels the liquid surface, allowing the solvent to evaporate at lower temperatures and protecting heat-sensitive materials (Jayaprakash et al., 2023). Highly sensitive compounds such as essential oils can be effectively encapsulated using electrostatic spray drying, which allows particle formation at low temperatures under controlled voltage conditions. Although the application of this technique for the encapsulation of essential oils is still limited, it shows considerable potential for the preservation of thermolabile bioactives.

5. Applications in Food Industry

Encapsulated essential oils can be used in various areas of the food industry; first and foremost, they can be used as food preservatives due to their antioxidant and antimicrobial properties.

Thyme essential oil has been encapsulated in chia mucilage and used in meat sausage as a partial or total substitute for sodium nitrate and nitrite (A. S. Souza et al., 2025). TEO from the capsules inhibited the growth of coagulase-positive staphylococci, E. coli, mesophilic aerobic bacteria and Salmonella. In another study by Radünz et al. (2020), in which TEO was encapsulated, it was concluded that TEO can be used as a natural preservative in hamburger-like meat products. Rosemary essential oil was encapsulated using whey protein isolate and inulin as the encapsulation matrix, effectively extending the shelf life of Minas Frescal cheese (Fernandes et al., 2017).

Spray-dried essential oils also have great potential in the flavour industry, where they can be used as flavour enhancers. In a study by Mehran et al. (2020), mentha essential oil was encapsulated in gum arabic and inulin. The results showed that SEO microcapsules can be used in various foods as flavourings and in chewing gum.

The essential oil of hops (*Humulus lupulus* L.) (HEO) has shown various applications in hot beverages (Su et al., 2023). HEO was encapsulated in modified starch and the controlled release from the capsules was determined. HEO microcapsules showed significant potential, highlighting the suitability of essential oil microcapsule formulations as promising flavouring agents for use in a range of hot beverage systems.

The dietary supplement sector is expanding rapidly and encapsulated essential oils have also proven to be functional ingredients in human nutrition. Spray-dried powder containing encapsulated oregano essential oil has been used to produce tablets (Partheniadis et al., 2019). Tablets with encapsulated essential oil successfully inhibited Gramme-negative and Gramme-positive bacteria and provided a controlled-release form of oral administration.

6. Conclusions

This review highlights the significant advances that have been made in the encapsulation of essential oils through the development of innovative wall materials and advanced spray drying techniques. Various biopolymers, including proteins, polysaccharides and lipids, have been investigated as encapsulation matrices to improve encapsulation efficiency, oxidative stability and controlled release properties. New wall materials such as chia mucilage, hemp, pea and rice proteins and chachafruto flour have shown promising results in improving the protective function of microcapsules. Novel emulsion production methods, including ultrasonic treatment and high-pressure homogenisation, have helped to produce more stable emulsions with uniform droplet size prior to spray drying.

Recent technological advances in spray drying, such as electrostatic spray drying and nanospray drying, have expanded the possibilities for producing microcapsules with improved structural and functional properties. These innovations have made it possible to better preserve the bioactivity of essential oils and to better control the release kinetics in food and dietary supplements. The integration of encapsulated essential oils into food systems has demonstrated the potential for natural preservation, flavour enhancement and the development of functional products. Overall, spray drying technologies hold promise for expanding the use of essential oils in the food industry while maintaining product safety, stability and sensory quality.

Funding: This research was supported by ERA Chair – Foodomics project 101186975 and Slovenian Research and Innovation Agency by P4-0121.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Amorati R, Foti MC, Valgimigli L. Antioxidant Activity of Essential Oils. J Agric Food Chem. 2013; 61:10835–47. DOI: 10.1021/jf403496k
2. Campelo PH, Junqueira LA, Resende JVD, Zacarias RD, Fernandes RVDB, Botrel DA, et al. Stability of lime essential oil emulsion prepared using biopolymers and ultrasound treatment. Int J Food Prop. 2017; 20(sup1): S564–79. DOI: 10.1080/10942912.2017.1303707
3. Chen H, Zhang Y, Zhong Q. Physical and antimicrobial properties of spray-dried zein–casein nanocapsules with co-encapsulated eugenol and thymol. J Food Eng. 2015; 144:93–102. DOI: 10.1016/j.jfoodeng.2014.07.021
4. Chouhan S, Sharma K, Guleria S. Antimicrobial Activity of Some Essential Oils—Present Status and Future Perspectives. Medicines. 2017; 4:58. DOI: 10.3390/medicines4030058
5. Daza LD, Umaña M, Eim VS. Effect of the addition of Chachafruto flour on the stability of oil-in-water emulsions and the physicochemical properties of spray-drying microcapsules. Food Chem. 2025; 462:141025. DOI: 10.1016/j.foodchem.2024.141025
6. Dima C, Dima S. Essential oils in foods: extraction, stabilization, and toxicity. Curr Opin Food Sci. 2015; 5:29–35. DOI: 10.1016/j.cofs.2015.07.003
7. Fernandes RVDB, Borges SV, Botrel DA. Gum arabic/starch/maltodextrin/inulin as wall materials on the microencapsulation of rosemary essential oil. Carbohydr Polym. 2014; 101:524–532. DOI: 10.1016/j.carbpol.2013.09.083

8. Fernandes RVDB, Guimarães IC, Ferreira CLR, Botrel DA, Borges SV, De Souza AU. Microencapsulated Rosemary (*Rosmarinus officinalis*) Essential Oil as a Biopreservative in Minas Frescal Cheese: Rosemary oil as a biopreservative in cheese. J Food Process Preserv. 2017; 41: e12759. DOI: 10.1111/jfpp.12759
9. Jafari SM, Arpagaus C, Cerqueira MA, Samborska K. Nano spray drying of food ingredients; materials, processing and applications. Trends Food Sci Technol. 2021; 109:632–646. DOI: 10.1016/j.tifs.2021.01.061
10. Jayaprakash P, Maudhuit A, Gaiani C, Desobry S. Encapsulation of bioactive compounds using competitive emerging techniques: Electrospraying, nano spray drying, and electrostatic spray drying. J Food Eng. 2023; 339:111260. DOI: 10.1016/j.jfoodeng.2022.111260
11. Kurek MA, Pratap-Singh A. Plant-Based (Hemp, Pea and Rice) Protein–Maltodextrin Combinations as Wall Material for Spray-Drying Microencapsulation of Hempseed (Cannabis sativa) Oil. Foods. 2020; 9:1707. DOI: 10.3390/foods9111707
12. Laina KT, Drosou C, Krokida M. Comparative assessment of encapsulated essential oils through the innovative electrohydrodynamic processing and the conventional spray drying, and freeze-drying techniques. Innov Food Sci Emerg Technol. 2024; 95:103720. DOI: 10.1016/j.ifset.2024.103720
13. Lakshmayya NSV, Mishra AK, Mohanta YK, Panda J, Naik B, Mishra B, et al. Essential oils-based nano-emulsion system for food safety and preservation: Current status and future prospects. Biocatal Agric Biotechnol. 2023; 53:102897. DOI: 10.1016/j.bcab.2023.102897
14. Márquez-Gómez M, Galicia-García T, Márquez-Meléndez R, Ruiz-Gutiérrez M, Quintero-Ramos A. Spray-dried microencapsulation of orange essential oil using modified rice starch as wall material. J Food Process Preserv. 2018; 42:e13428. DOI: 10.1111/jfpp.13428
15. Maurya A, Singh VK, Das S, Prasad J, Kedia A, Upadhyay N, et al. Essential Oil Nanoemulsion as Eco-Friendly and Safe Preservative: Bioefficacy Against Microbial Food Deterioration and Toxin Secretion, Mode of Action, and Future Opportunities. Front Microbiol. 2021; 12:751062. DOI: 10.3389/fmicb.2021.751062
16. McClements DJ. Edible nanoemulsions: fabrication, properties, and functional performance. Soft Matter. 2011; 7:2297–2316. DOI: 10.1039/C0SM00549E
17. Mehran M, Masoum S, Memarzadeh M. Microencapsulation of Mentha spicata essential oil by spray drying: Optimization, characterization, release kinetics of essential oil from microcapsules in food models. Ind Crops Prod. 2020; 154:112694. DOI: 10.1016/j.indcrop.2020.112694
18. Meng W, Sun H, Mu T, Garcia-Vaquero M. Future trends in the field of Pickering emulsions: Stabilizers, spray-dried microencapsulation and rehydration for food applications. Trends Food Sci Technol. 2024; 150:104610. DOI: 10.1016/j.tifs.2024.104610
19. Miguel MG. Antioxidant and Anti-Inflammatory Activities of Essential Oils: A Short Review. Molecules. 2010; 15:9252–9287. DOI: 10.3390/molecules15129252
20. Ming L, Wu H, Liu A, Naeem A, Dong Z, Fan Q, et al. Evolution and critical roles of particle properties in Pickering emulsion: A review. J Mol Liq. 2023; 388:122775. DOI: 10.1016/j.molliq.2023.122775
21. Partheniadis I, Vergkizi S, Lazari D, Reppas C, Nikolakakis I. Formulation, characterization and antimicrobial activity of tablets of essential oil prepared by compression of spray-dried powder. J Drug Deliv Sci Technol. 2019; 50:226–236. DOI: 10.1016/j.jddst.2019.01.031
22. Pathania R, Khan H, Kaushik R, Khan MA. Essential Oil Nanoemulsions and their Antimicrobial and Food Applications. Curr Res Nutr Food Sci J. 2018; 6:626–643. DOI: 10.12944/CRNFSJ.6.3.05
23. Piñón-Balderrama CI, Leyva-Porras C, Terán-Figueroa Y, Espinosa-Solís V, Álvarez-Salas C, Saavedra-Leos MZ. Encapsulation of Active Ingredients in Food Industry by Spray-Drying and Nano Spray-Drying Technologies. Processes. 2020; 8:889. DOI: 10.3390/pr8080889
24. Plati F, Papi R, Paraskevopoulou A. Characterization of Oregano Essential Oil (Origanum vulgare L. subsp. hirtum) Particles Produced by the Novel Nano Spray Drying Technique. Foods. 2021; 10:2923. DOI: 10.3390/foods10122923
25. Radünz M, Dos Santos Hackbart HC, Camargo TM, Nunes CFP, De Barros FAP, Dal Magro J, et al. Antimicrobial potential of spray drying encapsulated thyme (Thymus vulgaris) essential oil on the conservation of hamburger-like meat products. Int J Food Microbiol. 2020; 330:108696. DOI: 10.1016/j.ijfoodmicro.2020.108696
26. Sharma K, Babaei A, Oberoi K, Aayush K, Sharma R, Sharma S. Essential Oil Nanoemulsion Edible Coating in Food Industry: a Review. Food Bioprocess Technol. 2022; 15:2375–2395. DOI: 10.1007/s11947-022-02811-6
27. Sharma S, Barkauskaite S, Jaiswal AK, Jaiswal S. Essential oils as additives in active food packaging. Food Chem. 2021; 343:128403. DOI: 10.1016/j.foodchem.2020.128403

28. Shishir MRI, Xie L, Sun C, Zheng X, Chen W. Advances in micro and nano-encapsulation of bioactive compounds using biopolymer and lipid-based transporters. Trends Food Sci Technol. 2018; 78:34–60. DOI: 10.1016/j.tifs.2018.05.018
29. Souza AG, Ferreira RR, Paula LC, Mitra SK, Rosa DS. Starch-based films enriched with nanocellulose-stabilized Pickering emulsions containing different essential oils for possible applications in food packaging. Food Packag Shelf Life. 2021; 27:100615. DOI: 10.1016/j.fpsl.2020.100615
30. Souza AS, Borges CD, Radünz M, Gandra TKV, Da Costa DA, Borba CS, et al. Encapsulation of thyme essential oil (Thymus vulgaris) in chia mucilage (Salvia hispanica L.) and its application in fresh pork sausage. Int J Biol Macromol. 2025; 285:138284. DOI: 10.1016/j.ijbiomac.2024.138284
31. Su X, Xu Y, Xu Z, Hurley K, Feng Y, Yin Y. Encapsulation of hop (*Humulus lupulus* L.) essential oil for controlled release in the non-alcoholic beverage application. Food Hydrocoll. 2023; 134:108039. DOI: 10.1016/j.foodhyd.2022.108039
32. Tavares L, Zapata Noreña CP, Barros HL, Smaoui S, Lima PS, Marques De Oliveira M. Rheological and structural trends on encapsulation of bioactive compounds of essential oils: A global systematic review of recent research. Food Hydrocoll. 2022; 129:107628. DOI: 10.1016/j.foodhyd.2022.107628
33. Veiga RDSD, Aparecida Da Silva-Buzanello R, Corso MP, Canan C. Essential oils microencapsulated obtained by spray drying: a review. J Essent Oil Res. 2019; 31:457–473. DOI: 10.1080/10412905.2019.1612788
34. Weisany W, Yousefi S, Tahir NA razzak, Golestanehzadeh N, McClements DJ, Adhikari B, et al. Targeted delivery and controlled released of essential oils using nanoencapsulation: A review. Adv Colloid Interface Sci. 2022; 303:102655. DOI: 10.1016/j.cis.2022.102655
35. Yammine J, Chihib NE, Gharsallaoui A, Ismail A, Karam L. Advances in essential oils encapsulation: development, characterization and release mechanisms. Polym Bull. 2024; 81:3837–3882. DOI: 10.1007/s00289-023-04916-0
36. Yilmaz MT, Yilmaz A, Akman PK, Bozkurt F, Dertli E, Basahel A, et al. Electrospraying method for fabrication of essential oil loaded-chitosan nanoparticle delivery systems characterized by molecular, thermal, morphological and antifungal properties. Innov Food Sci Emerg Technol. 2019; 52:166–178. DOI: 10.1016/j.ifset.2018.12.005