A Review and Bibliometric Analysis on Essential Oil Nanoencapsulation

Wahyudi Budi Sediawan[1](✉), Indah Hartati[2], Hary Sulistyo[1] and Muhammad Mufti Azis[1]

[1]Department of Chemical Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
hartatiprasetyo@gmail.com

[2]Department of Chemical Engineering, Universitas Wahid Hasyim, Semarang, Indonesia

Abstract. The potential applications of essential oils are limited by their natures as they are oxidized easily by light, heat, and other environmental factors. Essential oil impediments and their short shelf life promote the development and application of essential oil nanoencapsulation. Nanoencapsulation techniques employed in formulation of essential oil nano capsules are diverse. Therefore, this paper presents the review of nanoencapsulation technology applied on essential oil as well as the analysis of the bibliometric on term of essential oil nanoencapsulation technology. The review was conducted by investigate and study the literatures available on nanotechnology applied on essential oil. The bibliometric analysis was conducted by using Vos-Viewer program in order to analyze the journals and articles published in Scopus database. The search was performed on keywords of essential oil, nanoencapsulation, and nanoencapsulation specific techniques. Based on the direction of the size of the nanomaterial formulation, nanoencapsulation is classified into top-down and bottom-up technique. Nanoemulsion and liposomal entrapment are two top-down methods that gain wide interest from researchers, while ionic gelation is the bottom-up methods widely applied in essential oil nanoencapsulation. The bibliometric analysis of the publication on essential oil nanoencapsulation based on nanoemulsion and ionic gelation methods show that the trend of the essential oil nanoencapsulation performed via top down and bottom-up techniques are mostly intended to investigate the pharmacological activities of the bioactive compounds of the essential oil as well as investigated for their application as drugs release system.

Keywords: Essential Oil, Nanoencapsulation, Nanoemulsion, Bibliometric

1 Introduction

Essential oils (EOs) is an aromatic products contain a complex mixture of volatile, semi-volatile and non-volatile organic molecules obtained from different parts of botanically sources by various separation techniques [1–3]. The volatile compounds of EOs are mainly lipophilic terpenoids, benzenoids, and phenylpropanoids [4]. Nicotine, neophytadiene and hexadecenoic acid are example of semi-volatile compounds exist in

M. Setiyo et al. (eds.), *Proceedings of the 4th Borobudur International Symposium on Science and Technology 2022 (BIS-STE 2022)*, Advances in Engineering Research 225,
https://doi.org/10.2991/978-94-6463-284-2_11

EOs [5]. Non-volatile compounds reported exist in EOs are including glucose monoterpene esters, flavonoid glycosides, trypanocide lignans, anthocyanidin glycosides, and flavanones [6–8]. EOs is isolated from different plant parts including flowers, woods, bud peels, leaves, fruits, twigs, seeds, stem as well as roots and whole plants by applied one of the following techniques i.e: distillation, extraction or pressing.

EOs is bio-synthesized by secretory structures in plastids and cytoplasm of plant cells via methyl-D-erythritol-4-phosphate (MEP), mevalonic acid, shikimic acid, and malonic acid pathways. The methylerythritol pathway leads to the synthesis of mono and diterpenes. Meanwhile sesquiterpenes and phenylpropenes are synthesized via mevalonate and shikimic pathway, respectively [4,9–11]. It was also reported that very diverse of plant cells morphology such as glandular trichomes, osmophoric, conical papillate cells, ducts, and cavities secrete EOs via two types of secretion mechanism i.e granulocrine and eccrine mechanisms [3]. The secretions of EOs in plants act as acting as chemical deterrents, defense mechanism against predators like insects, herbivores and fungi; internal messenger system; as well as attracting agents for pollinating species [12,13].

In spite of their internal functions, study of EOs chemical compositions and their potential activities revealed that EOs possessed several biological and ethno-medicinal activities including anti-spasmodic, anti-proliferative, sedative, anti-septic, anti-oxidant, anti-cancer, anti-inflammatory, stimulant, anti-helminthic, anti-hypertension, anti-bacterial, and analgesic [14,15]. However, the natures of EOs such as their high volatility, poor chemical stability, low aqueous solubility, poor bioavailability, hydrophobicity limit the potential application of EOs [1,16,17]. Nevertheless, these impediments can be overcome by the application of EOs nanoencapsulation.

2 Result

2.1 Nanoencapsulation Techniques

Nanoencapsulation is defined as the art of science process of producing capsules having size of less than 1 μm, specifically ranging from 1 to 100 nm, although some nanomaterials may have sizes up to 1000 nm [18]. Nanoencapsulation is classified into three different techniques comprising of chemical, physical, and physicochemical method. Molecular inclusion, sol gels, precipitation, interfacial polymerization, interfacial polycondensation, and interfacial cross-linking in situ polymerization are types of chemical method applied in the synthesis of nanocapsules. Spray drying, cooling, crystallization, fluid bed coating, extrusion, centrifugal extrusion, supercritical fluids are example of physical method applied in nanocapsules production. Meanwhile physicochemical technique can be applied through one of the following methods i.e. gelation, nanoemulsification, ionic gelation, phase inversion, hot melt coating, layer by layer deposition, solvent evaporation extraction, controlled precipitation or coacervation [19,20].

Moreover, based on the main mechanism or ingredient used to formulate the nanocapsule, nanoencapsulation is classified into five groups including: (i) lipid-based techniques, (ii) nature-inspired techniques, (iii) specialized equipment techniques, (iv) biopolymer-based techniques, and (v) other miscellaneous techniques. Nanoemulsion, nanostructured phospholipid carriers, nanoliposomes, solid lipid nanoparticles, and nanolipid structured carriers are examples of lipid based techniques of nanoencapsulation [21,22]. Zein, soy protein, casein, alginate, albumin, protein, chitosan, phytoglycogen, cyclodextrin and amylose are natural materials used in nature-inspired techniques of nanoencapsulation [22,23]. Specialized equipments applied in nanoencapsulation process comprising nanofluidics, spray drying, spray chilling, electro spinning, electro spraying, and extrusion. Moreover, single and complex biopolymer nanocarriers, nanogels and nanotubes are groups of biopolymer-based techniques of nanoencapsulation. Meanwhile, other miscellaneous techniques are comprise of nanocrystals, nanofiber, inorganic nanocarriers, chemical polymer nanoparticles and nano structured surfactants [18,22,24].

In spite of nanoencapsulation classification as describe above, based on the direction of the material size formation, nanoencapsulation can be performed via one of the following methods i.e top down and bottom up technique [25]. Later, the focus of this paper is on appraising the top down and bottom up techniques of essential oil nanoencapsulation.

Top-Down Techniques. Top-down technique, in which include liposome entrapment, emulsification, emulsification-solvent evaporation, melt extrusion, melt injection, extrusion coating, electro spraying, spray chilling, electrospinning, spinning disk and centrifugal co-extrusion, deals with the formation of nano-size range material from the larger size materials. Types of mechanical ways applied in the size reduction and structural shaping in to top down technique are including milling, shredding, and grinding, in which may apply by the following forces i.e shear, impact, and compression for its particle disruption [18,26]. Various top-down approach has been applied in nanoencapsulation of a number of essential oil (Table 1).

Varied essential oils are encapsulated via different methods result in capsule size range from 25 nm, in which obtained via liposomal entrapment of Bunium persicum and Trachyspermum ammi essential oil using phosphatidylcholine and cholesterol, to 3 mm of nanocapsule of carvone essential oil obtained via melt extrusion method using ethylene–vinyl acetate (EVA) and linear low-density polyethylene as the polymeric materials. It can be seen that extrusion gives relatively larger size of nanocapsule compare to other top down nanoencapsulation technique. Extrusion process is performed by mixing of essential oil emulsion with polymer solution in which then extruded into a crosslinking agent or a gelling solution. The extrusion can be performed using a syringe or an atomization process based on simple dripping, multiple-nozzle extrusion, coaxial airflow, electrostatic extrusion, spinning disk atomization, concentric nozzle, or jet-cutter technologies. Although extrusion technique results in relatively bigger size of nanocapsule, it does not require harsh processing conditions like high shear, pressure, or temperature as well as harsh solvent, in the process of making nanocapsule. Therefore this technique could preserve the active material as well as the shell materials from deterioration [27,28].

Electrospinning and electrospraying employ a uniform electrohydrodynamic force in disrupting the droplet of polymer solution and in turning it into nanosized polymer fiber and nanosized particle, respectively. Both of electro based nanoencapsualtion methods attract researcher's interest as those methods are versatile; relatively ease of use, simple, scalable, facile and cost effective. Nanoscale fibers produced from electrohydrodynamic based technique can be in various forms, including core-shell, porous, and hollow nanofibers. Nanofibers possessed several structural and functional merits, such as having high surface to volume ratio, porous structure, and tunable fiber diameters which providing unique properties to the system and give high encapsulation efficiency [29,30]. The absence of high temperature during the electro-based nanoencapsulation processes also gives benefits in protecting the encapsulated-heat sensitive compounds. Essential oil of thyme, cinnamon oil, rose hip seed, Zataria multiflora Boiss, lavender, clove, betel, and oregano are some example of EO in which encapsulated in nanofibers, characterized and being investigated for various applications [31].

Table 1. Top-down techniques applied in nanoencapsulation of essential oil

Technique	Essential oil Sources	Encapsulant materials	Application/ activity	Capsule size	Ref
Emulsification	Myrtus communis	Tween 80%, Span 20	Larvicidal activity	177 nm	[32]
	Mentha spcata L, Ocimum basilicum L	Tween 80	Nematicide activity	48.10 nm and 97.3 nm	[33]
	Clove	Tween 80, chitosan	Fungal inhibitor	16.47± 1.20 – 137.0±0.52	[34]
Electrospinning	Cinnamon oil	polyvinyl alcohol and b-cyclodextrin	Anti-microbial activity	240±40 nm	[35]
	Rose hip seed oil	Zein prolamine	Food packaging	700 nm	[36]
	Zataria multiflora Boiss.	Gelatine and chitosan	Anti-microbial activity	205-251 nm	[37]
Electrospraying	Origanum vulgare	Chitosan	Anti-fungal	290-483 nm	[38]
Extrusion coating	Rosmarinus officinalis L.	Alginate and sodium chloride	Anti-microbial	0.95 mm	[28]
	Kaffir lime oil, lemon grass oil, and citronella grass oil	low-density polyethylene	Insecticide activity	-	[39]
Liposome entrapment	Chrysanthemum flos	Single layer: - thin layer hydration method - lecithin and cholesterol Second and third layer: - Method: electrostatic deposition Layer-	Antibacterial acitivity	132.4 nm	[40]

Technique	Essential oil Sources	Encapsulant materials	Application/ activity	Capsule size	Ref
		by-layer Chitosan and pectin			
	Cymbopogon citratus	Single layer: lecithin and cholesterol	Antibiotic activity	63.6±1.76 - 196.8±3.54 nm	[41]
	Bunium persicum and Trachyspermum ammi	Single layer: - thin-film method phosphatidylcholine and cholesterol	Anti-Trichomonas activity	25-40 nm	[42]
Melt Extrusion	Spearmint essential oil and carvone	Polymer: ethylene–vinyl acetate (EVA) and linear low-density polyethylene	Antifungal activity	2.0 ±0.1 - 3.0 ±0.3 mm	[43]

Emulsification and liposome entrapment are the two nanoencapsulation techniques that also gain wide interest. This might be due to the advantages offer by those two methods. Nanoemulsion in which formulated using one of the following method i.e mechanical or physicochemical approach is part of a broad class of multiphase colloidal dispersions and having relatively small droplet diameters (20 to 200 nm) than the one of emulsion. The small size of nanoemulsion leads to the increasing of their resistance to aggregation and gravitational separation. In compare to micro sized emulsion, nanoemulsion exhibit better efficacy in term of appearance, gravitational stability, kinetic stability, bioavailability, viscocity, texture, and activity [30,44]. Avoiding emulsion coalescence as well as increasing its stability can be performed by the addition of anionic, nonionic, cationic, amphoteric or zwitterionic surfactants which encircle the dispersed droplets and reduce interfacial tension or increase droplet-droplet repulsion [25]. Sodium dodecyl sulfate, Span 20, Span 80, sucrose esters, lauric alginate, sorbitan fatty acid esters, polyglycerols, polysorbates and polyoxyethylene ether are used as surfactant in nanoemulsion of essential oil. However, Tween 80 and Tween 20 (polysorbates) are the two most used surfactants for the nanoencapsulation of essential oil. Nanoemulsion formulated with Tween 80 and 20 is stable without the need of a co-surfactant addition [45]. Furthermore, liposomes, a spherical bilayer vesicles in which made up by dispersion of one or more concentric phospholipidic bilayers in an internal aqueous phase, are widely used to encapsulate various components because of their merits characteristic such as being nontoxic, bioavailable, biodegradable, biocompatible, permeable, having nonimmunogenic properties, and being able to be used as carriers for both hydrophilic, amphiphilic and lipophilic molecules [41,46].

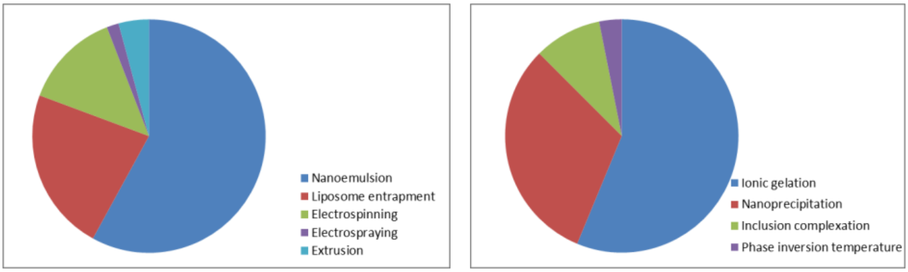
Bottom-Up Techniques. On the contrary to the top down technique, depends upon their natural properties, bottom-up deals with the formation of nano-size range material from the automatic/self-organization and self-assembly of atom by atom, molecule by molecule or atoms and molecules. Phase inversion temperature, co-crystallization, ionic gelation, coacervation, fluid bed coating, thin film hidration sonication, inclusion complexation, self-assembly supercritical fluid, and nanoprecipitation are example of techniques which follow bottom-up approach [18,22,25]. Various essential oil have been encapsulated using different bottom up techiques with varied nanocapsule size obtained from each techniques (Table 2). Inclusion complexation of Citrus bergamia by using Methyl-βcyclodextrin as the encapsulant material result in relatively bigger size of nanocapsule (359.70 ± 8.50 nm) [47] while nanocapsule formulated from ionic gelation of Citrus aurantium by using chitosan, glacial acetic acid, pentasodium triphosphate, and tween 80 is having size of 20-60 nm [48]. Moreover, co-crystallization has been applied in the encapsulation of orange peel oil. However, the lack of versatility of this method has been stated as the impediment of this technique [49]. Among the bottom-up methods applied in essential oil nanoencapsulation, ionic gelation is the one of widely used technique. Ionic gelation is conducted based on the creation of a gel in the presence of multivalent ions such as Ca2+, Ba2+ and Al3+. The interaction that occurs is a divalent ionic crosslinking between the divalent molecule ions and the envelope polymer [46]. Ionic gelation of Citrus aurantium, Citrus reticulata L. and Artemisia dracunculus L have been performed by using Chitosan, glacial acetic acid, pentasodium triphosphate, and tween 80 as the encapsulan materials. Relatively small size of essential oil nanocapsules, in range of 20-158.6 nm, is obtained via ionic gelation process compare to the ones of other techniques (Table 2).

Table 2. Bottom-up techniques applied in nanoencapsulation of essential oil

Technique	Essential oil Sources	Encapsulant materials	Application/ activity	Capsule size	Ref
Inclusion complexation	Citrus bergamia	Methyl-βcyclodextrin	-	359.70 ± 8.50	[47]
Ionic gelation	Citrus aurantium	Chitosan, glacial acetic acid, pentasodium triphosphate, and tween 80	Antioxidant	20–60 nm	[48]
	Citrus reticulata L.	Chitosan, acetic acid, pentasodium triphosphate, and tween 80	Antibacterial	158.6 nm	[50]
	Artemisia dracunculus L	Chitosan, acetic acid, pentasodium triphosphate, and tween 80	Antimicrobial	30–60 nm	[51]
Nanoprecipitation	Origanum vulgare L	Poly-caprolactone, acetone, glycerin, sorbitan monooleate, center ES-FF resin, and citric acid.	Antibacterial for fabrix	235 nn	[52]
Phase inversion temperature	C. Sinensis	Step 1: heating to 15°C above the phase PIT. Step 2: cooling to the PIT Step 3: instant cooling at 5°C	-	46.5 nm	[53]
Thin film hidration sonication	Lemonene	Soy-based lecithin and diacetylene	Edible coating		[54]

2.2 Bibliometric Analysis

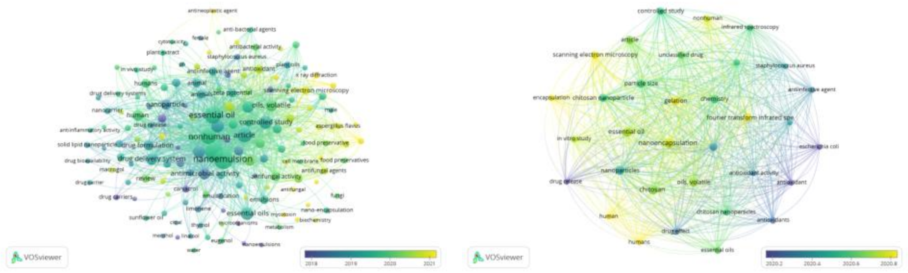
Trends of a certain research field as well as analyzing the scientific activities on that research area can be evaluating by applying bibliometric in which belong to the scientometrics. In this paper, bibliometrics analysis was applied in order to evaluate the trend in essential oil nanoencapsulation techniques. Among the reported top down and bottom-up methods of nanoencapsulation, based on number of scopus indexed publication on nanoencapsulation of essential oil from 2019 until January 2023, it seem that emulsification and liposome entrapment and ionic gelation are nanoencapsulation techniques that gain wide interest (Fig. 1). Therefore, the bibliometric analysis of the top down technique of nanoencapsulation of essential oil was performed by applied with the keywords of "nanoencapsulation, essential oil, nanoemulsion" while for bottom up technique, keywords of "nanoencapsulation, essential oil, ionic gelation" was applied. As much as 92 and 18 publications are obtained from the search with the mentioned keywords, respectively. Furthermore, the trend and occurrence of keywords in published paper with keywords of nanoencapsulation of essential oil by nanoemulsion and ionic gelation are presented in Fig. 2.



a b

Fig. 1. Pie chart of the number of scopus indexed publication on nanoencapsulation of essential oil from 2019 until January 2023 for (a) top down, and (b) bottom up nanoencapsulation techniques

It was showed that nodes on overlay visualization for nanoemulsion, non-human, essential oil, drug delivery system and antimicrobial activity are relatively bigger than the other node of keywords (Fig. 2a). It seems that the essential oil nanoemulsion were formulated and investigated for its antimicrobial activity. Various bioactive compounds of essential oil such as linalool, methyl cinnamate, carvacrol, Carvone D, thymol, cymene, (E)-Cinnamaldehyde exhibit antimicrobial activity [25]. Moreover, relatively uniform node size appeared on overlay visualization of keywords occurrence of paper with keywords of essential oil, nanoencapsulation, and ionic gelation (Fig. 2b). Nodes of drugs release, antioxidant, and effect of drugs are appearing on overlay visualization of keywords occurrence of paper with keywords of essential oil, nanoencapsulation, and ionic gelation. Fig. 2a and Fig. 2b show that the trend of the essential oil nanoencapsulation performed via top down and bottom up techniques are mostly intended to investigate the pharmacological activities of the bioactive compounds of the essential oil as well as investigated for drugs release system.



a b

Fig. 2. Overlay visualization of keywords occurrence of paper with keywords of: (a) essential oil, nanoencapsulation, nanoemulsion and (b) essential oil, nanoencapsulation, ionic gelation

3 Conclusion

Based on the direction of the size of the nanomaterial formulation, nanoencapsulation is classified into top down and bottom-up technique. Nanoemulsion and liposomal entrapment are two top-down methods that gain wide interest from researchers, while ionic gelation is the bottom up methods widely applied in essential oil nanoencapsulation. The bibliometric analysis of the publication on essential oil nanoencapsulation based on nanoemulsion and ionic gelation methods show that the trend of the essential oil nanoencapsulation performed via top down and bottom-up techniques are mostly intended to investigate the pharmacological activities of the bioactive compounds of the essential oil as well as investigated for drugs release system.

Acknowledgments. The authors thank for The Ministry of Education and Culture Republic of Indonesia for funding this research through PDUPT grant of 2022 with contract number of 1662/UN1/DITLIT/Dit-Lit/PT.01.03/2022.

References

1. Weisany, W.; Yousefi, S.; Tahir, N.A. razzak; Golestanehzadeh, N.; McClements, D.J.; Adhikari, B.; Ghasemlou, M. 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.
2. Eslahi, H.; Fahimi, N.; Sardarian, A.R. *Chemical Composition of Essential Oils*; 2017; ISBN 9781119149392.
3. Rehman, R.; Asif Hanif, M. Biosynthetic Factories of Essential Oils: The Aromatic Plants. *Nat. Prod. Chem. Res.* **2016**, *04*, doi:10.4172/2329-6836.1000227.

4. Moghaddam, M.; Mehdizadeh, L. *Chemistry of Essential Oils and Factors Influencing Their Constituents*; 2017; ISBN 9780128114124.
5. Coleman, W.M. The Volatile and Semivolatile Components of Supercritical Fluid and Methylene Chloride Extracts of Selected Tobaccos. *J. Essent. Oil Res.* **1992**, *4*, 113–120, doi:10.1080/10412905.1992.9698030.
6. Ramírez, J.; Andrade, M.D.; Vidari, G.; Gilardoni, G. Essential Oil and Major Non-Volatile Secondary Metabolites from the Leaves of Amazonian Piper Subscutatum. *Plants* **2021**, *10*, doi:10.3390/plants10061168.
7. Goodger, J.Q.D.; Cao, B.; Jayadi, I.; Williams, S.J.; Woodrow, I.E. Non-Volatile Components of the Essential Oil Secretory Cavities of Eucalyptus Leaves: Discovery of Two Glucose Monoterpene Esters, Cuniloside B and Froggattiside A. *Phytochemistry* **2009**, *70*, 1187–1194, doi:10.1016/j.phytochem.2009.06.004.
8. Vuko, E.; Radman, S.; Jerkovi, I.; Kamenjarin, J.; Vrki, I. A Plant Worthy of Further Study — Volatile and Non-Volatile Compounds of Portenschlagiella Ramosissima (Port .) Tutin and Its Biological Activity. **2022**.
9. Sharifi-Rad, J.; Sureda, A.; Tenore, G.C.; Daglia, M.; Sharifi-Rad, M.; Valussi, M.; Tundis, R.; Sharifi-Rad, M.; Loizzo, M.R.; Oluwaseun Ademiluyi, A.; et al. *Biological Activities of Essential Oils: From Plant Chemoecology to Traditional Healing Systems*; 2017; Vol. 22; ISBN 9819919533.
10. Franz, C.; Novak, J. *Sources of Essential Oils*; 2015; ISBN 9781466590472.
11. Sadgrove, N.J.; Padilla-González, G.F.; Phumthum, M. Fundamental Chemistry of Essential Oils and Volatile Organic Compounds, Methods of Analysis and Authentication. *Plants* **2022**, *11*, doi:10.3390/plants11060789.
12. Kesraoui, S.; Andrés, M.F.; Berrocal-Lobo, M.; Soudani, S.; Gonzalez-Coloma, A. Direct and Indirect Effects of Essential Oils for Sustainable Crop Protection. *Plants* **2022**, *11*, 1–10, doi:10.3390/plants11162144.
13. Letseka, T.E.; Sepheka, N.J.; Dubery, I.A.; George, M.J. Bioprospecting of Essential Oil-Bearing Plants: Rapid Screening of Volatile Organic Compounds Using Headspace Bubble-in-Drop Single-Drop Microextraction for Gas Chromatography Analysis. *Plants* **2022**, *11*, doi:10.3390/plants11202749.
14. Jaradat, N.; Al-Maharik, N.; Abdallah, S.; Shawahna, R.; Mousa, A.; Qtishat, A. Nepeta Curviflora Essential Oil: Phytochemical Composition, Antioxidant, Anti-Proliferative and Anti-Migratory Efficacy against Cervical Cancer Cells, and α-Glucosidase, α-Amylase and Porcine Pancreatic Lipase Inhibitory Activities. *Ind. Crops Prod.* **2020**, *158*, 112946, doi:10.1016/j.indcrop.2020.112946.
15. Moradi, S.; Barati, A. Essential Oils Nanoemulsions: Preparation, Characterization and Study of Antibacterial Activity against Escherichia Coli. *Int. J. Nanosci. Nanotechnol.* **2019**, *15*, 199–210.
16. Keivani Nahr, F.; Ghanbarzadeh, B.; Hamishehkar, H.; Kafil, H.S.; Hoseini, M.; Moghadam, B.E. Investigation of Physicochemical Properties of Essential Oil Loaded Nanoliposome for Enrichment Purposes. *Lwt* **2019**, *105*, 282–289, doi:10.1016/j.lwt.2019.02.010.
17. Lin, L.; Chen, W.; Li, C.; Cui, H. Enhancing Stability of Eucalyptus Citriodora Essential Oil by Solid Nanoliposomes Encapsulation. *Ind. Crops Prod.* **2019**, *140*, 111615, doi:10.1016/j.indcrop.2019.111615.
18. Martins, V.F.R.; Pintado, M.E.; Morais, R.M.S.C.; Morais, A.M.M.B. Valorisation of Micro/Nanoencapsulated Bioactive Compounds from Plant Sources for Food Applications Towards Sustainability. *Foods* **2023**, *12*, doi:10.3390/foods12010032.

19. Jafari, S.M. *Nanoencapsulation of Food Bioactive Ingredients: Principles and Applications*; 2017; Vol. 4; ISBN 9780128097403.
20. Anandharamakrishnan, C. *Techniques for Nanoencapsulation of Food Ingredients*; 2014; ISBN 978-1-4614-9386-0.
21. Fathi, M.; Mozafari, M.R.; Mohebbi, M. Nanoencapsulation of Food Ingredients Using Lipid Based Delivery Systems. *Trends Food Sci. Technol.* **2012**, *23*, 13–27, doi:10.1016/j.tifs.2011.08.003.
22. Assadpour, E.; Jafari, S.M. *An Overview of Specialized Equipment for Nanoencapsulation of Food Ingredients*; Elsevier Inc., 2019; ISBN 9780128156711.
23. Luo, Y.; Wang, Q.; Zhang, Y. Biopolymer-Based Nanotechnology Approaches to Deliver Bioactive Compounds for Food Applications: A Perspective on the Past, Present, and Future. *J. Agric. Food Chem.* **2020**, *68*, 12993–13000, doi:10.1021/acs.jafc.0c00277.
24. Ojeda-Piedra, S.A.; L., Z.-Z.M.; González-Reza, R.M.; García-Betanzos, C.I.; Real-Sandoval, S.A.; Quintanar-Guerrero, D. Nano-Encapsulated Essential Oils as a Preservation Strategy for Meat and Meat Products Storage. *Molecules* **2022**, *27*, 1–21, doi:10.1016/B978-0-12-374136-3.00008-0.
25. Prakash, B.; Kujur, A.; Yadav, A.; Kumar, A.; Singh, P.P.; Dubey, N.K. Nanoencapsulation: An Efficient Technology to Boost the Antimicrobial Potential of Plant Essential Oils in Food System. *Food Control* **2018**, *89*, 1–11, doi:10.1016/j.foodcont.2018.01.018.
26. Ravichandran, R. Nanotechnology Applications in Food and Food Processing: Innovative Green Approaches, Opportunities and Uncertainties for Global Market. *Int. J. Green Nanotechnol. Phys. Chem.* **2010**, *1*, P72–P96, doi:10.1080/19430871003684440.
27. Pimentel-Moral, S.; Verardo, V.; Robert, P.; Segura-Carretero, A.; Martínez-Férez, A. *Nanoencapsulation Strategies Applied to Maximize Target Delivery of Intact Polyphenols*; Elsevier Inc., 2016; ISBN 9780128043073.
28. Dolçà, C.; Ferrándiz, M.; Capablanca, L.; Franco, E.; Mira, E.; López, F.; García, D. Microencapsulation of Rosemary Essential Oil by Co-Extrusion/Gelling Using Alginate as a Wall Material. *J. Encapsulation Adsorpt. Sci.* **2015**, *05*, 121–130, doi:10.4236/jeas.2015.53010.
29. Wen, P.; Zong, M.H.; Linhardt, R.J.; Feng, K.; Wu, H. Electrospinning: A Novel Nano-Encapsulation Approach for Bioactive Compounds. *Trends Food Sci. Technol.* **2017**, *70*, 56–68, doi:10.1016/j.tifs.2017.10.009.
30. Awuchi, C.G.; Morya, S.; Dendegh, T.A.; Okpala, C.O.R.; Korzeniowska, M. Nanoencapsulation of Food Bioactive Constituents and Its Associated Processes: A Revisit. *Bioresour. Technol. Reports* **2022**, *19*, doi:10.1016/j.biteb.2022.101088.
31. Partheniadis, I.; Stathakis, G.; Tsalavouti, D.; Heinämäki, J.; Nikolakakis, I. Essential Oil—Loaded Nanofibers for Pharmaceutical and Biomedical Applications: A Systematic Mini-Review. *Pharmaceutics* **2022**, *14*, doi:10.3390/pharmaceutics14091799.
32. Firooziyan, S.; Osanloo, M.; Basseri, H.R.; Moosa-Kazemi, S.H.; Mohammadzadeh Hajipirloo, H.; Amani, A.; Sedaghat, M.M. Nanoemulsion of Myrtus Communis Essential Oil and Evaluation of Its Larvicidal Activity against Anopheles Stephensi. *Arab. J. Chem.* **2022**, *15*, 104064, doi:10.1016/j.arabjc.2022.104064.
33. Hammad, E.A.; El-Sagheer, A.M. Comparative Efficacy of Essential Oil Nanoemulsions and Bioproducts as Alternative Strategies against Root-Knot Nematode, and Its Impact on the Growth and Yield of Capsicum Annuum L. *J. Saudi Soc. Agric. Sci.* **2022**, doi:10.1016/j.jssas.2022.06.002.
34. Wang, H.; Ma, Y.; Liu, L.; Liu, Y.; Niu, X. Incorporation of Clove Essential Oil Nanoemulsion in Chitosan Coating to Control Burkholderia Gladioli and Improve Postharvest Quality of Fresh Tremella Fuciformis. *Lwt* **2022**, *170*, 114059, doi:10.1016/j.lwt.2022.114059.

35. Wen, P.; Zhu, D.H.; Wu, H.; Zong, M.H.; Jing, Y.R.; Han, S.Y. Encapsulation of Cinnamon Essential Oil in Electrospun Nanofibrous Film for Active Food Packaging. *Food Control* **2016**, *59*, 366–376, doi:10.1016/j.foodcont.2015.06.005.
36. Yao, Z.C.; Chang, M.W.; Ahmad, Z.; Li, J.S. Encapsulation of Rose Hip Seed Oil into Fibrous Zein Films for Ambient and on Demand Food Preservation via Coaxial Electrospinning. *J. Food Eng.* **2016**, *191*, 115–123, doi:10.1016/j.jfoodeng.2016.07.012.
37. Vafania, B.; Fathi, M.; Soleimanian-Zad, S. Nanoencapsulation of Thyme Essential Oil in Chitosan-Gelatin Nanofibers by Nozzle-Less Electrospinning and Their Application to Reduce Nitrite in Sausages. *Food Bioprod. Process.* **2019**, *116*, 240–248, doi:10.1016/j.fbp.2019.06.001.
38. Yilmaz, M.T.; Yilmaz, A.; Akman, P.K.; Bozkurt, F.; Dertli, E.; Basahel, A.; Al-Sasi, B.; Taylan, O.; Sagdic, O. 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.
39. Pangnakorn, U. Toxicity of Essential Oils to Stored Product Pest and Application to Extrusion Coating Film for Extend Rice Storage Life. *Int. J. Environ. Monit. Anal.* **2018**, *6*, 65, doi:10.11648/j.ijema.20180602.14.
40. Lin, L.; Gu, Y.; Sun, Y.; Cui, H. Characterization of Chrysanthemum Essential Oil Triple-Layer Liposomes and Its Application against Campylobacter Jejuni on Chicken. *Lwt* **2019**, *107*, 16–24, doi:10.1016/j.lwt.2019.02.079.
41. Cui, H.Y.; Wu, J.; Lin, L. Inhibitory Effect of Liposome-Entrapped Lemongrass Oil on the Growth of Listeria Monocytogenes in Cheese. *J. Dairy Sci.* **2016**, *99*, 6097–6104, doi:10.3168/jds.2016-11133.
42. Siyadatpanah, A.; Norouzi, R.; Mirzaei, F.; Haghirosadat, B.F.; Nissapatorn, V.; Mitsuwan, W.; Nawaz, M.; Pereira, M.L.; Hosseini, S.A.; Montazeri, M.; et al. Green Synthesis of Nano-Liposomes Containing Bunium Persicum and Trachyspermum Ammi Essential Oils against Trichomonas Vaginalis. *J. Microbiol. Immunol. Infect.* **2022**, doi:10.1016/j.jmii.2022.06.006.
43. Phala, K.; Mapossa, A.B.; Augustyn, W.; Combrinck, S.; Botha, B. Development of EVA and LLDPE Polymer-Based Carvone and Spearmint Essential Oil Release Systems for Citrus Postharvest Diseases Applications. *Arab. J. Chem.* **2023**, *16*, 104458, doi:10.1016/j.arabjc.2022.104458.
44. McClements, D.J. Stability of Food Emulsions (2). *Univ. Massachusetts* **2008**, 1–37.
45. Pavoni, L.; Perinelli, D.R.; Bonacucina, G.; Cespi, M.; Palmieri, G.F. An Overview of Micro-and Nanoemulsions as Vehicles for Essential Oils: Formulation, Preparation and Stability. *Nanomaterials* **2020**, *10*, doi:10.3390/nano10010135.
46. Razola-Díaz, M. del C.; Guerra-Hernández, E.J.; García-Villanova, B.; Verardo, V. Recent Developments in Extraction and Encapsulation Techniques of Orange Essential Oil. *Food Chem.* **2021**, *354*, doi:10.1016/j.foodchem.2021.129575.
47. Zambito, Y.; Piras, A.M.; Fabiano, A. Bergamot Essential Oil: A Method for Introducing It in Solid Dosage Forms. *Foods* **2022**, *11*, 1–9, doi:10.3390/foods11233860.
48. Karimirad, R.; Behnamian, M.; Dezhsetan, S. Bitter Orange Oil Incorporated into Chitosan Nanoparticles: Preparation, Characterization and Their Potential Application on Antioxidant and Antimicrobial Characteristics of White Button Mushroom. *Food Hydrocoll.* **2020**, *100*, 105387, doi:10.1016/j.foodhyd.2019.105387.
49. Majeed, H.; Bian, Y.-Y.; Ali, B.; Jamil, A.; Majeed, U.; Khan, Q.F.; Iqbal, K.J.; Shoemaker, C.F.; Fang, Z. Essential Oil Encapsulations: Uses, Procedures, and Trends. *RSC Adv.* **2015**, *5*, 58449–58463, doi:10.1039/c5ra06556a.

50. Song, X.; Wang, L.; Liu, T.; Liu, Y.; Wu, X.; Liu, L. Mandarin (Citrus Reticulata L.) Essential Oil Incorporated into Chitosan Nanoparticles: Characterization, Anti-Biofilm Properties and Application in Pork Preservation. *Int. J. Biol. Macromol.* **2021**, *185*, 620–628, doi:10.1016/j.ijbiomac.2021.06.195.
51. Zhang, H.; Liang, Y.; Li, X.; Kang, H. Effect of Chitosan-Gelatin Coating Containing Nano-Encapsulated Tarragon Essential Oil on the Preservation of Pork Slices. *Meat Sci.* **2020**, *166*, 108137, doi:10.1016/j.meatsci.2020.108137.
52. Salinas, C.; Lis, M.J.; Coderch, L.; Martí, M. Formation and Characterization of Oregano Essential Oil Nanocapsules Applied onto Polyester Textile. *Polymers (Basel).* **2022**, *14*, doi:10.3390/polym14235188.
53. Do, D.N.; Nguyen, D.P.; Pham, H.D.; Trieu, T.A.; Luu, X.C. Influence of Oil Phase, Surfactant on Nano-Emulsion Based on Essential Oil from Orange Using Phase Inversion Temperature Method. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *991*, 0–9, doi:10.1088/1757-899X/991/1/012043.
54. Dhital, R.; Mora, N.B.; Watson, D.G.; Kohli, P.; Choudhary, R. Efficacy of Limonene Nano Coatings on Post-Harvest Shelf Life of Strawberries. *Lwt* **2018**, *97*, 124–134, doi:10.1016/j.lwt.2018.06.038.