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REVIEW ARTICLE

# Flower-based essential oils and encapsulation: a synergistic approach for bioavailability improvement

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## Abstract

Essential oils (EOs) are intricate blends of volatile and semi-volatile organic compounds sourced from various plant tissues like flowers, buds, leaves and bark. However, their clinical utility is significantly constrained by inherent physicochemical properties that limit bioavailability-including high volatility, poor water solubility and susceptibility to degradation. Encapsulation has emerged as an effective approach to overcome these challenges by entrapping the essential oil within polymeric nanocarriers, which acts as a shield, preserving their integrity. Techniques like spray drying, freeze drying, molecular inclusion and coating have been investigated for the encapsulation of these flower crop essential oils, with significant outcomes. Key findings reveal that cyclodextrin inclusion complexes increased the half-life of rose oil terpenoids by 300 %, while chitosan-based nano emulsions enhanced antimicrobial efficacy of jasmine oil by 5-fold. Additionally, liposomal encapsulation of lavender oil demonstrated a 70 % improvement in dermal penetration compared to non-encapsulated forms. This review provides key insights on using encapsulation for unlocking the full potential of flower crop-based essential oils. With optimization of techniques and careful material selection, encapsulation can successfully enhance bioavailability, stability and efficacy.

**Keywords:** encapsulation; essential oil; flower crops; nano carriers; pharmaceuticals applications; spray drying

## Introduction

The global essential oils market has seen significant growth in recent years, driven by increasing demand across various industries such as food and beverage, personal care, aromatherapy and pharmaceuticals. As of 2023, the market will grow with an anticipated CAGR of 8.10 % by revenue and CAGR of 7.59 % in tonnes during the forecast period and will reach the revenue of $16224.79 million by 2027 (1). Essential oils are highly volatile lipophilic mixture of plant secondary metabolites. Often referred to as the "essence" of plants, they are concentrated hydrophobic liquids containing volatile aroma compounds extracted from plants. The volatile aromatic compounds are derived from various plant parts, including flowers, leaves, stems, roots etc. and are renowned for their characteristic fragrances and diverse biological activities (2). The extraction of essential oils is typically achieved through methods such as steam distillation, cold pressing or solvent extraction, preserving the volatile compounds responsible for their aroma and medicinal effects. The biological activities of essential oils include antibacterial, antifungal, antioxidant, anti-inflammatory, analgesic, antispasmodic and antioxidant properties (3). These properties have led to their utilization in diverse fields, including aromatherapy, natural medicine, skincare, food preservation and biopesticides. However, since the properties of essential oils depend on aroma compounds which readily evaporate, compromising the potency of the oils over time, strategies to prevent their evaporation are required. Encapsulation of essential oils is one such widely used strategy to prevent the evaporation of volatile compounds from essential oils.

Encapsulation is the process of encasing molecules in solid, liquid or gaseous states in matrices that can release their payload at a regulated rate under specific conditions (4, 5). It was first used in biotechnology to enhance production processes and promote the breakdown of generative cells and their intermediary products (6). Traced the concept of encapsulation back to the cell model, where the nucleus protects genetic information and a semipermeable membrane regulates transport of various agents. Encapsulation aims to preserve labile and sensitive bioactive molecules from unfavourable situations. It is a versatile technique used in various industries to enclose active ingredients within a protective coating material or matrix, offering numerous advantages such as improved stability, controlled release and targeted delivery (7). Encapsulation is based on the principle of entrapping active ingredients within a carrier material to form encapsulated particles or droplets. The carrier material, often referred to as the encapsulant, can be selected based on its compatibility with the active ingredient and desired properties such as biocompatibility, biodegradability and stability. They provide a protective barrier around the volatile oil molecules, shielding them from degradation and preserving their chemical integrity over time. This enhanced stability prolongs the shelf-life of essential oils, ensuring their potency and efficacy are maintained for longer periods (8). Encapsulation allows for precise control over the release kinetics of essential oils by modulating the properties of the encapsulation matrix such as porosity, thickness and composition. The release of active compounds can be altered to achieve desired therapeutic or functional effects over time. Controlled release ensures a sustained and prolonged release of essential oil constituents, providing prolonged benefits to users.

Encapsulation also enables targeted delivery of essential oils to specific sites within the body or environment (9). By encapsulating essential oils within targeted delivery systems such as liposomes or nanoparticles, it is possible to enhance their accumulation at specific tissues or cells, maximizing their therapeutic impact while minimizing systemic side effects. Some essential oils have strong or unpleasant odours or flavours that may be undesirable in certain products. It can also help mask these sensory attributes, improving consumer acceptability and compliance with essential oil-based products (10). Direct application of essential oils is also limited as they are prone to degradation by heat, light, oxygen and moisture. Encapsulation reduces the volatility of essential oils and their susceptibility to degradation. It can also help in enhancing their water solubility and bioavailability (11).

Flower crops, including roses, jasmine, chamomile, lavender are some of the prime sources of essential oils. These essential oils contain a diverse blend of active phytochemicals such as phenolic, terpenes, terpenoids and each contributes to their characteristic aroma and therapeutic effects (12). Encapsulation can aid in controlled release, protection against the environment, enhancement of solubility and bioavailability of flower crop's essential oil. Numerous encapsulation technologies have been explored for essential oils, utilizing various matrix materials, preparation methods and release mechanisms. A wide variety of coating materials are available - carbohydrates, gums, proteins, lipids and their combinations (13). Techniques like spray drying, freeze drying, emulsion, molecular inclusion, coating and nano encapsulation have been investigated for encapsulation of flower crop essential oils (14). This review aims to provide comprehensive insights into using encapsulation as a tool for enhancing the stability and bioavailability of essential oils derived from flower crops (Fig. 1).

## Botanical sources of flower-based essential oils

Essential oils are aromatic oily liquids obtained from different parts of plants - leaves, flowers, fruits, seeds, wood, bark and roots. They are secondary metabolites that play a key ecological role in the plant defence mechanism. Essential oils are a complex mixture of terpenic hydrocarbons, especially monoterpenes and sesquiterpenes and oxygenated derivatives like aldehydes (citronellal, sinensal), ketones (menthone, p-vetivone), alcohols (geraniol, α-bisabolol), phenols (thymol) and esters (γ-tepinyl acetate, cedryl acetate) (15). Essential oils also contain non terpene compounds known as phenylpropanoids, which give a specific flavor and odor when they are present. Essential oils are extracted from plant materials by expression, fermentation, effleurage or various distillation methods - steam distillation, dry distillation, aqueous distillation (16). Their composition is influenced by geographic origin, harvest season, plant genetics and extraction method. Over 3000 types of essential oils have been identified of which 300 are commercially important. The global market for essential oils is anticipated to reach 14 billion USD by 2025, driven by consumer preference for natural products (17).

Flower crops, including roses, jasmine, lavender and chamomile are among the main plant sources that produce commercially valuable essential oil (Table 1). These oils contain a diverse blend of terpenes, terpenoids, phenolics and other phytochemicals that contribute to their therapeutic effects. However, direct incorporation of these labile hydrophobic phytochemicals faces limitations like volatility, poor water solubility, chemical degradation and low oral bioavailability.

## Encapsulation techniques for essential oils

Encapsulation offers a promising solution by entrapping the essential oil within a protective coating or matrix. This aids in controlled release, protection against the environment, enhancement of solubility and bioavailability. Materials employed can be carbohydrates, gums, proteins, lipids and their combinations, depending on the intended purpose (28). Broadly, encapsulation

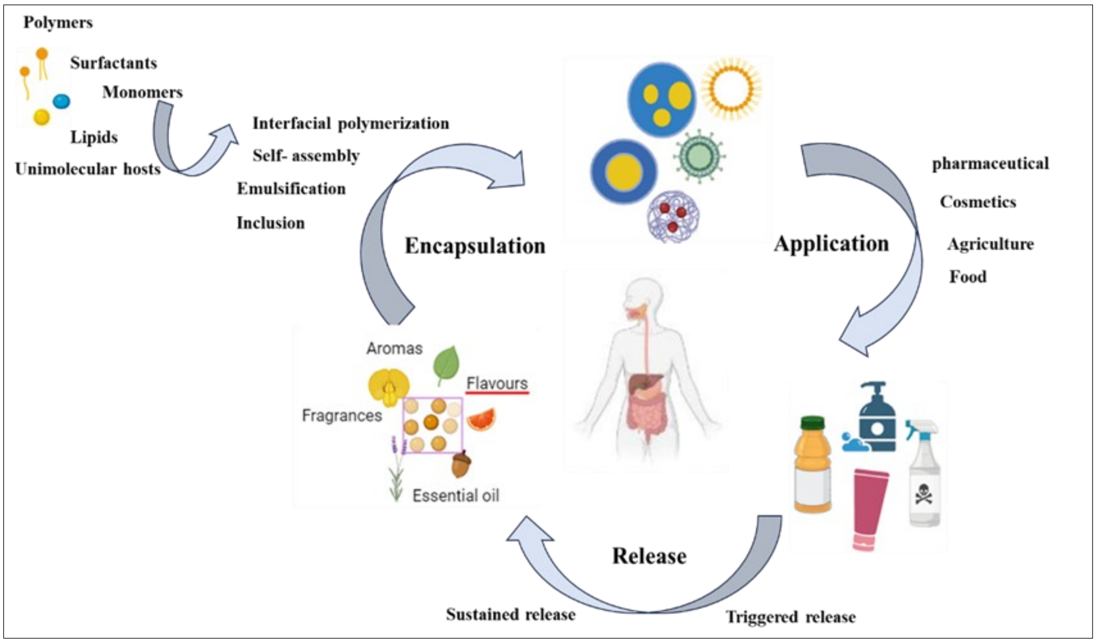


**Fig. 1.** Diverse industrial application of encapsulation technique.

**Table 1**. Bioactive components of various flower crops

| Flower Crops key | Scientific name | Bioactive components | Reference |
|---|---|---|---|
| Rose | *Rosa rubiginosa* | Citronellol, Geraniol, Nerol, Kaempferol, Quercetin | (18) |
| Jasmine | *Jasminum* spp. | Linalool, Benzyl acetate, Indole, Linalyl acetate, Cis- jasmone | (19) |
| Lavender | *Lavandulla officinallis* | Linalool, Linalyl acetate, Terpinen -4-ol, Camphor, Limonene | (20) |
| Chamomile | *Matricaria recutita* | α - bisabolol, Chamazulene, α - bisabolol oxides | (21) |
| Butterfly pea | *Clitoria ternatea* | β-sitostrerol, Stigmasterol, Taxaxerol, Campesterol, Sitostanol. | (22) |
| Ylang Ylang | *Cananga odorata* | Benzyl acetate, Linalool, Geranyl acetate, Methyl benzoate | (23) |
| Clary sage | *Salvia sclarea* | Linalyl acetate, Linalool, α-terpineol | (24) |
| Helichrysum | *Helichrysum italicum* | Neryl acetate, α- pinene, γ -curcumene | (25) |
| Magnolia | *Magnolia grandiflora* | Octanol, Linalool, α-terpineol, Magnolol | (26) |
| Red frangipani | *Plumeria rubra* | Benzyl salicylate, Benzyl benzoate, Nerolidol | (27) |

techniques are classified as - physical methods that rely on physical interactions between material and core, like spray drying, freeze drying, emulsification etc.; chemical methods that chemically crosslink wall material using covalent bonding; physicochemical methods utilizing both physical and chemical interactions and mechanical methods based on mechanical equipment (29) (Fig. 2).

**Nanoencapsulation techniques**

Nanotechnology-enabled encapsulation systems include either nano-sized capsules having an oily core surrounded by a thin polymer membrane or nanospheres with uniform polymer matrix dispersing oil (30). Advantages comprise high stability, versatility in surface modification and controlled release properties. Natural polymers like protein, polysaccharides and synthetic polymers like poly-epsilon-caprolactone are materials of choice (31). Emulsion diffusion, nanoprecipitation and emulsion-solvent evaporation are commonly used preparation methods (32). Table 2 summarises key encapsulation techniques along with their principle, materials used, advantages and limitations. The above discussion indicates carbohydrates, proteins, gums and lipids have been most investigated as encapsulation materials owing to biocompatibility, non-toxic nature and emulsifying properties (33). A combination of materials is often utilized to leverage individual advantages. Technique selection is governed by core properties, cost and equipment availability. Overall, nanoencapsulation and emulsion-based approaches have shown maximum potential for essential oil encapsulation.

Nanoencapsulation is a cutting-edge technique in the field of encapsulation that involves the encapsulation of active ingredients within nanoscale carriers or delivery systems. This approach offers numerous advantages over conventional encapsulation methods, including improved stability, enhanced bioavailability, controlled release and targeted delivery of encapsulated substances (34)(Fig. 3).

**Principles of Nanoencapsulation:** Nanoencapsulation exploits the unique properties of nanomaterials to encapsulate active ingredients within carriers that are typically in the range of 1 to 1000 nanometres in size (35). The encapsulation process can be achieved using various nanomaterials, including lipids, polymers, proteins and inorganic nanoparticles. Nanoencapsulation allows for precise control over the size, shape, surface properties and composition of the carrier systems, thereby enabling tailored delivery of encapsulated substances (36).

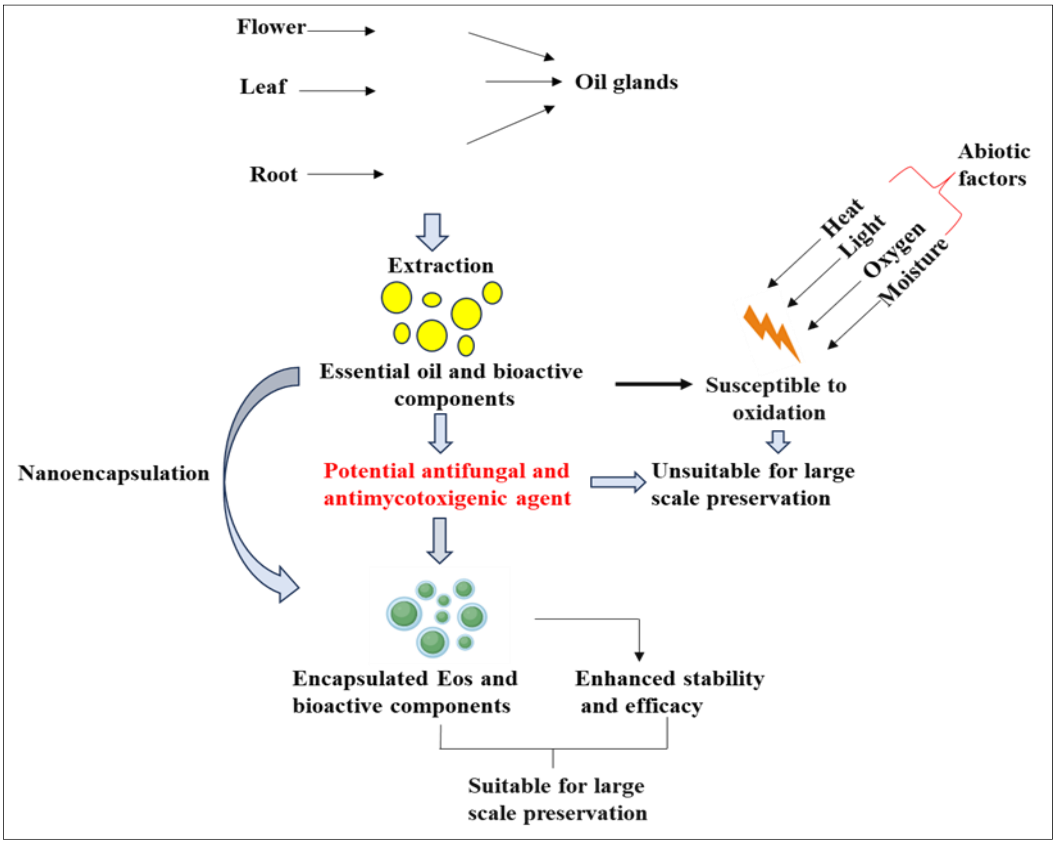


**Fig. 2.** Encapsulation of essential oil.

**Table 2.** Summary of various encapsulation techniques for essential oil

| Technique | Principle | Materials used | Advantages | Limitations |
|---|---|---|---|---|
| Spray Drying | Dispersion of core in coating solution, atomization in hot chamber enabling rapid solvent evaporation and dried capsules formation | Maltodextrin, gum Arabic, whey protein, modified starch | Cost-effective, scalable, suitable for heat-stable oils | High temperatures may degrade heat-sensitive essential oils |
| Freeze Drying (Lyophilization) | Water removal by freezing and dehydration | Maltodextrin, gum Arabic, whey protein | Less thermal damage, better retention of volatiles | High coat longer processing |
| Emulsion | Dispersion as fine droplets in aqueous phase using emulsifier | Gelatin, gum Arabic, modified starch, whey protein | Simple and effective for liquid formulations | Limited stability for volatile oils without additional coatings |
| Molecular Inclusion | Entrapment in central cavity of supramolecules like cyclodextrins shielding from environment | Cyclodextrins, liposomes | Improves solubility, protects oils from oxidation | Limited oil loading capacity and relatively high cost |
| Coating | Film formation around oil droplets using coating materials | Alginate, chitosan, waxes, fatty acids | Protection, Controlled release | Multiple steps, process complexity |
| Nano encapsulation | Formation of nano capsules and nano spheres using polymers | Chitosan, whey protein, Poly (lactic acid) | High stability tailored controlled release | High coat needs for process optimization |
| Coacervation | Involves phase separation of wall materials (e.g. gelatin) to form a capsule around the oil droplets | Ethylcellulose, Gelatin, carragenan and carboxymethyl cellulose (CMC) | High encapsulation efficiency and controlled release | Requires precise pH and temperature control |
| Fluidized Bed Coating | Oils are coated onto solid particles using biopolymer solutions in a fluidized bed system | Nylon, Polyethylene | Good for producing granular or powder-like encapsulates | Equipment-intensive and challenging for highly volatile oils |
| Electrospinning | A polymer solution containing essential oils is electrospun to form nanofibers encapsulating the oils | polyamide, polyacrylonitril, polyethylene oxide (PEO) and carbon nanotube | Produces nanoscale encapsulates with high surface area | Requires specialized equipment and may not suit large-scale use |

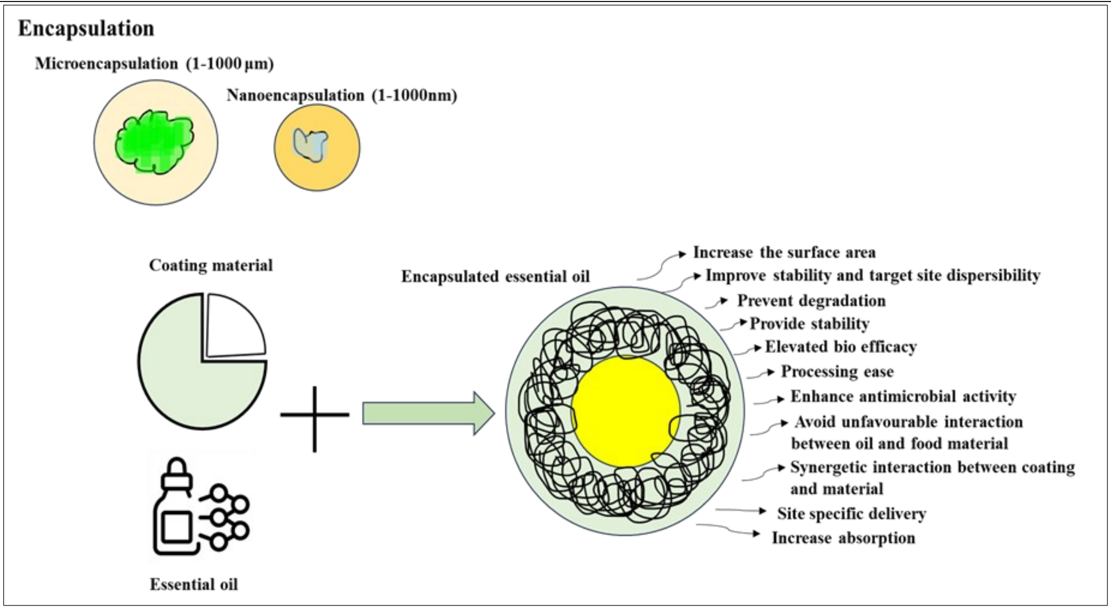


**Fig. 3.** Merits of Nano encapsulated essential oil.

Encapsulation techniques can be tailored to suit different requirements and applications, making them versatile tools for incorporating essential oils into diverse products and formulations. It provides a protective barrier that helps prevent interactions between essential oils and other ingredients in formulations, preserving their integrity and potency (37). These include the utilization of small droplet sizes to mitigate gravitational forces, thereby addressing sedimentation issues during storage and preventing flocculation, facilitating dispersion within solutions (38). It also enables targeted delivery of essential oils to specific sites or tissues, enhancing their bioavailability and therapeutic impact while minimizing potential side effects (Table 2).

**Spray drying:** Spray drying stands out as one of the most frequently employed techniques for microencapsulation and drying in the food and pharmaceutical sectors due to its flexibility, cost-effectiveness, efficiency, scalability, readily available equipment and ability to produce high-quality powder (39). Spray drying works by atomizing a liquid feed (emulsion or suspension) into a chamber of hot air, where the solvent evaporates rapidly, leaving microcapsules of the active material embedded in a matrix. This method has been extensively utilized for decades in encapsulating various bioactive food components such as proteins, fats, vitamins, enzymes, pigments and flavours. However, its application in thermo-sensitive substances like microorganisms and essential oils is restricted due to the high temperatures involved, which can lead to the volatilization or degradation of the product (40). The process of microencapsulation through spray drying typically entails creating an emulsion, solution or suspension containing the core material and the encapsulating material, followed by atomization in a drying chamber where hot air circulates. Upon contact with the hot air, water evaporates rapidly, resulting in the encapsulation of the core material within the matrix (41).

Spray dried capsules of rosemary essential oil using a combination of whey protein and maltodextrin showed up to 90 % encapsulation efficiency and enhanced thermal stability (42). Spray dryers use hot air to dry, which is more energy efficient and faster than freeze drying. The dryer airflow can be easily optimized to dry products within a few seconds. The advantages make it a popular choice for large-scale powder production (43). Few foods with high sugar or low molecular weight materials can produce powders that are sticky. They may stick to the dryer chamber walls and pipes. This requires frequent cleaning and maintenance. While spray drying works for many heat-sensitive materials, some very sensitive products, like enzymes, may become inactive during drying. The high temperatures can damage the product (44).

**Freeze drying:** Freeze drying, also known as lyophilization, is a low temperature dehydration process that involves freezing the product, lowering pressure and then removing water by sublimation (45). It causes less damage to oil volatiles and better retention.

The absence of a liquid water phase prevents collapse or structural changes in the product matrix, leading to high-quality porous powders that retain the active's bioactivity and chemical integrity. Carbohydrates like maltodextrin or gums combined with proteins like gelatin and whey protein are typically used to form a protective encapsulating matrix. This technique is especially effective for essential oils, probiotics, enzymes and pharmaceuticals that degrade at higher temperatures (46). In spite of these advantages, the very slow and lengthy process, high energy requirements for refrigeration and vacuum, the requirement for protective packaging of the final dried product and high equipment costs necessitate the development of improved methods for preparing nano formulations. Although freeze drying provides unmatched product preservation, it is a slow, expensive and low throughput process (47).

**Emulsion:** Among the myriad encapsulation techniques available, the emulsion technique stands out as a versatile and widely employed method due to its ability to encapsulate both hydrophilic and hydrophobic substances efficiently (48). Oil in water emulsions offer excellent protection for lipophile essential oils by dispersing in aqueous phase using an emulsifier, materials commonly used are proteins like gelatin, casein, polysaccharides like gum Arabic, modified starch and maltodextrin or their combinations. Nano emulsions are kinetically stable emulsion systems with droplet size < 200 nm that manifest high encapsulation capacity due to large surface area (49).

The emulsion technique relies on the formation of stable emulsions, which are colloidal dispersions of two immiscible liquids - typically oil and water - stabilized by surfactants or emulsifiers (50). These emulsions serve as matrices for encapsulation, with the active ingredient dispersed within one phase (either oil or water) and the shell material forming around it during encapsulation. Emulsions used in encapsulation can be categorized based on the phase in which the active ingredient is dispersed (Fig. 4).

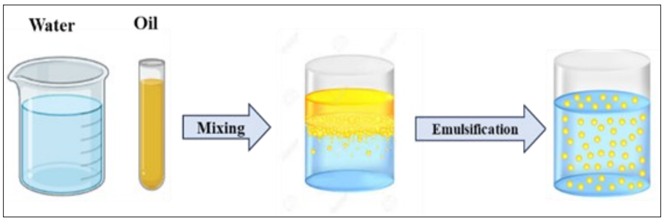


**Fig. 4.** Preparation of emulsion.

***Oil-in-Water (O/W) emulsions:*** where the active ingredient is dispersed in the oil phase, which is then emulsified in an aqueous phase. This type of emulsion is suitable for encapsulating hydrophobic substances.

***Water-in-Oil (W/O) emulsions:*** which, conversely to O/W emulsions, involve dispersing the active ingredient in the aqueous phase, which is then emulsified in an oil phase. W/O emulsions are ideal for encapsulating hydrophilic substances (51).

**Molecular inclusion:** Molecular inclusion is a specialized form of encapsulation that involves the formation of host-guest complexes between a host molecule (the encapsulating agent) and a guest molecule (the active ingredient). It is governed by the principles of supramolecular chemistry, which focuses on non-covalent interactions between molecules to form well-defined complexes. This encapsulation technique relies on specific interactions, such as hydrogen bonding, Van der waals forces and hydrophobic interactions, to entrap the guest molecule within the host structure (52). It provides protection against environmental factors such as light, heat, moisture and oxidation, thereby improving the stability of encapsulated materials. It can enhance the solubility of poorly soluble guest molecules by forming water-soluble inclusion complexes, facilitating their formulation and delivery. Host molecules can be designed to selectively encapsulate specific guest molecules, allowing for targeted encapsulation and controlled release (53).

Molecular inclusion has diverse applications in various fields. Such as in pharmaceuticals, it can be used to enhance the solubility, stability and bioavailability of poorly soluble drugs. Cyclodextrin complexes, for example, are employed to formulate drug delivery systems with improved therapeutic efficacy and reduced side effects (54). Mostly, it is utilized to encapsulate volatile flavour and fragrance compounds, protecting them from degradation and improving their stability. Cyclodextrin complexes are commonly used to formulate encapsulated flavours and fragrances for use in food, beverages and personal care products (55). Plays a major role in encapsulating environmental pollutants for remediation purposes. Cyclodextrin complexes, for instance, have been employed to encapsulate and remove organic contaminants from soil, water and air through adsorption or complexation processes (56).

**Coating:** Coating is a fundamental technique in encapsulation that involves the application of a protective layer around an active ingredient or core material. This process aims to isolate the core material from its surrounding environment, enhance its stability, control its release and provide additional functionalities (57). Materials with good film forming and coating properties like polysaccharides, proteins and lipids are deposited around essential oil droplets using techniques like fluidized bed coating, centrifugal extrusion, vibrating nozzles. Alginate and chitosan-based coating are popular owing to gelling properties in presence of calcium ions and antimicrobial activity respectively (58).

It is also employed to encapsulate flavours, fragrances, nutrients and functional ingredients, improve shelf-life, control release and enhance sensory properties (59). It is utilized to encapsulate active ingredients such as vitamins, antioxidants and UV filters in skincare and cosmetic products, improving efficacy, stability and skin penetration in cosmetic industries (60, 61). The foremost is used to encapsulate agrochemicals such as pesticides, fertilizers and plant growth regulators, enhancing efficacy, reducing environmental impact and enabling controlled release (62). Coating facilitates targeted delivery of the encapsulated material to specific sites within the body or environment, enhancing efficacy and minimizing side effects or environmental impact, allows for precise control over the release kinetics of the encapsulated material, enabling tailored release profiles for optimal therapeutic or functional effects. It can mask unpleasant tastes, odours or appearances of the core material, enhancing consumer acceptability and particularly in pharmaceuticals and food products (63).

## Encapsulation for enhancing bioavailability of flower crops essential oil

Encapsulation technology has been extensively investigated for enhancing the bioavailability of key flower crop essential oils, with significant improvements in stability, efficacy and therapeutic potential. Table 3 presents a comprehensive comparison of encapsulation techniques and their quantitative impact on various flower crop essential oils.

### Rose Essential Oil

Rose oil encapsulation has been achieved using chitosan nanoparticles prepared via the ionic gelation method. *In vivo* pharmacokinetic evaluation in a rat model demonstrated a 3-fold enhancement in oral bioavailability ($AUC_{0\text{-}24}$ increased from 247.6 ± 18.9 to 742.3 ± 45.2 µg·h/L) compared to free oil (64). This significant improvement was attributed to the mucoadhesive properties of chitosan, which prolonged GI tract residence time and protected the oil from enzymatic degradation. Additionally, the encapsulated formulation exhibited 87 % retention of phenolic compounds after 24 hr compared to only 43 % in unencapsulated oil.

When encapsulated within solid lipid particles comprising glyceryl dibehenate, rose oil achieved 2.7-fold deeper skin penetration (189 ± 12 µm vs. 70 ± 8 µm) as tested using Franz diffusion cell methodology (65). This formulation also demonstrated superior stability, maintaining 92 % of its initial citronellol and geraniol content after 6 months of storage at 25 °C, while unencapsulated oil retained only 51 %. The enhanced penetration was correlated with a 76 % increase in anti-inflammatory activity in an *in vitro* keratinocyte model.

### Jasmine Essential Oil

Jasmine essential oil nano-encapsulated with sodium caseinate via an emulsion evaporation method resulted in enhanced antioxidant activity in an *in vitro* gastrointestinal digestion model owing to efficient protection (66, 72). The DPPH radical scavenging activity of encapsulated oil ($IC_{50}$ = 3.42 ± 0.18 µg/mL) was significantly higher than that of free oil ($IC_{50}$ = 8.76 ± 0.43 µg/mL) after simulated gastric digestion, representing a 156 % improvement in antioxidant potency. The encapsulation efficiency reached 89.7 ± 2.3 %, with controlled release kinetics showing 24.3 % release at gastric pH and 78.6 % cumulative release after intestinal phase.

Comparatively, jasmine oil encapsulated in β-cyclodextrin complexes showed moderate improvement in stability (62 % increased half-life) but demonstrated exceptional thermal stability, maintaining 94 % of bioactive components even after exposure to 80 °C for 30 min, whereas unencapsulated oil retained only 38 % under identical conditions.

### Lavender Essential Oil

Lavender oil has been encapsulated using a complex coacervation technique with gelatin and gum Arabic. This formulation displayed reduced oil volatilization (84 % retention vs. 22 % for free oil after 30 days at ambient conditions) and improved thermal stability (degradation temperature increased from 125 °C to 195 °C), ensuring retention of oil therapeutic efficacy (67). Headspace gas chromatography revealed that linalool and linalyl acetate retention was improved by 275 % compared to unencapsulated oil when stored at ambient temperature for 90 days.

Oral and dermal bioavailability enhancement has been exhibited by lavender oil loaded nanostructured lipid carriers (NLCs) prepared from precirol and miglyol (68). The NLC formulation increased transdermal permeation by 4.2-fold compared to conventional emulsion (flux of 24.7 ± 1.8 µg/cm²/h vs. 5.9 ± 0.7 µg/cm²/h). Pharmacokinetic analysis demonstrated a 2.8-fold increase in maximum plasma concentration ($C_{max}$) and a 3.2-fold increase in area under the curve ($AUC_{0\text{-}24}$) following oral administration, indicating significantly enhanced bioavailability. The formulation maintained 93 % stability over 6 months at 4 °C, compared to 31 % for unencapsulated oil.

### Chamomile Essential Oil

Chamomile oil encapsulated in whey protein isolate-based particles has been produced using spray drying, achieving an encapsulation efficiency of 78.3 ± 3.2 % and particle size of 3.8 ± 0.4 µm. *In vivo* experiments in diabetes-induced rats revealed better hypoglycaemic effects compared to free oil, with a 38 % reduction in blood glucose levels versus 17 % for unencapsulated oil, indicating improved bioavailability (69). The spray-dried formulation demonstrated exceptional stability, retaining 92 % of active chamazulene after 12 months of storage compared to complete degradation of the compound in unencapsulated oil.

**Table 3.** Studies on encapsulation for bioavailability enhancement of flower crops essential oil

| Essential Oil | Encapsulation Material/ Technique | Encapsulation Efficiency (%) | Stability Enchancement (%)/ Bioavailability Improvement (fold) | Reference |
|---|---|---|---|---|
| Rose oil | Chitosan nanoparticles | 82.5 ± 3.7 | 3-fold enhancement in oral bioavailability | (18) |
| Rose oil | Solid lipid particles | 86.3 ± 2.1 | High thermal & digestive stability | (18) |
| Jasmine | β-cyclodextrin complexes | 76.2 ± 4.9 | Increase stability and bioavailability | (19) |
| Lavender | Nanostructured lipid carriers | 88.7 ± 2.4 | Improved bioavailability & controlled release | (20) |
| Chamomile | Liposomes | 74.6 ± 5.3 | Enhanced stability/bioavailability | (21) |
| Chamomile | Cyclodextrin inclusion | 69.8 ± 4.1 | Significantly enhanced thermal and oxidative stability | (21) |
| Calendula oil | Improved skin penetration | 81.4 ± 2.6 | Improve the stability of natural components | (61) |
| Jasmine oil | Sodium caseinate nanoparticles | 89.7 ± 2.3 | Enhanced antioxidant activity | (19) |
| Lavender oil | Gelatin – gum Arabic complex coacervation | 91.3 ± 1.8 | Reduced volatilization, improved thermal stability | (20) |
| Rosemary oil/ Lavender oil | Oral and dermal bioavailability enhancement | 88.6 ±3.4 | Improve oral bioavailability | (20) |
| Chamomile oil | Whey protein isolate particles via spray drying | 78.3 ± 3.2 | Better hypoglycaemic effect indicating improved bioavailability | (21) |

When comparing encapsulation techniques for chamomile oil, liposomal delivery systems showed a 3.1-fold increase in anti-inflammatory activity compared to free oil, whereas solid lipid nanoparticles demonstrated a 2.7-fold increase. However, cyclodextrin inclusion complexes provided the most significant improvement in aqueous solubility, increasing it by 24-fold from 0.13 mg/mL to 3.12 mg/mL.

Thus, studies have demonstrated potential of encapsulation in bioavailability enhancement of key flower crops essential oil making them more amenable for pharmaceutical, nutraceutical, cosmetic and food application. Nanoencapsulation along with emulsion and spray drying seem most promising due to high encapsulation efficiency, stability and controlled release characteristics.

## Factors influencing encapsulation efficiency of essential oil

Encapsulation efficiency (EE) refers to the percentage of essential oil successfully encapsulated within a carrier material relative to the initial amount used. Achieving high encapsulation efficiency is critical for ensuring the stability, protection and controlled release of essential oils in applications ranging from food to pharmaceuticals. Several factors influence EE, including the properties of the essential oil, encapsulating material, processing conditions and encapsulation techniques (70). Multiple parameters govern encapsulation efficiency as highlighted below.

### Core to coating ratio

The choice of wall material directly affects EE due to differences in binding affinity, solubility and film-forming properties. Common biopolymers used for essential oil encapsulation include gum arabic, maltodextrin, chitosan, gelatin and modified starch. Gum arabic and maltodextrin are often favored for their emulsifying properties and ability to form stable matrices. Meanwhile, protein-based materials like gelatin and polysaccharides like chitosan offer high oil retention and controlled release capabilities. However, the encapsulation efficiency is also influenced by the ratio of core (essential oil) to wall material; an inadequate ratio can lead to leakage or incomplete encapsulation. An optimal ratio is necessary for high efficiency. Excess core material leads to inadequate coat formation while too little core renders the process redundant (71).

### Core and coating properties

The chemical composition and physical properties of essential oils, such as their volatility, solubility and polarity, plays a significant role in encapsulation efficiency. Essential oils with high volatility, like citrus oils, are more prone to evaporation during encapsulation processes like spray drying, potentially lowering EE. Additionally, hydrophobicity impacts how well oils interact with encapsulating materials, particularly when using water-based carriers. Compatibility between hydrophobic core and coating material is critical. Important core aspects are stability, particle size while coating properties like solubility, viscosity, interactions govern encapsulation (72).

### Process parameters

Encapsulation efficiency is also influenced by processing parameters such as temperature, pressure and drying rates. High temperatures, while speeding up drying, can degrade heat-sensitive compounds and increase oil volatility, leading to lower EE. Conversely, low temperatures may prolong processing time but help retain volatile components. Factors like concentration temperature, pH and stirring rate significantly impact interactions and assembly (73). Process optimization is vital for maximizing efficiency.

Thus, a balanced interplay between core material, coating properties and process parameters is essential for realizing maximum encapsulation efficiency. Careful selection of encapsulation technique along with systematic process optimization enables high value addition of essential oil into usable encapsulated form.

## Evaluation of encapsulation efficiency and bioavailability enhancement

In order to analyse the performance of different encapsulation strategies, systematic evaluation of the following key parameters is crucial:

### Encapsulation efficiency

Direct measurement by disrupting carrier and estimating entrapped active or indirect calculation by measuring non encapsulated fraction in supernatant (74).

### Particle characterization

Shape, surface morphology, size distribution and zeta potential using microscopy or dynamic light scattering (75).

**Thermal analysis:** Techniques like differential scanning calorimetry and thermogravimetric analysis provide insights into thermal transitions and stability (66).

### Spectroscopic analysis

Fourier transform infrared spectroscopy and Raman spectroscopy reveal composition and chemical interactions (76).

### *In vitro* digestion models

Simulated gastric and intestinal digestion examining release characteristics (77).

### *In vitro* cell culture models

Cytotoxicity evaluation along with uptake and transport studies in intestinal or dermal cell lines (77).

### *In vivo* studies

Pharmacokinetic studies analysing absorption, distribution, metabolism and elimination in animal models (78).

Above battery of tests offer valuable information of efficiency of encapsulation and its impact on stability, sustained release characteristics and bioavailability enhancement of essential oil. Combination of *in vitro* and *in vivo* studies provides conclusive evidence on applicability of developed carrier system for oral, topical or inhalation delivery.

## Mathematical modelling of encapsulation systems

Mathematical modelling and computer simulation have emerged as valuable tools providing molecular insights into encapsulation systems. Models based on fundamental physicochemical theories can efficiently predict and optimize fabrication process, release characteristics, stability behaviour and efficiency (79). Mathematical and computational modelling have significantly advanced encapsulation systems for flower essential oils, enabling fine-tuning of formulation and process variables with predictive confidence. For instance, using a Korsmeyer-Peppas model, researchers studied rosemary and lavender oil release from biopolymeric microspheres and microcapsules-determining that rosemary release from chitosan matrices adhered to Fickian diffusion and the optimal formulation (0.45% EO, 0.25% chitosan, 1% Tween-80) achieved reproducible, controlled release with $R^2 \approx 0.98$ (80). Additionally, in a hybrid microcapsule system for rosemary oil, model fitting with the Peppas equation accurately described release kinetics from particles, informing capsule design for improved antioxidant retention. Such modelling has also been applied to lemongrass oil in sodium caseinate matrices, where the Weibull and Peppas models ($R^2 \approx 0.98$) revealed how matrix parameters alter release behavior-guiding selection of wall materials and composition for controlled, sustained delivery (79). Beyond empirical equations, mechanistic and theoretical models-such as compartmental diffusion, phase-field simulations and Monte Carlo approaches-have supported the design of nanoemulsions and nanogel systems encapsulating flower-derived oils by predicting release profiles under physiological or food-processing conditions. For example, microemulsion-based delivery of lavender, basil and clove oils used surface tension and phase behavior models to optimize droplet stability and predict increased bioavailability in intestinal environments (80).

Combined with response-surface methodologies (RSM), these models have enabled scalable process optimization for flower EO encapsulation, improving efficiency and reducing experimental workload. Collectively, this integrated modelling toolkit has transformed the encapsulation of flower essential oil from rosemary and lavender to lemongrass and basil from empirical trial-and-error into a scientifically predictive and scalable process.

Mathematical and computational models such as zero-order, first-order, Higuchi, Korsmeyer-Peppas and Peppas-Sahlin have been successfully applied to flower essential oil encapsulation systems. For example, the Korsmeyer-Peppas model, expressed as

$$Mt/M\infty = k\,t^n$$

(where $Mt/M\infty$ is the fraction released at time t, k is the rate constant and n is the release exponent), has accurately described the controlled release of rosemary and lavender oils from chitosan- or biopolymer-based microspheres with $R^2$ values above 0.98 (81, 82). When combined with Peppas-Sahlin models of the form,

$$Mt/M\infty = k_1 t^m + k_2 t^{2m},$$

they enable quantification of the dual contributions of diffusion ($k_1$) and matrix relaxation ($k_2$) as seen in basil and angelica oil-loaded gelatin/chitosan systems where this model achieved superior fits ($R^2 \approx 0.99$), clarifying the transition between release mechanisms (82).

The Higuchi Mode,

$$Qt = k_H \sqrt{t}$$

has also frequently been applied, particularly in essential oils like angelica, where it produced the highest fit ($R^2 \approx 0.98$), confirming predominantly diffusion-controlled release (83).

Further theoretical modelling-such as Weibull-type kinetic functions,

$$Mt/M\infty = 1\text{-}\exp\,[-(t/\tau)^{b}]$$

(where τ is a scale parameter and b the shape exponent)-has been used for oils like citronella encapsulated in cyclodextrin or gum matrices. Studies reported shape exponents ($0.5 < b < 1$) indicating anomalous diffusion, with excellent data correlation ($R^2 \approx 0.98$-$0.99$) (84). Meanwhile, advanced mechanistic models-including phase-field, Monte Carlo and diffusion-erosion crossover simulations—have delivered deep molecular-level insights into capsule formation, porosity effects and the diffusional-to-erosional release transition, enabling parameter prediction (e.g. characteristic time τ scaling with size) without exhaustive experimentation. Collectively, these mathematical tools have revolutionized flower essential oil encapsulation—optimizing microcapsule efficiency, predicting release behaviour, reducing experimental burden and accelerating formulation to scale-up.

Table 4 below elaborates on the different mathematical modelling of encapsulation techniques.

## Safety evaluation

Systematic toxicity evaluation is vital if essential oil-loaded capsules are intended for pharmaceutical or nutraceutical applications. *In vitro* cytotoxicity assays in cell cultures throw light on biocompatibility and safety (85). Toxicity evaluation of encapsulated essential oils encompasses various considerations. Firstly, it involves assessing the toxicity of formulation components such as the shell material, emulsifiers and additives. Additionally, attention must be given to potential toxicity from degradation products, which may arise from the erosion of the encapsulation shell. Understanding the dose and duration of exposure is crucial, as toxicity can vary depending on the range of doses administered and the duration of exposure. Moreover, toxicity evaluation must account for the administration route, whether oral, topical or intravenous, as this significantly impacts the toxicity profile. Mechanistic studies are essential for elucidating the underlying cellular mechanisms of toxicity. Furthermore, it's important to consider species differences, acknowledging variations in toxicity between human, animal and cell models. By comprehensively addressing these factors, a thorough toxicity evaluation of encapsulated essential oils can be achieved, ensuring the safety of the product for consumers.

## Challenges and Future Perspective

Encapsulation is a promising technique for enhancing the bioavailability of flower crop-based essential oils by improving their stability, solubility and controlled release. However, despite its advantages, several challenges hinder its widespread application.

**Table 4.** Modelling approach

| Modelling Approach | Description | Key Insights Provided |
|---|---|---|
| Mechanistic models | Based on mass transport phenomena and kinetics to mathematically describe encapsulation process and release | Useful for optimization and scaleup |
| Molecular dynamics simulation | Models' interactions and motions of individual molecules in encapsulation matrix | Provides atomistic-level detail on particle formation, oil-matrix interactions, structural organization |
| Molecular mechanics | Determines energy minimized stable conformations | Reveals thermodynamically favourable carrier and payload conformations |
| Quantitative structure-activity relationships | Correlates encapsulation efficiency with carrier properties | Predicts optimal carriers based on their molecular features |
| Artificial neural networks | Empirical modelling tool trained on experimental data | Rapidly predicts optimal formulations for new payloads and carriers |
| Computational fluid dynamics | Simulates complex parameters in industrial processes like spray drying and emulsification | Provides understanding for scale-up and process optimization |

One of the primary issues is the volatility and instability of essential oils, which are highly sensitive to environmental factors such as heat, oxygen and light. Encapsulation can help protect these bioactive compounds, but maintaining their integrity during processing and storage remains difficult. Additionally, the choice of encapsulation material plays a critical role in determining bioavailability. While biopolymers like chitosan, alginate and starch are commonly used, their interaction with essential oil components can sometimes affect the release profile or therapeutic efficacy. Another major challenge is achieving targeted and controlled release. Essential oils often require precise release mechanisms to maximize their therapeutic benefits. However, conventional encapsulation techniques may lead to premature degradation, burst release or reduced absorption in the gastrointestinal tract or skin. Moreover, the size and morphology of encapsulated particles significantly impact bioavailability. Nanotechnology-based encapsulation, such as nanoemulsions, liposomes and solid lipid nanoparticles, has shown promise in improving permeability and absorption. Yet, scalability and cost-effectiveness remain major concerns, particularly for commercial production.

Current methodologies also face limitations in terms of encapsulation efficiency, with many techniques unable to consistently achieve high loading capacities for volatile compounds. Furthermore, batch-to-batch reproducibility presents significant challenges for quality control and standardization of encapsulated essential oil products, particularly when transitioning from laboratory to industrial scale. The regulatory landscape for encapsulated essential oils presents significant hurdles for commercialization. In the European Union, novel encapsulation systems must undergo rigorous safety assessments under the Novel Food Regulation (EU) 2015/2283, while in the United States, achieving Generally Recognized as Safe (GRAS) status from the FDA requires substantial safety documentation. Nanoscale encapsulation systems face particularly intense scrutiny due to concerns about bioaccumulation and long-term exposure effects. Additionally, the combination of multiple ingredients in encapsulation matrices often complicates regulatory approval processes, as each component must be individually assessed for safety. These regulatory requirements significantly increase development timelines and costs for manufacturers seeking to bring encapsulated essential oil products to market in nutraceutical and pharmaceutical applications.

Emerging techniques such as stimuli-responsive encapsulation (pH, enzyme or temperature-triggered release) and bio-inspired encapsulation using natural lipid-based carriers offer new possibilities for enhancing bioavailability. These "smart" systems can respond to specific environmental triggers, releasing their payload only under predetermined conditions. pH-responsive systems utilizing polymers such as Eudragit or pH-sensitive lipids can target release to specific regions of the gastrointestinal tract, while enzyme-responsive systems incorporating peptide linkers or enzyme-degradable polymers enable site-specific release at locations with elevated enzyme activity. Bio-inspired encapsulation systems enhance essential oil delivery by mimicking natural mechanisms. Plant-derived exosomes improve mucosal penetration and stability, while archaeosomes, made from archaeal lipids, offer exceptional resilience under extreme conditions. Phytosomes, combining essential oils with phospholipids, facilitate better absorption by emulating cell membrane interactions. Protein-based carriers like zein, casein micelles and silk fibroin provide biocompatible matrices with adjustable release properties, making them effective for targeted and sustained essential oil delivery. Hybrid encapsulation systems enhance essential oil delivery by combining materials like polymers, lipids and inorganic compounds to improve stability and control release. Techniques such as layer-by -layer assembly and core-shell structures allow precise tuning of release profiles. Advancements in computational modelling and machine learning are optimizing these systems by predicting interactions and release kinetics, while sustainable methods like supercritical fluid processing and 3D printing enable efficient, eco-friendly production.

Additionally, machine learning and computational modelling are expected to optimize encapsulation techniques, improving efficiency and stability. Collaborative research integrating nanotechnology, biotechnology and materials science will be crucial in unlocking the full potential of encapsulation for flower crop-based essential oils. Future studies should also focus on clinical validation to establish the efficacy and safety of encapsulated formulations, paving the way for their broader application in nutraceuticals, pharmaceuticals and functional foods (Fig. 5).

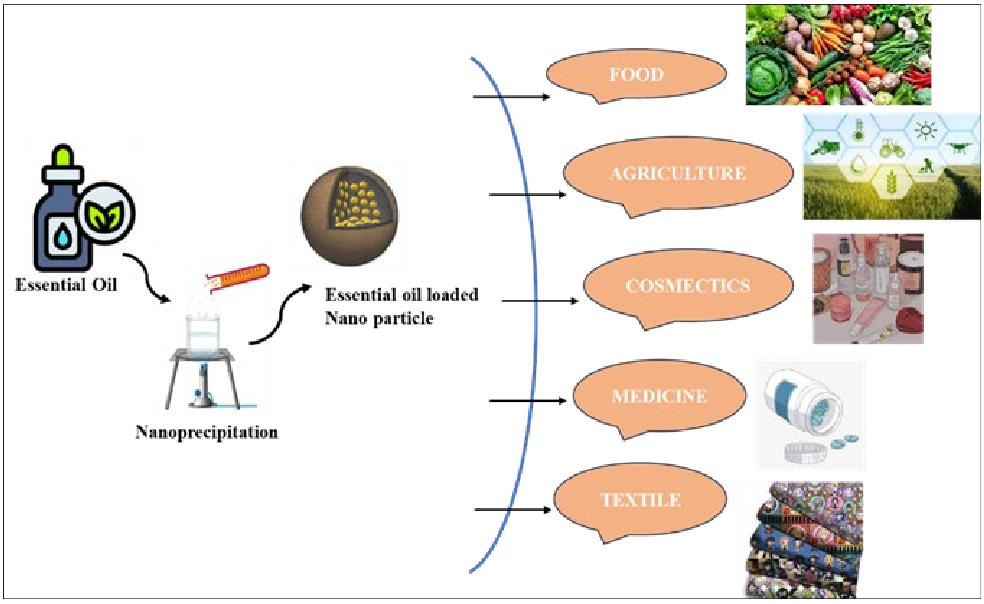


**Fig. 5.** Essential oil used in different field.

## Conclusion

Currently, growing concern for essential oils with the same efficiency or even more than chemical synthesized drugs has prompted scientists to focalize most of their efforts on developing new approaches to preserve the stability, bioactivity and bioavailability of these bioactive agents. The occurrence of oil nanoencapsulation has been noticed as efficient approach to resolve such restrictions. The present review provides comprehensive insights into harnessing encapsulation technology for enhancing bioavailability and efficacy of essential oil. Their promising pharmacological activities have high value in pharmaceuticals, nutraceuticals, cosmetics and food. However, characteristics like volatility, degradation susceptibility, poor water solubility and bioavailability necessitates suitable delivery systems for practical utility. Encapsulation offers multifaceted advantages by entrapping oils within protective matrices and coating. Materials like carbohydrates, gums, proteins, lipids and combination thereof have been investigated with techniques ranging from spray drying, freeze drying, emulsion, molecular encapsulation to nano encapsulation. Systematic studies have demonstrated success of different encapsulation strategies in stability enhancement and bioavailability augmentation of key flower crops oil, making them amenable for product development. Scale-up the nanoprecipitation in industries constitute another important aspect to be taken into consideration due to the fact that using polymeric nanoparticles for the delivery of essential oils is one of the newest approaches in the pharmaceutical technology. Thus, with careful material selection and process optimization, encapsulation can serve as an efficient tool for harnessing the immense health beneficial potential of essential oil in flower crops.

## Authors' contributions

All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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