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Current Overview of Microencapsulation in Brazil

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Abstract:
Background: *Microencapsulation is a crucial process in biological and pharmaceutical sciences, particularly for preserving and maintaining biological activities of essential oils. This technique enhances the stability, bioavailability, and controlled release of these oils, which are prone to degradation from environmental factors. By using microencapsulation, researchers can improve the shelf life and efficacy of essential oils, making them suitable for various applications in food, pharmaceuticals, textiles and cosmetics.*
Materials and Methods: *A systematic literature search was conducted across databases like PubMed, Scopus, Web of Science, Google Scholar and ScienceDirect, focusing on peer-reviewed articles published between 2021 and 2025. The search utilized keywords related to essential oils and microencapsulation. The selected studies were analyzed to categorize microencapsulation techniques, encapsulant materials, and characterization methods. Quantitative and qualitative analyses were performed to identify patterns and relationships within the dataset.*
Results: *The analysis revealed that spray-drying combined with emulsification was the most commonly used technique, appearing in 73.3% of the studies. Maltodextrin was identified as the most frequently used encapsulating material. The results highlighted consistent patterns in the techniques and materials employed for microencapsulation of essential oils in Brazilian research.*
Conclusion: *This review provides a comprehensive overview of the current microencapsulation techniques for essential oils in Brazil. It emphasizes the importance of selecting appropriate methods to ensure the stability and functionality of essential oils, ultimately enhancing their application in various industries.*
Key Word: *Encapsulation, Essential Oils, Microencapsulation, Techniques.*

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I. Introduction

Microencapsulation is a pivotal process in sciences and technology, enhancing the preservation and delivery of essential oils. It involves enclosing active compounds within a protective coating to enhance stability, bioavailability, and controlled release[1]. Due to environmental factors such as light, heat, and oxygen, essential oils, renowned for their aromatic and therapeutic properties, are prone to degradation. By employing microencapsulation, researchers can significantly improve the shelf life and efficacy of these volatile compounds, making them more suitable for various applications in the food, pharmaceutical, and cosmetic industries[2,3].

Microencapsulation techniques are diverse, encompassing a range of methodologies tailored to different essential oils and intended outcomes[4]. Techniques such as spray drying, coacervation, and solvent evaporation are among the most commonly employed methods, each offering unique advantages and limitations. The choice of microencapsulation technique is influenced by factors such as the physicochemical properties of the essential oils, the intended application, and the desired release profile. This diversity not only highlights the versatility of microencapsulation but also underscores the need for a comprehensive understanding of each method to optimize the encapsulation process[5,6].

Selecting the appropriate microencapsulation technique is crucial for achieving the desired stability and functionality of essential oils. An unsuitable technique may fail to protect active compounds, leading to potency loss and diminished effectiveness[7,8]. Additionally, encapsulation process can affect sensory attributes, such as flavor and aroma, key factors in consumer acceptance. Therefore, a thorough evaluation of the various microencapsulation methods is essential to ensure that the encapsulated essential oils meet the specific requirements of their intended applications[9,10].

The objective of this review is to conduct an integrative analysis of the microencapsulation techniques of essential oils as documented in Brazilian research. This review synthesizes findings from scientific databases to provide a comprehensive overview of current knowledge in microencapsulation. Then, it will highlight advancements, challenges, and future directions in microencapsulation, thereby serving as a valuable resource for researchers and practitioners seeking to enhance the application of essential oils through effective encapsulation strategies.

II. Material And Methods

Revised Methodology

A systematic literature search was conducted across the PubMed, Scopus, Web of Science, Google Scholar and ScienceDirect databases using the search terms "essential oil", "essential oils", and "microencapsulation". Boolean operators ("OR" and "AND") refined the search strategy. Inclusion criteria encompassed peer-reviewed, open-access articles published from 2021 to 2025 on essential oils microencapsulation techniques. Only original research studies were included, excluding reviews to maintain a focus on primary data. Additionally, only nationally produced publications were included to ensure regional relevance.

Meta-Analysis

The selected studies were analyzed through a multi-stage process. First, key variables were extracted and categorized into three groups: (1) microencapsulation techniques, such as spray-drying, emulsification, cryogelation, lyophilization, and ionic gelation; (2) encapsulant materials, such as maltodextrin, arabic gum, modified starch, and protein-based matrices; and (3) characterization methods, spanning physical (e.g., mass calculations, electron microscopy), chemical (e.g., FTIR, XRD), and functional (e.g., absorbance, release kinetics) analyses.

Quantitative and qualitative analyses were performed to identify patterns and relationships in the dataset. Frequency analysis revealed the prevalence of specific techniques and materials, while trend analysis mapped the evolution of research focus over the four-year period. Correlation mapping was employed to establish connections between encapsulant materials and characterization approaches, and network analysis visualized the co-occurrence of techniques and materials using graph theory principles.

To enhance the robustness of our findings, we employed statistical and computational tools. Descriptive statistics, such as proportions and cross-tabulations, were computed using Python's pandas library. Data visualization tools such as matplotlib and seaborn were used to create heatmaps, bar charts, and network graphs, providing intuitive representations of complex relationships. Advanced algorithms, including k-means clustering and principal component analysis (PCA), were applied to identify technique-material synergies and reduce dimensionality in characterization data.

III. Result

The results of this meta-analysis, presented in Table 1 and Figures from 1 to 4, reveal consistent patterns in the techniques and materials used for essential oil microencapsulation between 2021 and 2024. As summarized in Table 1, which compiles data from 15 studies, spray-drying combined with emulsification emerged as the most commonly employed technique, appearing in 11 out of the 15 analyzed articles (n = 11; 73.3%). Less frequently used approaches included cryogelation with freeze-drying and ionic gelation with freeze-drying, each reported only once (n = 1 each). Regarding encapsulating materials, maltodextrin was the most frequently used (n = 9; 60%), followed by arabic gum (n = 6; 40%) and modified starch (n = 3; 20%), as illustrated in Figure 1.

Table no 1. Overview of Encapsulation Techniques, Characterization Methods, Materials Used, and Corresponding References

Employed Techniques	Microcapsule Analyses	Encapsulating Materials	Reference
Emulsion and Spray-Drying	Gas Chromatography	Maltodextrin and Modified Starch	Ramos *et al.*,[11]
Emulsion and Spray-Drying	Mass Calculations	Maltodextrin and Gelatin	Alencar *et al.*,[12]
Emulsion and Spray-Drying	Mass Calculations	Maltodextrin and Pea Protein Concentrate	Francisco *et al.*, [13]
Emulsion and Spray-Drying	Electron Microscopy	Maltodextrin and Arabic Gum	Acácio *et al.*,[14]
Emulsion and Spray-Drying	Electron Microscopy	Arabic Gum	Berreta *et al.*,[15]
Emulsion and Spray-Drying	Absorbance	Arabic Gum	Berreta *et al.*,[16]

Emulsion and Spray-Drying	X-Ray Diffraction, Fourier Transform Infrared Spectroscopy, Electron Microscopy	Maltodextrin and Modified Starch	Reis *et al.*,[17]
Emulsion and Spray-Drying	—	Modified Starch, Arabic Gum, and Maltodextrin	Carvalho *et al.*,[18]
Cryogelation and Lyophilization	Mass Calculations	Albumin and Pectin	Chaux-Gutiérrez *et al.*,[19]
Emulsion and Spray-Drying	Mass Calculations	Maltodextrin, Cashew Gum, and Inulin	Granados *et al.*,[20]
Ionic Gelation and Lyophilization	Mass Calculations	Sodium Alginate	Mergulhão *et al.*,[21]
Emulsion and Spray-Drying	Absorbance	Xanthan Gum and Guar Gum	Ribeiro *et al.*,[22]
Emulsion and Spray-Drying	Mass Calculations	Maltodextrin	Silva *et al.*,[23]
Emulsion and Textile Impregnation	Particle Size Analyzer	Chitosan and Arabic Gum	Valle *et al.*,[24]
Emulsion and Lyophilization	Electron Microscopy	Arabic Gum and Maltodextrin	Zanela *et al.*,[25]

Figure no 1. Prevalence of Encapsulant Materials in Essential Oil Microencapsulation Brazilian Studies (2021-2024)

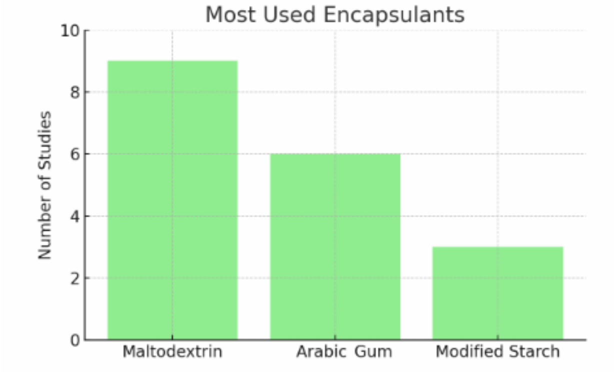


Figure no 2 confirms the dominance of spray-drying (n = 11) compared to alternative methods such as cryogelation with freeze-drying (n = 1), ionic gelation with freeze-drying (n = 1), emulsion with textile impregnation (n = 1) and emulsion with freeze-drying (n = 1). In terms of characterization methods, Figure 3 shows that mass yield calculations were the most frequently employed (40%), followed by electron microscopy (20%) and Absorbance analyses (~13,3%).

Figure no 2. Frequency Distribution of Microencapsulation Techniques Across Analyzed Studies

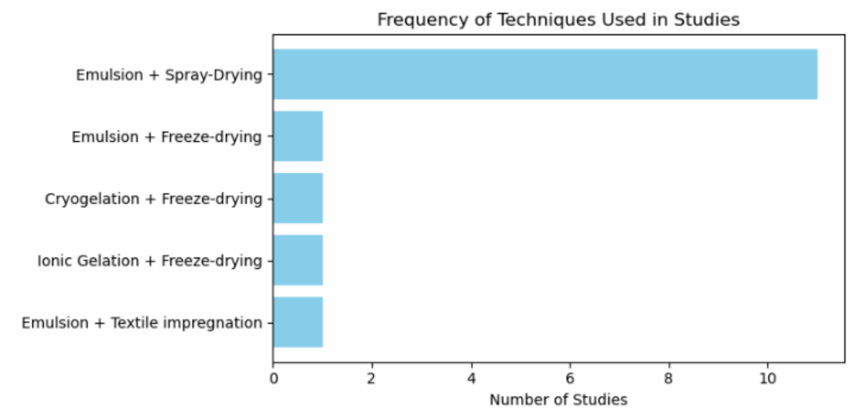
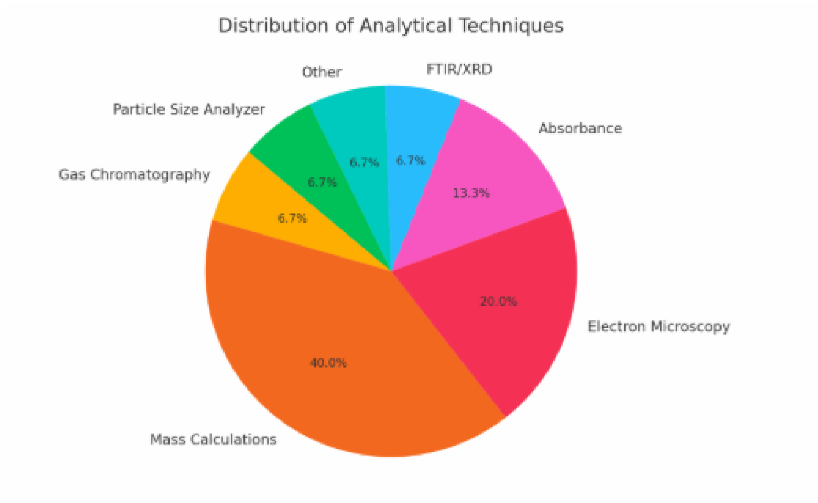
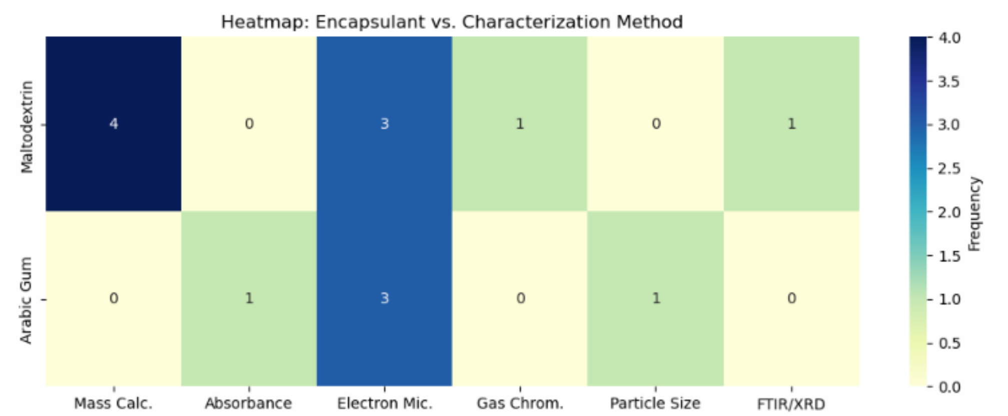


Figure no 3. Proportional Utilization of Characterization Methods in Microcapsule Analysis



The heatmap in Figure no 4 highlights specific associations between encapsulating materials and analytical methods. Maltodextrin was primarily associated with mass yield calculations (n = 4) and electron microscopy (n = 3), while arabic gum exhibited a balanced distribution across electron microscopy (n = 3), and absorbance analysis (n = 1). Materials such as sodium alginate and chitosan appeared exclusively in combination with specific characterization techniques.

Figure no 4. Heatmap Correlation: Encapsulant Materials vs. Characterization Techniques



IV. Discussion

Microencapsulation is a valuable technique widely used in the food and pharmaceutical sectors. This technique encases active compounds in a protective layer, enhancing stability, bioavailability, and controlled release. In recent years, a growing body of research has emphasized its effectiveness, especially when applied to essential oils and other bioactive substances[11,12,13,17].

In one study, the essential oil of lemongrass (*Cymbopogon citratus*-CCEO) was microencapsulated using spray drying with maltodextrin and gelatin. Encapsulation efficiencies ranged from 15.86% to 61.95%, with optimal results at 148 °C inlet temperature, 15% maltodextrin, and 10% CCEO. These microcapsules also demonstrated antibacterial activity against pathogens such as Staphylococcus aureus and *Escherichia coli*, suggesting their potential use as natural preservatives in food products[12].

A similar approach was applied to the essential oil of Brazilian pepper tree or Red mastic (*Schinus terebinthifolius)*, using maltodextrin and arabic gum as encapsulating agents. The resulting microcapsules remained stable at temperatures of up to 200 °C, effectively shielding the essential oil from thermal degradation. These findings underscore microencapsulation's effectiveness in protecting thermosensitive compounds during processing and storage[11].

Propolis, a bee-derived substance known for its antimicrobial and antioxidant properties, presents another compelling application. In this case, arabic gum was used to produce microcapsules with an encapsulation efficiency of 93.7%. Microencapsulation strongly preserved propolis' bioactivity, reinforcing its potential as a functional food ingredient with extended shelf life and improved performance[13,14].

The essential oil of clove basil (*Ocimum gratissimum*) has also been successfully microencapsulated, preserving both its antimicrobial and antioxidant properties. With an encapsulation efficiency of 45.2%, the resulting microparticles exhibited a strong inhibitory effect against a variety of pathogenic bacteria. This further supports the idea that microencapsulation is an effective method for maintaining the bioactivity of natural compounds even under challenging conditions[18].

Beyond food preservation, microencapsulation holds promise for safeguarding volatile compounds used in other applications areas. For instance, clove essential oil encapsulated in alginate retained high thermal stability and encapsulation efficiency. This suggests broader microencapsulation's role in protecting sensitive substances from oxidation and degradation, extending its relevance to cosmetics, pharmaceuticals, and nutraceuticals[19].

In addition to technical advantages, economic and environmental aspects of microencapsulation have also been explored. A cost-benefit analysis of oregano oil microcapsules found that arabic gum provided the most sustainable option, balancing low environmental impact with economic viability. This highlights the need to optimize encapsulation processes for both efficacy and sustainability[15].

Microencapsulation has become a key technology across multiple sectors, especially in the development of biofunctional textiles and biodegradable materials. One area gaining particular attention is the incorporation of microencapsulated essential oils into textile substrates. This approach offers new possibilities for enhancing fabric functionality by incorporating bioactive antimicrobial or soothing properties. Controlled release of these active compounds depends on microcapsules interaction with textile fibers, influenced by the fabric composition. For example, studies have shown a reservoir effect in cotton and polyester, meaning the fabric can influence how slowly or quickly the oils are released. This modulation in release rate can improve the effectiveness of essential oils in areas like skincare and environmental protection[24].

In another promising development, cryogels are being explored as carriers for essential oils. These porous, sponge-like materials offer unique encapsulation capabilities. Albumin and albumin-pectin cryogels exhibit high encapsulation efficiency and strong antimicrobial activity against pathogens. The structural characteristics of the cryogels themselves appear to play a key role in determining the bioactivity of the encapsulated oils, pointing to the importance of carefully selecting carrier materials for targeted applications[16].

Rising sustainability concerns have spurred innovations in biodegradable packaging. One example is the incorporation of essential oils into starch/PBAT films. This approach protects volatile compounds during processing while enhancing films' mechanical properties. These biodegradable films maintain strong antioxidant activity, making them a promising alternative to conventional plastics for food packaging, especially at a time when consumers are increasingly concerned about synthetic additives and environmental impact[25].

Agricultural by-products offer a promising avenue for microencapsulation. For instance, phenolic compounds extracted from pracaxi seeds (*Pentaclethra macroloba*) - often considered waste - have been successfully encapsulated, showing strong antioxidant potential. This method opens up new opportunities for creating value-added products in the cosmetics and food sectors, while also contributing to waste reduction and resource efficiency[23].

Microencapsulation has proven effective in preserving the antioxidant qualities of oils from wild passion fruit (*Passiflora cincinnata)* seeds. The process significantly boosts the oxidative stability of essential fatty acids, which are otherwise prone to degradation. Combined with antioxidant extracts, microencapsulated oils exhibit enhanced stability and bioactivity, expanding their industrial applications[21].

In summary, microencapsulation is a crucial technology for improving the stability and efficacy of essential oils and bioactive compounds. The evidence gathered across recent studies confirms its utility in various applications, ranging from natural food preservatives to advanced pharmaceutical formulations. As the demand for stable, functional, and natural products continues to grow, microencapsulation is poised to play an increasingly important role in delivering high-quality, effective solutions.

V. Conclusion

This analysis highlights microencapsulation of essential oils as a versatile and promising strategy in Brazilian scientific landscape, with applications primarily focused on product formulation, preservation, and textile functionalization. Emulsion and spray-drying, the most frequently used methods, are efficient, cost-effective, and well-suited for industrial applications. Encapsulant selection and complementary techniques align with the final product's intended application, highlighting the importance of both practical and functional considerations in formulation planning. The methodological diversity observed reflects the Brazilian scientific community's ongoing progress in optimizing microencapsulation processes and enhancing the value of natural compounds.

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