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REVIEW PAPER

Technological and functional applications of vanilla (*Vanilla planifolia*) extracts

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Abstract

Vanilla (*Vanilla planifolia*) is a high-value spice, with a market projected to reach USD 6.29 billion by 2029, and its complex flavor is largely attributed to vanillin. However, production remains limited due to inefficient conventional extraction methods and the high susceptibility of the extract to thermal and oxidative degradation. This review critically analyzes recent advances in extraction techniques and encapsulation strategies, both of which are essential for the optimization and industrial application of vanilla extracts. Emerging methods such as Ultrasound-Assisted Extraction (UAE) and Supercritical Fluid Extraction (SFE-CO_2) offer faster, more selective, and more sustainable alternatives, with SFE-CO_2 standing out for enabling the selective fractionation of vanillin, volatiles, and lipid fractions, thus producing high-purity, value-added oleoresins. Encapsulation is equally crucial for protecting volatile compounds, with spray drying using wall materials such as β-cyclodextrin and whey protein concentrate (WPC) being the dominant technique, achieving high efficiency (up to 94.5%) and strong vanillin retention. Process parameter optimization is vital to ensure stability and performance. Beyond summarizing existing literature, this review provides an innovative perspective by examining the integration of selective extraction and robust encapsulation techniques. Special emphasis is given to novel combinations of wall materials, strategies to enhance vanillin retention and controlled release, and considerations of process scalability and cost-effectiveness. By addressing these aspects, this work identifies technological opportunities that may drive the sustainable industrial application of vanilla extracts in the food, cosmetic, and nutraceutical sectors.

Graphical abstract



Keywords Vanillin · Supercritical fluid extraction · Encapsulation · Spray drying · Bioactive compound

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Introduction

Vanilla (*Vanilla planifolia* Andrews) is one of the most highly valued spices worldwide, recognized for its characteristic aroma and complex sensory profile, which justifies its wide application in the food, beverage, cosmetics, and pharmaceutical industries [1]. The production of natural extract, however, is marked by high complexity, due to the need for manual pollination and the lengthy curing process of the beans, which can exceed nine months—factors that restrict supply and increase costs [2]. It is estimated that in 2021 the global vanilla extract market reached USD 5.26 billion, with forecasts of growth to USD 6.29 billion by 2029, driven by increasing demand for natural and sustainable ingredients [2, 3].

Natural vanilla extract contains more than 170 volatile compounds, with vanillin (4-hydroxy-3-methoxybenzaldehyde) as the main constituent, responsible for 80–90% of its characteristic aroma [4, 5]. However, conventional extraction techniques, such as maceration and percolation in hydroalcoholic solutions, present significant limitations, including long processing times, high consumption of organic solvents, and the risk of thermal degradation of bioactive compounds [6, 7].

In recent years, methodological advances have driven the development of alternative extraction techniques, such as Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), Supercritical Fluid Extraction (SFE), and Pressurized Liquid Extraction (PLE). These approaches allow greater efficiency, selectivity, and preservation of the chemical integrity of the extracts, while reducing solvent consumption and meeting the demands for cleaner and more sustainable processes [8–10].

In addition to the extraction step, the encapsulation of vanilla extracts has gained prominence as a strategy to improve the stability, bioavailability, and industrial applicability of aromatic compounds. Techniques such as spray drying, using different wall materials, for instance, gum arabic, maltodextrin, and polysaccharide derivatives, have proven effective in protecting bioactive compounds from degradation, enabling controlled release, and expanding application possibilities in food and cosmetic matrices [11, 12].

The bibliographic search was conducted on September 29, 2025, in electronic databases including Science Direct, Springer Nature, Wiley Online Library, Taylor & Francis, ACS, MDPI, and SciELO, using the term vanilla in the title, abstract, and keywords, and considering publications of research articles, book chapters, and short communications from 2015 to 2025 (Fig. 1).

The bibliometric analysis (Fig. 1) shows that, although vanilla is one of the most highly valued spices worldwide, the number of scientific publications on the subject is still relatively limited compared to other raw materials of industrial importance. Between 2015 and 2025, only 455 articles were identified in international databases, reflecting modest scientific output in light of the species' economic relevance and technological potential. This scenario reveals both the scarcity of systematic research and the broad opportunity for advances across different fronts.

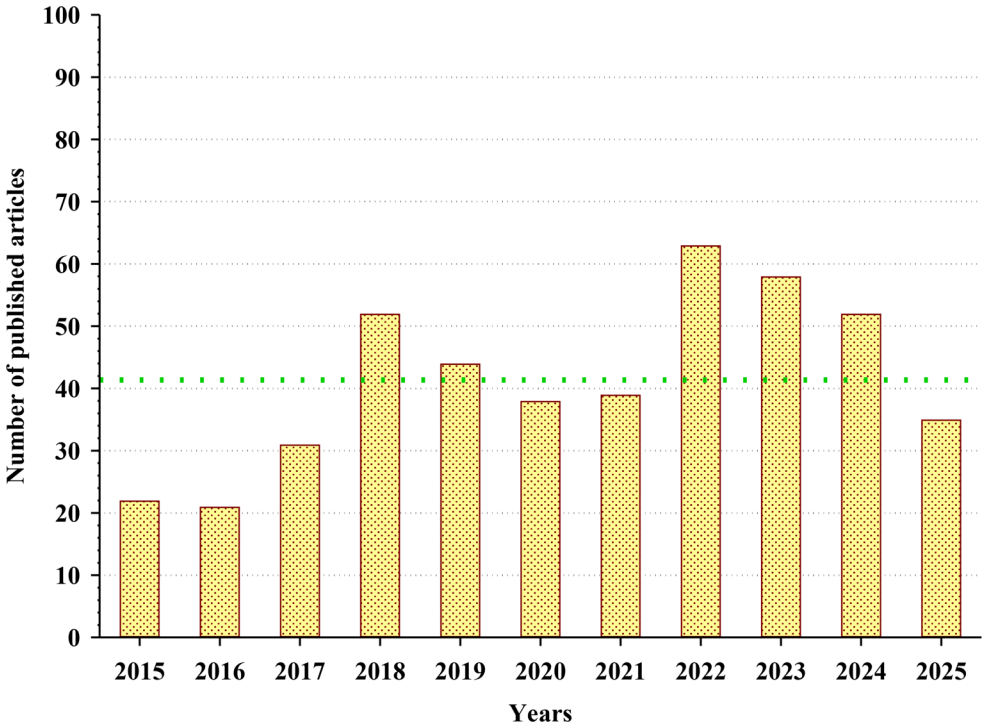


Fig. 1 Evolution of scientific publications on *Vanilla planifolia* between 2015 and 2025. Average publication value of articles (green dashed line)

Despite the limited volume, existing studies highlight the significant scientific and industrial potential of *Vanilla planifolia*, particularly in the development of more efficient and sustainable extraction techniques, as well as encapsulation strategies aimed at preserving bioactive compounds. The growing global demand for natural, high-value-added ingredients further reinforces the need to intensify research in this field, creating a strategic space for innovation and technology transfer.

Therefore, beyond compiling and discussing recent advances, this review aims to highlight relevant aspects that differentiate the present contribution from previous literature. In particular, it discusses how advances in extraction techniques and encapsulation strategies can contribute to improving the quality and functional performance of vanilla extracts. Attention is given to vanillin retention, wall material selection, and technological considerations related to process feasibility and scalability, reinforcing the practical relevance of *Vanilla planifolia* extracts for food, cosmetic, and pharmaceutical applications.

In this context, the review adopts an integrative perspective by addressing extraction and encapsulation within the same framework, emphasizing parameters such as vanillin recovery, extract purity, encapsulation efficiency, and stability. By distinguishing total extract yield from vanillin-specific recovery and considering measurable quality attributes, the manuscript contributes to a clearer understanding of how processing conditions may influence ingredient standardization and formulation performance in bioactive systems.

Market and economic relevance

Natural vanilla is considered one of the most expensive and valuable spices in international trade. Global production is dominated by a few countries, with Madagascar accounting for more than 50% of the global supply, followed by Indonesia and Uganda [2]. The production process, which involves manual pollination and prolonged curing of the beans, restricts supply and keeps prices at high levels [1].

In 2021, the global vanilla extract market was estimated at USD 5.26 billion, with projections to reach USD 6.29 billion by 2029, at a compound annual growth rate (CAGR) of 3.5% [2]. More recent estimates indicate that the pure extract segment generated around USD 1.2 billion in 2024, with expectations to reach USD 2.5 billion by 2033 [3]. This appreciation is directly associated with the growing demand for natural, sustainable, and synthetic-free ingredients in food, cosmetics, and nutraceutical products.

In the Brazilian market, natural vanilla stands out as a high value-added spice. Dried beans can reach prices between BRL 3.00 and BRL 5.00 per gram, surpassing BRL 6,000.00 per kilogram [13]. For liquid extracts, prices range from approximately BRL 42.00 per 30 mL to around BRL 450.00 for concentrated 500 mL versions [14, 15]. In the international market, the price of beans also varies significantly depending on quality, origin, and curing degree. For instance, export/import prices ranged from USD 15 to USD 199 per kilogram in 2024, depending on these factors [16]. In European markets, Madagascar vanilla has been quoted between €394 and €455 per kilogram for premium dried beans, with additional premiums for organic versions [17]. Major companies such as McCormick, Nielsen-Massey, Firmenich, Symrise, and Adams Extract maintain a strong presence in global trade, reinforcing the strategic and economic importance of the vanilla sector.

Recent data from FAO and trade databases reveal that global production of raw vanilla reached approximately 7.94 million kg in 2023, with Madagascar accounting for ~ 41.9% of this global production [18, 19]. International exports generated around USD 472.96 million, while global imports totaled ~ USD 536.07 million in the same year [19]. The economic importance of vanilla is further evidenced in the United States, where vanilla beans are ranked as the highest-value spice import, according to USDA/ERS reports, being among the seven spices that account for more than 75% of the total value of spice imports into the U.S [20]. In 2023, U.S. imports totaled ~ USD 194.35 million for 1,283 tons, with Madagascar as the main supplier [21]. In 2022, this value reached ~ USD 350.7 million, highlighting significant price volatility and dependence on external supply [21]. These figures reinforce both the high economic value of vanilla and its sensitivity to fluctuations in production, export, and international pricing.

This scenario highlights the strategic importance of vanilla in international trade and demonstrates how variations in production, exchange rates, and logistics directly impact economic flows. When compared to prices observed in Brazil for beans and extracts, the data reveal the magnitude of margins and potential gains through internationalization or value addition.

Figure 2 illustrates the main forms of vanilla commercialization, which include dried beans, concentrated paste, and liquid extract. Beans represent the most traditional and valued form, widely used in gourmet gastronomy and as a raw material for the flavor industry. However, their high cost and processing complexity limit access to large-scale markets. Vanilla paste, obtained by combining extract with ground seeds and stabilizing agents, offers convenience and enhanced aromatic intensity, being increasingly used in confectionery and premium products. Liquid extract, in turn, is the most commercially relevant form, widely applied in food, beverages, cosmetics, and pharmaceuticals, and is considered the primary pathway for industrial vanilla processing.



Fig. 2 Vanilla is commercially available in three predominant formats: (**A**) Dried beans, the most traditional and premium form, used in gourmet gastronomy and as raw material for extraction; (**B**) Concentrated paste, obtained by combining extract, ground seeds, and stabilizing agents, applied in confectionery and premium products due to its practicality and aromatic intensity; and (**C**) Liquid extract, the most industrially relevant form, widely employed in foods, beverages, cosmetics, and pharmaceuticals

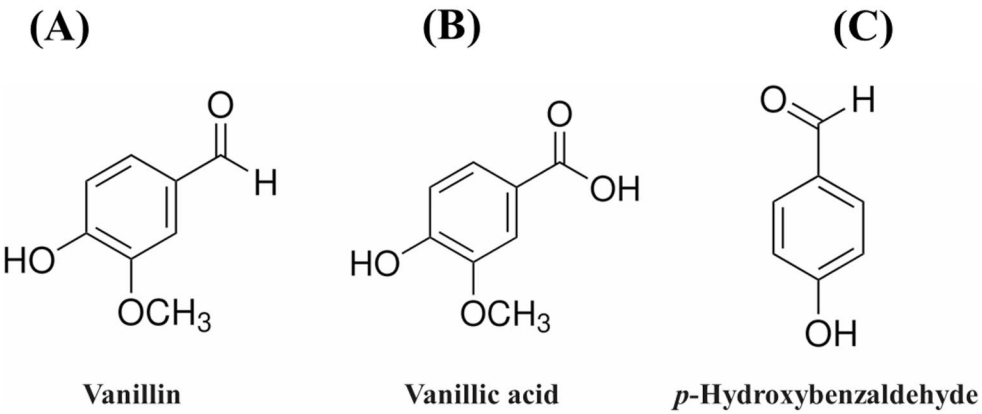


Fig. 3 Chemical structure of the main compounds presents in vanilla extract

Although these three forms dominate commercialization, there is growing interest in new presentation formats, such as microencapsulated powders, which offer greater stability and versatility of application. This trend underscores the importance of research into encapsulation technologies, capable of extending shelf life and reducing volatile compound losses, directly linking scientific advances to market demands.

Thus, the production and commercialization of vanilla represent not only an agricultural and technological challenge but also an opportunity to add value across different production chains. The development of more efficient extraction and encapsulation techniques may therefore contribute to strengthening industrial competitiveness and meeting the growing demand for high-quality natural products.

However, beyond considerations of industrial feasibility and scalability, the scientific and technological relevance of vanilla extraction and encapsulation is fundamentally linked to quality consistency and measurable performance parameters. Variations in curing methods, extraction selectivity, and processing conditions directly influence vanillin concentration, co-extracted constituents, and extract purity, which subsequently impact encapsulation efficiency, volatile retention, and storage stability. Therefore, establishing standardized extraction protocols and characterization approaches based on quantifiable indicators—such as vanillin recovery, purity ratios, encapsulation efficiency, and stability metrics—is essential to ensure reproducibility and controlled formulation performance. This shift from predominantly economic evaluation toward measurable quality attributes reinforces the technical foundation of vanilla-based ingredient development.

Chemical composition of vanilla

The aromatic complexity of vanilla arises from a matrix rich in volatile, phenolic, and lipid compounds. More than 170 components have been identified, with vanillin (4-hydroxy-3-methoxybenzaldehyde) standing out as the main quality marker (Fig. 3), representing 80–90% of the characteristic aroma [1, 4, 5]. In addition, compounds such as vanillic acid (the second most abundant compound), p-hydroxybenzaldehyde (the third most abundant) (Fig. 3), p-hydroxybenzoic acid, vanillyl alcohol, and anisaldehyde also contribute to the sensory profile [7, 22].

Hernández-Fernández et al. [22] expanded this perspective by characterizing the oleoresins obtained through supercritical extraction of *Vanilla planifolia*. The study identified not only vanillin but also a wide diversity of aromatic aldehydes, phenolic alcohols, fatty acids, and esters. Among the volatile compounds detected were acetovanillone, guaiacol, anisaldehyde, and cinnamic acid derivatives, which intensify aromatic complexity. Regarding fatty acids, palmitic, stearic, oleic, and linoleic acids were prominent, suggesting that vanilla oleoresin contains a lipid fraction with additional functional potential. These results demonstrate that the chemical composition of vanilla goes beyond classical phenolic compounds, encompassing volatile and lipid fractions that can be modulated depending on the extraction method.

The chemical profile of vanilla is influenced by several factors, including geographical origin, cultivation conditions, bean curing methods, and the extraction techniques employed [4]. In addition to aromatic compounds, the extracts present phenolic fractions with recognized antioxidant activity and potential nutraceutical applications [23].

This diversified composition explains the preference for natural vanilla over synthetic substitutes, since no single isolated compound can fully reproduce its aromatic complexity. Therefore, understanding the detailed chemical composition of the extract is essential both to optimize extraction techniques and to guide encapsulation strategies that preserve the integrity and stability of bioactive compounds.

Functional relevance of major chemical groups

Beyond their structural classification, the major chemical groups identified in Vanilla planifolia extracts exhibit relevant functional and bioactive properties that extend their importance beyond flavor contribution. Vanillin, the principal phenolic aldehyde and main flavor compound (representing approximately 80–90% of the flavor fraction) [4], has been widely reported to possess antioxidant, antimicrobial, and potential anticancer activities. Studies have demonstrated that vanillin can induce apoptosis and modulate cellular signaling pathways, supporting its relevance in pharmaceutical and nutraceutical applications [24].

In addition to vanillin, other phenolic compounds such as p-hydroxybenzaldehyde and vanillic acid contribute to the overall antioxidant capacity of vanilla extracts [4]. The presence of volatile phenols, guaiacol derivatives, and related aromatic compounds has also been associated with bioactivity and functional properties in food systems [22]. Furthermore, variations in curing processes influence phenolic concentration and metabolite profiles, which may directly impact functional performance and biological activity [25].

At the molecular level, transcriptomic studies have shown that enzymes involved in phenylpropanoid and lignin-related pathways regulate vanillin biosynthesis and accumulation [26]. This biochemical basis reinforces the importance of understanding compositional variability not only from a sensory perspective but also in terms of bioactive potential and standardization for functional ingredient development.

By expanding the discussion beyond compound identification to include demonstrated biological and technological applications, the chemical composition section highlights the broader relevance of vanilla-derived compounds in food preservation, cosmetic formulations, and bioactive systems.

Vanilla extract extraction methods

Conventional methods

Hydroalcoholic percolation

Percolation in hydroalcoholic solutions (30–40% v/v) is considered the traditional method for obtaining vanilla extract. The process, which can last from 48 to 72 h, involves the continuous passage of solvent through the plant material, allowing the solubilization of vanillin and other aromatic compounds [7]. Despite being simple and widely used, the method is inefficient in terms of time and may cause partial degradation of compounds due to limited temperature control [1].

Soxhlet extraction

Soxhlet extraction is another conventional technique applied to vanilla, using ethanol or hydroalcoholic mixtures in successive reflux cycles. Although it provides more complete extraction than percolation, it has disadvantages such as high solvent consumption and the risk of thermal degradation of bioactive compounds due to prolonged heat exposure [6].

Maceration

Maceration is one of the oldest techniques for obtaining vanilla extracts, performed by prolonged immersion of the beans in alcoholic solutions. While simple and low-cost, it has important limitations: the process may take weeks or even months for complete diffusion of compounds, with low yield and risk of microbial contamination [27]. Moreover, maceration tends to be less selective, resulting in extracts

with high solvent content and increased susceptibility to oxidative degradation of volatile and lipid compounds [22]. Compared to modern methods, maceration is limited in preserving the chemical diversity of the extract, particularly of more sensitive compounds.

Emerging methods

Ultrasound-assisted extraction (UAE)

UAE promotes acoustic cavitation in the solvent, facilitating cell wall disruption and enhancing mass transfer. Applied to vanilla, this technique has proven effective in reducing extraction time and increasing yield, while allowing the use of less aggressive solvents [27].

Microwave-assisted extraction (MAE)

In MAE, microwave radiation selectively heats polar molecules, accelerating diffusion and solubilization of bioactive compounds. Studies show that the technique provides higher vanillin extraction in shorter times and with lower solvent consumption, maintaining chemical integrity of the compounds [7].

Supercritical fluid extraction (SFE)

Supercritical carbon dioxide extraction (SFE-CO_2) is considered one of the most promising techniques for obtaining high-quality vanilla extracts. This approach offers advantages such as selectivity, absence of toxic residues, and preservation of volatile compounds due to moderate operating temperatures [28, 29].

Hernández-Fernández et al. [22] demonstrated the efficiency of SFE-CO_2 in obtaining oleoresins rich in volatile compounds and lipid fractions. They observed that parameters such as pressure, temperature, and extraction time directly influence extract composition. Milder conditions favored recovery of light volatiles (e.g., anisaldehyde and guaiacol), while higher pressures enhanced extraction of lipid fractions, including unsaturated (oleic, linoleic) and saturated (palmitic, stearic) fatty acids. These results indicate that SFE allows modulation of the final extract composition, expanding its applicability in the food, cosmetic, and pharmaceutical sectors.

Thus, SFE-CO_2 not only overcomes the limitations of conventional methods (such as maceration and Soxhlet) but also enables the production of extracts with higher added value, rich in bioactive compounds beyond vanillin. This versatility reinforces its potential as a key technology for markets that prioritize natural and sustainable ingredients.

Pressurized liquid extraction (PLE)

PLE, also called subcritical extraction, employs solvents under pressure (4–20 MPa) and moderate temperatures (50–200 °C), which increases solubility and reduces extraction time [9]. This technique has been applied to agro-industrial residues to recover bioactive compounds, such as phenolics and antioxidants [30, 31]. In the case of vanilla, PLE can provide richer and more stable extracts, with lower solvent consumption and higher efficiency.

The evolution of vanilla extraction methods reflects not only technological advances but also the growing demand for sustainable and economically viable processes. However, the instability of many extracted bioactive compounds, especially vanillin, requires complementary strategies to ensure their preservation during storage and industrial application. In this context, encapsulation emerges as a crucial step, allowing protection, stabilization, and controlled release of extracts, which will be addressed in the following section.

A comparative analysis of different studies (Table 1) highlights the significant evolution of extraction techniques applied to *Vanilla planifolia*, ranging from conventional methods to advanced process-intensification approaches. Traditional techniques, such as maceration and Soxhlet extraction, although widely used and low-cost, present important limitations: low yield, high solvent consumption, and long extraction times [27].

For industrial process selection, it is essential to distinguish between total extract yield and vanillin-specific extraction efficiency. Quantitative data from the literature indicate substantial differences among techniques. In supercritical CO_2 extraction (SFE), oleoresin yields as high as 10.5 wt% (oleoresin/dry beans) have been reported at 110 bar and 36 °C [4]. More importantly, vanillin recovery can reach up to 95% of the initial vanillin present in the beans [32], with vanillin representing 74–97% of the quantified flavor compounds, compared to approximately 61% for conventional ethanol extraction [32]. This demonstrates that SFE not only provides competitive total yields but also significantly enhances vanillin purity and selectivity.

Conventional Soxhlet extraction at 95 °C using ethanol released approximately 180 ppm of vanillin after 8 h under a solvent-to-solid ratio of 66.7 mL/g [27]. In contrast, ultrasound-assisted extraction under similar solvent proportions achieved approximately 140 ppm in only 1 h at ambient temperature [27], demonstrating improved time efficiency but slightly lower absolute vanillin concentration under the reported conditions.

Microwave-assisted extraction (MAE) has consistently shown superior vanillin extraction power compared to UAE,

Table 1 Comparison of different extraction methods of vanillin from *Vanilla planifolia*

Extraction Method	Operating Conditions	Total Extract Yield	Vanillin Recovery / Content	Extraction Time	Vanillin-Specific Efficiency	Reference
Supercritical CO_2 (SFE)	110 bar, 36 °C	10.5 wt% (oleoresin/dry beans)	Up to 95% recovery of initial vanillin; 74–97% of flavor compounds were vanillin	Up to 160 h	Very high selectivity and purity	[32]
Supercritical CO_2 (fractionation study)	140–180 bar; 310–348 K	2–10 g oleoresin/kg CO_2 (solubility basis)	Selective extraction of vanillin (main flavor compound)	Batch process	High selectivity tunable via P–T control	[4]
Conventional Ethanol Extraction	35–40% ethanol	—	Vanillin ≈ 61% of quantified flavor compounds	48–72 h	Moderate selectivity	[32]
Soxhlet Extraction	95 °C; 66.7 mL/g solvent ratio	—	~ 180 ppm vanillin	8 h	Moderate yield; long time	[27]
Ultrasound-Assisted Extraction (UAE)	Ambient T; 66.7 mL/g	—	~ 140 ppm vanillin	1 h	Faster than Soxhlet; lower absolute vanillin under reported conditions	[27]
Microwave-Assisted Extraction (MAE)	4 g/100 mL; optimized ethanol concentration	Highest extraction power among compared methods	Higher vanillin yield than UAE, PAE, maceration	Shortest time among tested methods	High kinetic efficiency; purity depends on optimization	[7]
Baseline Vanillin Content in Cured Beans	—	—	≈ 20 g vanillin/kg dry beans (~ 2% w/w)	—	Theoretical maximum extraction benchmark	[4]

maceration, and pressure-assisted extraction, providing higher vanillin yields in shorter extraction times [7]. Under optimized MAE conditions (4 g/100 mL sample-to-solvent ratio), enhanced extraction kinetics were observed, supporting its suitability for industrial intensification [7]. However, higher extractive power does not necessarily imply higher vanillin purity, as co-extraction of secondary compounds may increase total soluble solids without proportionally increasing vanillin selectivity.

Additionally, cured vanilla beans typically contain approximately 20 g vanillin/kg dry beans (≈ 2% w/w) [4], providing a theoretical maximum extraction benchmark for evaluating process efficiency. Therefore, methods achieving high vanillin recovery percentages relative to this baseline are more economically advantageous when targeting vanillin as the primary value-added molecule.

Assisted extraction methods, such as Ultrasound-Assisted Extraction (UAE) and Microwave-Assisted Extraction (MAE), have shown significant gains in efficiency and processing time. Dong et al. [7] and Yeh et al. [33] reported that these techniques not only significantly reduced extraction time but also yielded higher amounts of phenolic compounds and antioxidants compared to maceration. However, results indicate that UAE may exhibit lower selectivity, while MAE, although more efficient, still lacks robust industrial scalability. Although ultrasound-assisted extraction (UAE) significantly enhances mass transfer and reduces extraction time, its mechanism—based on cavitation-induced cell disruption—may promote the simultaneous release of multiple intracellular compounds, thereby reducing selectivity toward vanillin specifically. In comparative studies, UAE achieved approximately 140 ppm vanillin under reported conditions, whereas Soxhlet extraction reached approximately 180 ppm under optimized thermal conditions [27]. Similarly, microwave-assisted extraction demonstrated higher vanillin extraction efficiency than UAE under comparable solvent systems [7]. These findings suggest that while UAE improves process intensification, its selectivity toward vanillin may be lower than techniques optimized for vanillin-targeted extraction.

Supercritical Fluid Extraction (SFE-CO_2), in turn, has proven to be highly selective for vanillin and other volatile compounds [22, 32]. Furthermore, recent studies indicate that SFE enables fractionation of different chemical classes, such as phenols and fatty acids [4], reinforcing its potential as a clean and sustainable technology. Its limitations remain operational costs and the need for optimization at an industrial scale.

More recent studies have expanded the scope of vanilla extraction to include pre-treatment effects and biomedical applications. Cuan-Escobar et al. [25] demonstrated that the "killing" method during curing directly influences the phenolic profile and vanillin concentration, highlighting the importance of the post-harvest stage. Chang et al. [24] investigated ethanolic extracts from stems and leaves, showing promising effects against glioblastoma cells, suggesting that vanilla agricultural by-products may have added value beyond food use. Additionally, Gastelbondo et al. [26] integrated transcriptomic analyses to identify genes involved in vanillin biosynthesis, pointing to the possibility of genetically optimizing production.

Finally, Liang et al. [34] emphasized the influence of drying methods on the preservation of aromatic compounds: while infrared radiation drying (IRD) ensured higher retention of volatiles and reduced processing time, vacuum freeze-drying (VFD) better preserved color but caused significant aromatic losses. These findings underscore the need to integrate curing, drying, and extraction steps into optimized strategies to maximize yield, sensory quality, and process sustainability.

Thus, the evolution of vanilla extraction methods reflects the ongoing pursuit of more efficient, selective, and environmentally responsible technologies, opening perspectives not only for the food and cosmetic industries but also for pharmaceutical and biomedical applications.

Downstream separation and purification strategies

Beyond the extraction stage, the separation and purification of vanillin and other bioactive compounds represent critical steps for ensuring quality, safety, and functional performance in pharmaceutical, nutraceutical, and high-end cosmetic applications. Although extraction techniques determine yield and initial selectivity, downstream strategies are essential to enhance purity and standardization of the final ingredient.

Supercritical Fluid Extraction (SFE-CO_2) presents intrinsic fractionation capabilities that can be exploited for selective purification. Experimental studies have demonstrated that variations in pressure and temperature significantly influence both oleoresin solubility and vanillin selectivity. At pressures between 140 and 180 bar and temperatures ranging from 310.5 to 348.3 K, significant changes in solubility (2–10 g oleoresin/kg CO_2) were observed, directly affecting the preferential extraction of vanillin [4]. Moreover, controlled batch fractionation under equilibrium conditions enabled complete vanillin recovery using a defined solvent-to-feed ratio, while progressively reducing co-extracted compounds in subsequent fractions [4]. This stepwise fractionation allows partial separation of vanillin from lipid fractions and other volatile components, reducing the burden on subsequent purification stages.

The choice of extraction parameters directly influences the initial purity of the crude extract. In microwave- and ultrasound-assisted extraction systems, solvent composition and energy input affect both yield and selectivity. For example, ethanol/water mixtures (40:60 v/v) provided higher extraction efficiency, and microwave-assisted extraction produced extracts with higher vanillin content compared to ultrasound-assisted extraction [32]. Similarly, microwave-assisted extraction showed stronger extraction power and higher vanillin yields compared to other conventional techniques [7]. However, increased extraction intensity may also enhance co-extraction of secondary compounds, reinforcing the importance of optimizing operating conditions to balance yield and purity. Furthermore, mass transfer modeling demonstrates that diffusivity and equilibrium constants are temperature-dependent, indicating that extraction temperature influences both extraction kinetics and selectivity [35]. Proper parameter optimization therefore facilitates downstream purification by reducing impurity load at the source.

After extraction, additional purification approaches such as chromatographic techniques and crystallization can be employed to isolate vanillin from structurally related phenolics and co-extracted volatiles. Advanced analytical and hyphenated chromatographic methods are widely applied for differentiation and purification of vanillin in complex matrices [5], enabling separation from compounds such as vanillic acid, p-hydroxybenzaldehyde, and other phenolics naturally present in vanilla [36]. Controlled solvent evaporation followed by crystallization can further enhance vanillin purity, particularly when starting from ethanolic extracts or oleoresins [4]. The purity of the extract also directly impacts the efficiency and stability of subsequent encapsulation processes. Vanilla extracts contain a highly complex mixture of volatile and semi-volatile compounds [36]. While this complexity contributes to sensory richness, co-extracted lipids, acids, and reactive aldehydes may interfere with encapsulation matrices. Vanillin, as an aromatic aldehyde, can react with amino groups in proteins to form Schiff bases [37], potentially affecting encapsulation efficiency and stability when protein-based wall materials are used. Therefore, higher purity extracts tend to improve encapsulation efficiency, enhance oxidative stability, promote controlled release behavior, and increase shelf-life performance. Additionally, advanced extraction technologies such as SFE provide higher selectivity and purity compared to conventional methods [5], which is advantageous for producing standardized, high-value ingredients suitable for regulated applications.

Encapsulation of vanilla extracts: performance, stability, and technological approaches

Encapsulation plays a critical role in improving the stability, handling, and functional performance of vanilla extracts, particularly due to the high volatility and oxidative susceptibility of vanillin and related aromatic compounds [38]. Beyond simply converting liquid extracts into powder form, encapsulation enables protection against thermal degradation, light exposure, and oxidation, while also allowing controlled release and improved incorporation into food and pharmaceutical matrices.

Spray drying: efficiency, retention and stability

Spray drying remains the most widely applied encapsulation method for vanilla extracts due to its cost-effectiveness, scalability, and ability to produce spherical particles with controlled morphology [39]. However, its effectiveness depends strongly on wall material selection and process optimization.

Calva-Estrada et al. [39] demonstrated that spray drying using whey protein concentrate (WPC) resulted in high vanillin retention and preserved antioxidant activity during processing and storage. The microcapsules showed favorable morphology and structural integrity, contributing to stability at different water activities.

Similarly, Aguirre-Alonso et al. [40] evaluated spray drying under nitrogen atmosphere and reported that process variables such as inlet temperature and carrier material concentration significantly influenced aromatic compound retention, including vanillin, vanillic acid, and p-hydroxybenzaldehyde. The use of inert gas minimized oxidative losses, reinforcing the importance of process control in maintaining flavor integrity.

Ocampo-Salinas et al. [41] developed modified rice starch as a wall material and achieved encapsulation efficiencies of up to 86.2% for natural vanilla extract. Structural analysis confirmed the formation of stable microcapsules, although interaction between wall material and core was limited, suggesting that electrostatic and surface properties play a key role in encapsulation performance.

These findings demonstrate that spray drying efficiency is not intrinsic to the technique itself, but rather dependent on formulation strategy, carrier composition, and drying parameters.

Cyclodextrin inclusion complexes

Beyond spray drying, molecular inclusion using β-cyclodextrin has shown high encapsulation efficiency and improved stability. Krasaekoopt and Jongyin [42] reported microencapsulation efficiencies up to 94.5% using the kneading method. Stability studies demonstrated that storage at 35 °C and controlled water activity significantly influenced degradation kinetics, reinforcing the importance of environmental control for maintaining vanillin stability.

Cyclodextrins offer a hydrophobic internal cavity capable of entrapping aromatic molecules such as vanillin, improving solubility and reducing oxidation susceptibility [42]. This approach is particularly promising for pharmaceutical and nutraceutical applications where stability and controlled release are critical.

Layer-by-layer and multilayer systems

Advanced encapsulation strategies include multilayer polyelectrolyte systems. Noshad et al. applied a layer-by-layer (LBL) electrostatic deposition method using soy protein isolate, OSA starch, and chitosan [43]. The three-layer system exhibited lower moisture content, reduced solubility, and controlled release behavior even at 80 °C, demonstrating superior thermal protection compared to single-layer systems. These multilayer approaches provide enhanced barrier properties and may represent a promising strategy for improving release control and long-term stability.

Stability considerations and functional performance

Encapsulation improves not only physical handling but also chemical stability. Vanillin is susceptible to enzymatic oxidation, thermal degradation, and light-induced reactions [42]. Spray-dried and inclusion-complex powders have demonstrated improved resistance to degradation during storage, particularly when moisture and oxygen exposure are controlled.

Moreover, the retention of antioxidant activity observed in spray-dried systems [39] suggests that encapsulation preserves not only aroma but also functional bioactivity, expanding potential applications in functional foods and nutraceutical formulations.

Comparative perspective

While spray drying remains the dominant industrial technique due to scalability and economic feasibility, alternative methods such as molecular inclusion and multilayer encapsulation offer superior protection and controlled release in specific applications. The choice of technique should therefore consider: required vanillin retention, storage stability conditions, release profile requirements, process scalability, and wall material compatibility.

Importance of encapsulation

The instability of vanillin and other phenolic compounds when exposed to light, heat, and oxygen reduces the shelf life and functional value of vanilla extracts [4]. Studies show that encapsulation icreases chemical stability, improves water solubility, and enhances antioxidant activity of the extracts. Encapsulation not only protects vanillin from oxidation and volatilization but can also enhance its apparent water solubility by dispersing the hydrophobic molecule within hydrophilic carrier matrices. Given that vanillin is a relatively hydrophobic aromatic aldehyde, its direct dispersion in aqueous systems is limited [37]. Encapsulation strategies

Table 2 Comparison of different studies on encapsulation of *Vanilla planifolia* extracts

Reference	Technique	Wall Material	Efficiency (%)	Vanillin Retention / Release	Moisture (%)	Solubility (%)
Noshad et al. [43]	Spray drying with multilayer deposition (LBL)	Soy Protein Isolate, Octenyl Succinic Anhydride Starch, Chitosan	45–52 (1–2 layers), 27 (3 layers)	Better release control (MDT up to 1.77 h at 37 °C)	2.3–3.6	10–12
Krasaekoopt & Jongyin [42]	Complexation (β-cyclodextrin)	β-CD	Up to 94.5	Increased stability ($t_1/_2$ = 4.54 h)	–	–
Calva-Estrada et al. [39]	Spray drying	Whey Protein Concentrate (WPC)	> 90	High retention (> 90%)	< 4.6	> 92
Aguirre-Alonso et al. [40]	Spray drying	Maltodextrin	85–90	~ 18–19 mg/g	~ 3–4	High
		Precipitated silica	> 90	> 20 mg/g	~ 3–4	Moderate
Ocampo-Salinas et al. [41]	Spray drying	Modified rice starch (hydrolyzed, succinylated, extruded)	Up to 86.2	Good retention, without strong matrix–extract interaction	–	–

that incorporate vanillin into ethanol-based extracts or bioactive formulations have demonstrated improved functional performance in aqueous biological systems [24], supporting the relevance of carrier-assisted solubilization for pharmaceutical and nutraceutical applications. By stabilizing and dispersing vanillin within biocompatible matrices, encapsulation enhances its bioavailability and application versatility in aqueous formulations.

Krasaekoopt & Jongyin [42] reported encapsulation efficiencies of up to 94.5% with β-cyclodextrin, while Calva-Estrada et al. [39] achieved yields > 90% and high vanillin retention using spray drying with whey protein.

Aguirre-Alonso et al. [40] further demonstrated that process variables — such as inlet and outlet air temperature, as well as the type and concentration of wall material — directly influence the retention of aromatic compounds (vanillin, vanillic acid, p-hydroxybenzaldehyde, p-hydroxybenzoic acid). Under optimized conditions (170–180 °C inlet; 80–90 °C outlet), using nitrogen as drying gas and heat-pump systems, microcapsules with higher preservation of phenolic compounds, low moisture content and water activity, improved color, and oxidative stability were obtained.

These results indicate that optimizing encapsulation allows alignment of technological efficiency and sustainability — for instance, using closed-loop nitrogen enables ethanol recovery from the extract and reduces oxidation risk.

Wall materials used

The success of the encapsulation process depends directly on the appropriate choice of wall materials, which should possess properties such as water solubility, low hygroscopicity, compatibility with the extract, and the ability to form a stable protective matrix.

Encapsulation performance is strongly dependent on the carrier material (CM). Recent studies highlight:

- β-Cyclodextrin – High affinity with vanillin, forming inclusion complexes that increase solubility and protect against oxidation and degradation [42].
- Whey Protein Concentrate (WPC) – Effective in retaining volatile compounds and maintaining antioxidant activity after spray drying [39].
- Maltodextrin (DE-10) and modified starches – Provide oxidative stability, reduced hygroscopicity, and good processability, widely used as carrier agents in spray drying [40].
- Precipitated silica – Provides high retention of vanillin and other aromatic compounds, representing an alternative material for microencapsulation [40].
- Polysaccharides such as gum arabic – Traditionally used in combination with maltodextrin or cyclodextrins, supporting emulsion stability and retention of volatile compounds [43].

According to Aguirre-Alonso et al. [40], each material has specific optimal concentrations to maximize aromatic compound retention. For instance, formulations with maltodextrin (2:1 relative to extract) under moderate temperatures ensured good vanillin retention, whereas precipitated silica showed even higher recovery (> 20 mg/g vanillin in some treatments). Table 2 presents the main data from studies on vanilla encapsulation, summarizing technique, efficiency, vanillin retention, moisture content, and solubility.

The comparative analysis of different studies (Table 2) shows that the choice of encapsulation method and wall material directly impacts encapsulation efficiency, vanillin retention, and the release profile of compounds. Complexation with β-cyclodextrin [42] demonstrated one of the

highest reported efficiencies (up to 94.5%) and the longest half-life, although its large-scale application may be limited by the cost of cyclodextrins. Spray drying with whey protein (WPC) [39] stood out for balancing yield, high solubility (> 92%), and low moisture content (< 4.6%), in addition to preserving antioxidant activity — desirable characteristics for food formulations. In the study by Aguirre-Alonso et al. [40], both maltodextrin and precipitated silica showed high performance, with the latter providing the highest vanillin retention (> 20 mg/g). Conversely, the Layer-by-Layer (LBL) method with soy protein isolate (SPI), OSA starch, and chitosan [43] demonstrated greater control over volatile compound release, albeit with lower efficiencies (27–52%), indicating potential for pharmaceutical and nutraceutical applications. Finally, the use of modified rice starch [41] proved to be a sustainable and competitive alternative, achieving up to 86.2% efficiency, highlighting the potential of renewable sources as promising carrier materials. Overall, the literature suggests that combined wall material systems can maximize encapsulation efficiency, reconciling high retention of volatile compounds, oxidative stability, sustainability, and economic feasibility for industrial applications.

The application of techniques such as spray drying, combined with appropriate wall materials, represents a robust solution to increase the stability and industrial versatility of vanilla extracts. When integrated with advances in extraction methods, this step enables a sustainable and efficient process, facilitating industrial-scale production of high-quality, value-added natural extracts.

Applications of vanilla extracts

Vanilla extracts are widely applied in food, cosmetic, and pharmaceutical systems; however, their technological and functional relevance extends beyond flavor contribution. Recent studies demonstrate that vanilla-derived compounds can be strategically utilized in different industrial contexts.

In food applications, vanilla extracts and their recovered fractions have been investigated as natural flavor enhancers and functional additives. Oliveira et al. [44] demonstrated that sequential alkaline–acid hydrolysis of vanilla bagasse residues allowed the recovery of important aroma-related compounds, including vanillin and vanillic acid, suggesting that post-extraction residues remain a valuable source of bioactive molecules for food applications. Additionally, vanilla is extensively used in beverage formulations due to its complex aroma profile and low odor perception threshold, properties that contribute to flavor enhancement even at low concentrations [37].

Beyond direct flavoring, vanilla essential oil has been incorporated into active packaging systems. Singh et al. [45] developed polylactic acid (PLA) films containing vanilla essential oil as an aroma corrector and demonstrated extended shelf life of packaged waffles up to 30 days, compared to only 2 days in control films. This application highlights the potential of vanilla compounds in functional food packaging technologies.

In pharmaceutical and bioactive contexts, vanillin and related phenolic compounds exhibit antioxidant, antimicrobial, anti-inflammatory, and anticancer properties [38]. Vanillin has also been reported to possess neuroprotective and antibiotic-potentiating activities [25]. These biological properties expand its relevance beyond flavoring into nutraceutical and therapeutic applications.

At the molecular level, advances in transcriptomic analysis have identified regulatory pathways associated with vanillin biosynthesis and accumulation [26], supporting breeding and biotechnological approaches aimed at enhancing vanillin content in cured capsules. This integration of metabolic understanding with application-driven research strengthens the potential for standardized, high-value vanilla-derived ingredients.

Collectively, these studies demonstrate that vanilla extracts are not only sensory ingredients but also multifunctional bioactive systems with applications in food preservation, active packaging, cosmetic perfumery, and pharmaceutical formulations.

Conclusion and future perspectives

Vanilla (*Vanilla planifolia*) is one of the most valuable spices in the global market, whose aromatic complexity and economic relevance drive continuous advances in extraction techniques and industrial applications. Conventional methods, although still employed, present limitations in terms of efficiency, solvent consumption, and compound preservation. In contrast, emerging techniques such as UAE, MAE, SFE, and PLE offer faster, more selective, and sustainable alternatives, aligned with demands for clean, high-yield processes.

Encapsulation emerges as an indispensable complementary step, ensuring the stability and controlled release of volatile compounds, expanding the potential applications of the extract in different matrices. Appropriate choices of wall materials and encapsulation methods represent a technological advantage for product valorization.

Looking ahead, three main trends stand out:

1. Sustainable industrial scale-up – adapting emerging extraction and encapsulation techniques for continuous, economically viable processes.

2. Integration into new markets – expanding the use of the extract's functional properties in nutraceuticals, pharmaceuticals, and cosmetics.
3. Green innovation – developing extraction routes based on alternative solvents and valorizing agro-industrial by-products, in line with circular economy principles and the Sustainable Development Goals (SDGs).

Thus, advances in the extraction and encapsulation of vanilla extracts not only contribute to preserving their sensory and functional properties but also establish a strategic pathway for technological innovation and strengthening the global industry.

Advances in selective extraction and downstream purification—particularly those that enhance vanillin-specific recovery and reduce co-extracted impurities—are expected to directly facilitate the development of more effective, standardized, and regulatory-compliant encapsulated ingredients. Improved selectivity at the extraction stage reduces variability in active compound concentration, thereby enabling the formulation of high-value nutraceutical and pharmaceutical products with consistent bioactive performance.

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Declarations

Ethical approval Not applicable.

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