Research and Development of Fragrance Retention Technology

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Abstract. Fragrance retention technology plays a pivotal role in the application of flavors and fragrances, particularly in industries such as cosmetics, food, and textiles, where enhancing the longevity of product scents is a growing demand. This paper provides a comprehensive review of the relationship between fragrance molecular structure and volatility, introduces key technologies including adsorption-based, encapsulation-based, and matrix-based carriers, and emphasizes the critical role of slow-release mechanisms in controlling fragrance diffusion. By utilizing various carriers and technical approaches, the release rates of fragrances can be regulated, significantly enhancing aroma persistence. Furthermore, the strategic use of fixatives and fragrance enhancers can further prolong scent duration and improve diffusion. However, current technologies face challenges, such as the stability of slow-release mechanisms and the potential impact of fixatives on fragrance profiles. Looking ahead, advancements in nanotechnology, biotechnology, and material science are anticipated to enable breakthroughs in precision-controlled fragrance release, fostering more intelligent and efficient aroma delivery systems and broadening their applications across multiple sectors.

Keywords: Aroma retention, flavors, fragrance carriers, fragrance precursors, flavoring agents

1. Introduction

As substances are capable of imparting distinctive scents, flavors find extensive applications across various sectors, including cosmetics, personal care products, food, and beverages. However, ensuring fragrance persistence remains a significant challenge in these applications. The advancement of aroma retention technologies is crucial for enhancing both the practical use of flavors and the overall quality of products. In recent years, substantial progress has been achieved in the fields of material science, chemical engineering, and biotechnology, leading to notable developments in molecular structure design, carrier selection, slow-release technologies, and the use of fragrance fixatives. By optimizing molecular structures, the volatility and stability of flavor molecules can be modulated to extend their scent longevity. Moreover, selecting appropriate carriers enables precise control of fragrance release rates, facilitating slow and sustained aroma dissemination. The integration of slow-release technologies further improves flavor stability, allowing for prolonged and consistent scent release. Additionally, fixatives and aroma enhancers interact with flavor molecules to strengthen their retention within the matrix, thereby enhancing fragrance persistence. While these advancements have significantly improved aroma retention in various applications, challenges remain. Research indicates that differences in molecular structure result in distinct spatial interactions, which influence both the binding and diffusion rates of fragrance molecules. Overcoming these challenges is critical for further innovation in fragrance retention technology.

2. The Relationship between the Molecular Structure of Flavor and Aroma

2.1. Molecular Structure and Aroma Stability

Fragrances are volatile aromatic compounds, and according to classical fragrance chemistry theory, specific molecular structures, known as fragrance groups, are required to stimulate the human olfactory system. These fragrance groups play a pivotal role in determining the scent profile and its interaction with sensory receptors. Below is table 1 outlining the main fragrance groups and their typical aromatic characteristics [1]:

Table 1. The main fragrance groups stimulate the human sense of smell

Fragrant substance	Scented incense stick	fragrant substance	Scented incense stick	Fragrant substance	Scented incense stick
sterols	—OH	thiol	—SH	carbylamine	—NC
phenol	—OH	aniline	—O—	Thiocyanogen	—SCN
amide	—COOH	sulfur ether	—S—	isothiocyanide	—NCS
esters	—COOR	nitro compound	—NO_2		
lactone	—OO—O—	acetonitrile	—CN		

Fragrance stability varies significantly depending on the molecular composition. Substances containing isonitrile or aldehyde groups tend to have poorer stability, whereas other fragrance groups exhibit greater stability compared to isonitrile and aldehyde-based compounds. The number of carbon atoms in fragrance molecules generally ranges between 4 and 20, which directly influences their volatility. Compounds with fewer carbon atoms have lower boiling points and thus volatilize quickly, while those with too many carbon atoms exhibit low vapor pressure, making them less volatile and producing a weaker aroma.

In aliphatic hydrocarbon compounds, those with 8 or 9 carbon atoms tend to produce the most intense aromas. As the molecular weight increases, the fragrance intensity decreases, and hydrocarbons with more than 16 carbon atoms are typically odorless. Furthermore, linear-chain compounds tend to have a stronger fragrance than their cyclic counterparts. Aliphatic alcohols behave similarly to hydrocarbons in that alcohols with 8 carbon atoms produce the strongest fragrance, while alcohols with more than 14 carbon atoms exhibit little to no scent. Aromatic alcohols generally produce a weaker aroma compared to aliphatic alcohols.

Aliphatic aldehydes and ketones are stronger in aroma, with aliphatic aldehydes containing 10 carbon atoms being the most aromatic. For aliphatic carboxylic acids, the most intense aroma is observed in those with 5 carbon atoms. Ester compounds typically display fragrance intensity between alcohols and acids, with macrolide compounds showing the strongest aroma when their ring structures contain 14-19 carbon atoms [1].

2.2. Relationship between Molecular Weight and Volatility

In general, fragrance molecules with smaller molecular weights are more volatile, releasing their aroma more quickly but with less persistence. This is due to the lower intermolecular forces in smaller molecules, making them more prone to enter the air. As molecular weight increases, the volatility of the fragrance molecules decreases, leading to greater aroma persistence. The enhanced van der Waals forces and other intermolecular interactions in larger molecules make them more difficult to volatilize, resulting in longer retention times. For instance, ethanol, with a molecular weight of 46, and citronellol, with a molecular weight of 156, demonstrate this difference—ethanol is highly volatile and disperses rapidly into the air, while citronellol has greater persistence than ethanol.

3. Development of Spice Carrier Technologies

Fragrance carrier technology is a critical approach to improving fragrance retention by controlling the release rate of the fragrance through physical or chemical mechanisms. This technology helps extend the duration of the aroma. Common types of carriers include adsorption-type, capsule-type, and matrix-type carriers, each offering distinct advantages and technical characteristics for different applications.

3.1. Adsorption Carriers

Adsorption carriers' function by physically attaching the fragrance to the surface of a substrate, enabling the slow release of the aroma. These carriers are typically composed of porous materials such as silica gel, activated carbon, or zeolite, which possess a large specific surface area and excellent adsorption properties, effectively extending the release time of the fragrance. For instance, Costa et al. encapsulated vanillin in mercerized zeolite and observed that it enhanced thermal stability and extended fragrance retention time [2]. The primary benefits of adsorption carriers include their simple preparation process, low cost, and versatility, making them suitable for a range of applications such as detergents and air fresheners [1].

3.2. Capsule-Based Carriers

Microencapsulation is one of the most widely utilized technologies for flavor carriers, where flavors are encapsulated within micron- or nanometer-sized shell materials through physical, chemical, or physicochemical methods, forming a capsule structure. This technology effectively protects fragrance components from oxidation or volatilization during storage and transportation while controlling the degradation or rupture of the shell material to achieve a slow-release effect [3]. Common microcapsule preparation methods include physico-mechanical, chemical, and physicochemical approaches [4]. Capsule-based carriers are extensively applied in cosmetics, daily chemical products, and textiles to provide long-lasting fragrance retention [5]. For example, Wang Jin et al. utilized interfacial polymerization to prepare aromatic microcapsules with a polyurethane capsule wall and lavender essential oil core, investigating the effects of preparation conditions on microcapsule morphology, particle size, and aroma release properties [6]. Similarly, Xiao Chaopeng et al. employed in situ polymerization to prepare melamine-formaldehyde resin-coated jasmine flavor microcapsules, analyzing the impact of wall material dosage, emulsification speed, and flavor addition on the slow-release performance [7]. Qu Jiale et al. also used in situ polymerization to prepare microcapsules of Artemisia absinthium essential oil, identifying it as a non-toxic and efficient alternative to current fungicidal and antimicrobial agents for leather [8]. Moreover, Xiao Xiuchan et al. investigated the adsorption effects of starch-β-cyclodextrin microspheres using dihydrolinalool, the primary component of jasmine flavor, offering valuable technical insights for its application in slow-release systems [9]. Yan Jin et al. further explored temperature-controlled flavor microcapsules (egHDI-O) prepared via interfacial polymerization, examining core content, slow-release performance, and the effects of raw material composition and preparation conditions on microcapsule morphology and structure [10].

3.3. Matrix-Based Carriers

Matrix-type carriers are designed to achieve prolonged fragrance retention by uniformly dispersing the flavor within a matrix, controlling its release rate. These carriers are typically made from natural or synthetic polymers, such as gelatin, polyurethane, and cyclodextrins, which are crosslinked physically or chemically to form a stable mesh structure that anchors the fragrance molecules within the matrix. The primary advantages of matrix-type carriers include their ability to provide a more uniform and long-lasting fragrance release, along with reduced sensitivity to external environmental changes. These characteristics make them particularly suitable for personal care and food products that require high fragrance persistence. For example, He Yi et al. developed matrix-type sustained-release materials based on a poly (ethylene glycol)/stearic acid composite system, incorporating Chenpi/mint composite fragrance for use in cigarette products. Their study revealed both the room-temperature locking mechanism of the poly (ethylene glycol)/stearic acid system and the sustained-release mechanism of the embedded fragrances [11].

4. Application of Slow-Release Technology

4.1. Principles of Slow-Release Technology

Slow-release technology refers to the controlled release of substances, where specific measures are employed to slow down the release rate over an anticipated period, ensuring the maintenance of a certain effective concentration in the system [3]. The triggering conditions for slow-release mechanisms can be influenced by environmental factors or external stimuli. For instance, temperature is one such environmental factor. When ambient temperatures reach a threshold, certain slow-release formulations undergo physical or chemical transformations, thereby triggering the release of drugs or active ingredients. Similarly, changes in pH can serve as a trigger for controlled release. In specific acidic or alkaline environments, certain formulations may undergo structural modifications, leading to the release of active components. This is often utilized in water treatment, where slow-release agents release flocculants or biocides under particular pH conditions to purify water [12]. Moreover, humidity can also influence the release rate and stability of certain formulations. High humidity may cause some materials to absorb water, altering their structure and modifying the release profile. Humidity's impact on the mechanical properties of polymer materials is well-documented, though the degree of influence varies by material. Thus, it is crucial to analyze typical polymers to understand humidity's effects, enabling manufacturers to consciously control moisture during production and usage to preserve the material's original performance and function [13].

4.2. Types of Slow-Release Technologies

Slow-release mechanisms can be categorized into physical and chemical types, with physical slow-release being a key tool in current fragrance applications by controlling the release rate and thereby extending the duration of the aroma. The performance of slow-release microcapsules is directly influenced by the preparation method. For instance, the spray drying method utilizes high-speed airflow to encapsulate fragrances in solid shell materials, forming micron-sized particles, which are commonly used in cosmetics and fragrance products [3]. Chemical slow release, on the other hand, relies on chemical reactions to trigger the release of fragrance. In situ polymerization, for example, is suitable for textile treatments, where a polymer film is generated on the fabric's surface to encapsulate the fragrance, allowing it to be gradually released during use [7]. The copolymer deposition method enhances the durability of detergents by co-depositing fragrance molecules with various polymers to form a robust shell that gradually breaks down, releasing the fragrance during washing and usage [5].

4.3. Practical Application of Slow-Release Technology

Slow-release flavor microencapsulation technology is extensively applied in textiles, daily chemical products, and air fresheners, with commonly used preparation methods including spray drying, copolymer deposition, and interfacial polymerization. These techniques enable the long-term, stable release of fragrances while enhancing their persistence across various environments. For instance, the spray drying method combines the flavor with carrier substances through high-speed spraying, creating a stable particle structure ideal for laundry detergents and perfumes [6]. Copolymer deposition, on the other hand, forms a multilayer protective structure by depositing flavor molecules between different materials, ensuring the continuous release of aroma over extended periods. Looking forward, the slow-release technology needs to standardize evaluation systems further, such as through sensory evaluation, mass attenuation, and instrumental analysis methods to accurately measure its fragrance retention effects, thereby improving the accuracy and consistency of the slow-release performance [14].

5. Applications

The application of fragrance technology in many fields provides a variety of solutions to enhance the durability of product aroma, especially in the fields of daily chemicals, food and textiles, the use of fragrance precursors, slow-release technology and fixative have a wide range of applications.

5.1. Applications of Aroma Precursors

Flavor precursors are compounds that decompose and release aroma molecules under specific environmental conditions. Lei et al. explored the use of glycoside-based flavor precursors as potential ingredients for high-temperature food flavoring, demonstrating their efficacy in controlled aroma release [15]. These precursors are typically formed by chemically linking an aromatic moiety to a stable molecular structure, utilizing reaction pathways such as esterification, amidation, and etherification. Degradation of these precursors can be triggered by temperature, humidity, pH, enzyme activity, and other factors. For instance, certain precursors decompose thermally or hydrolyze in high-humidity environments, releasing fragrance. pH can also act as a trigger, where specific acidic or alkaline conditions prompt chemical reactions that liberate the aroma, making such precursors useful in cosmetics, detergents, and similar applications.

Flavor precursors can be classified into natural and synthetic types. Natural precursors, such as glycosides and carotenoids, release aroma upon decomposition, while synthetic precursors are chemically designed to mimic or enhance the effects of natural ones [1]. These substances find extensive application in daily chemicals, food processing, and textile treatment. In laundry products, for instance, precursors release fragrance gradually as washing temperature increases, ensuring clothes retain a fresh scent throughout the washing and wearing process. In textiles, synthetic precursors can be applied to fiber surfaces to release fragrance in response to movement or sweating, enhancing the overall user experience.

5.2. The Use of Fixatives and Aroma Enhancers

Fixatives and aroma enhancers are essential additives used to regulate the longevity and intensity of fragrances. Fixatives work by reducing the volatilization rate of fragrance molecules, thereby extending the fragrance's duration. Common natural animal-based fixatives include musk, ambergris, civet, and castoreum, while plant-based fixatives often utilize essential oils and botanical extracts. Aroma enhancers, on the other hand, amplify the intensity and complexity of the overall fragrance by modifying the diffusivity of the aroma molecules. They are widely used in food products to enhance the flavor profile of foods, beverages, and other consumables. However, it is important to note that some components in aroma enhancers may trigger allergic reactions, such as skin redness and irritation.

In conclusion, significant advancements have been made in fragrance retention technology in recent years, particularly through the use of fragrance precursors, slow-release technologies, and fixatives, all of which have greatly improved the durability of fragrances in products. The use of adsorption-type, capsule-type, and matrix-type carriers offers tailored solutions for various application scenarios. In industries such as daily chemicals, food, and textiles, fragrance carrier technology has become a critical method for extending the release time of aromas. Future research should focus on further enhancing the stability and standardization of slow-release technologies, as well as optimizing the use of fixatives and aroma enhancers to better meet market demands. Ultimately, the development of fragrance retention technology will likely evolve through multidisciplinary collaboration and intelligent innovations, offering improved aroma experiences across a broader range of products.

6. Current Challenges and Future Trends

6.1. Technical Challenges

Slow-release technologies aim to extend the release duration of flavors, thereby enhancing fragrance persistence. However, existing slow-release technologies face challenges regarding stability. For instance, environmental factors such as temperature, humidity, and light can impact the performance of sustained-release carrier materials, causing the release rate of fragrances to fluctuate. Additionally, over time, interactions between slow-release carriers and the fragrance compounds may shift, which can compromise the slow-release effect.

Fixatives, intended to prolong the longevity of aromas, may also affect the quality and characteristics of a fragrance. For instance, certain fixatives may chemically interact with fragrance molecules, altering their composition and structure, or their inherent odor might mask or interfere with the original fragrance. To optimize fixative usage, it is important to consider their compatibility with the fragrance, stability, and influence on the overall aroma. Selecting the appropriate fixative, controlling its dosage, and optimizing the formulation can enhance the longevity of a fragrance without compromising its original qualities. There is also potential for developing new types of fixatives to meet evolving consumer demands.

Flavor enhancers, used to boost the intensity of aromas, can lead to overly strong or artificial scents when overused, which may result in consumer aversion. Optimizing the use of flavor enhancers involves selecting the right type and amount based on the fragrance and its intended application. Blending different enhancers and fragrances can also create more complex and appealing aromatic effects. Moreover, it is essential to prioritize the safety and environmental impact of these enhancers, ensuring that they do not pose risks to human health or the environment.

6.2. Future Directions

Nanotechnology offers significant opportunities for innovation in the field of flavors, particularly by enhancing slow-release mechanisms and fragrance delivery systems. The incorporation of nanomaterials as slow-release carriers enables precise control over the release rates of fragrances, improving both longevity and consistency. Additionally, nanotechnology can advance fragrance sensors and detection technologies, allowing for rapid and accurate analysis of aroma profiles.

Biotechnology also presents transformative potential by providing novel methods for synthesizing natural flavor analogs or substitutes, addressing issues related to resource scarcity and high costs. Through biotechnology, new biosynthetic pathways can be developed, improving both the efficiency and quality of flavor production. Furthermore, materials science plays a crucial role by offering advanced materials, such as new polymer composites and functional materials, which enhance slow release, flavor fixation, and aroma intensity. These materials possess excellent physicochemical properties and biocompatibility, contributing to improved fragrance stability, safety, and overall performance in various applications.

7. Conclusion

Fragrance retention technologies have made notable advancements in recent decades, particularly in the areas of fragrance molecule design, carrier technologies, slow-release systems, and the use of fixatives. By gaining deeper insights into the structure and volatility of flavor molecules, researchers have devised innovative strategies to extend the persistence of fragrances, significantly enhancing product value. The adoption of adsorption, encapsulation, and matrix carrier technologies has notably improved the slow release and stability of fragrances, showcasing broad applicability in daily chemicals, food, and textiles. Moreover, the optimization of slow-release systems and the use of fixatives have enhanced fragrance diffusion and prolonged scent duration in various products.

Despite these breakthroughs, challenges remain in achieving stability and consistency in slow-release effects, as well as addressing the impact of fixatives on aroma quality. Future research must focus on enhancing the reliability of slow-release carriers, developing novel fixatives and aroma enhancers, and leveraging nanotechnology and biotechnology to address the current limitations. By fostering interdisciplinary collaboration and integrating emerging technologies, fragrance retention technologies are poised to deliver more efficient, sustainable solutions across industries, driving innovation and intelligent development in the application of fragrances.

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