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Aging Odor and Indoor Air Odor: A Comparative Study of Chemical Mechanisms and Sustainable Removal Strategies

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Abstract

Purpose : This study investigates the biochemical mechanisms and removal strategies for aging odor (2-Nonenal) and indoor air odor (VOCs, H2S, NH3). Both odor types share volatile aldehydes as key contributors, making them persistent and challenging to eliminate with conventional deodorization methods. While aging odor originates from lipid peroxidation in sebaceous glands, indoor air odor is primarily caused by microbial metabolism and environmental pollutants. This study aims to develop a bio-based odor removal strategy integrating plant-based antioxidants, marine bio-adsorbents, and microbial degradation technologies for long-term odor control. **Research Design & Data** : A qualitative, literature-based research approach was employed, incorporating a systematic review of peer-reviewed journals, patents, and industrial reports. The study utilizes comparative analysis to evaluate the persistence, chemical structure, and removal techniques of aging and indoor air odor. Bio-based solutions are explored, including polyphenol-rich plant extracts, fucoidan-based marine bio-adsorbents, and enzymatic microbial filtration systems. **Research Results** : The findings reveal that conventional deodorization methods, such as chemical masking agents and activated carbon filters, provide only temporary relief and fail to address the underlying biochemical reactions leading to odor formation. In contrast, bio-based solutions offer sustainable, long-term odor management, effectively neutralizing both aging odor and indoor air pollutants. **Conclusion** : By integrating plant antioxidants, marine bio-adsorbents, and microbial enzymatic degradation, this study proposes a holistic, eco-friendly odor removal system applicable to personal hygiene, indoor air quality, and elderly care environments. Future research should focus on experimental validation and real-world application testing to optimize and commercialize bio-based deodorization technologies..

Keywords : Aging Odor, 2-Nonenal Removal, Indoor Air Quality, Bio-Based Deodorization, Microbial and Marine Bio-Adsorbents

JEL Classification Code : Q53, Q55, L65, O31, M11

1. Introduction

1.1. Research Background and Necessity

With the global increase in aging populations, concerns

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regarding aging-related body odor (commonly referred to as aging odor) have grown significantly. One of the primary contributors to this odor is 2-Nonenal, a volatile unsaturated aldehyde that forms as a result of lipid peroxidation in aging skin (Zhang et al., 2019; Iitani et al., 2023). As individuals age, sebum composition changes, particularly with an increase in oxidative stress and a reduction in natural antioxidants, leading to the breakdown of unsaturated fatty acids such as palmitoleic acid and linoleic acid (Carini et al., 2004). The oxidation of these fatty acids produces 2-Nonenal, which is characterized by its low volatility, hydrophobic nature, and persistence on skin and clothing, making it difficult to remove through conventional washing methods (Eder et al., 2008). This phenomenon is associated with reduced skin barrier function and altered sebaceous gland activity in aging individuals (Wietstock et al., 2013).

Aging odor has implications beyond personal hygiene. Studies indicate that strong or persistent body odor in elderly individuals can contribute to social stigma, reduced self-esteem, and psychological distress (Haze et al., 2001). Moreover, in enclosed environments such as elderly care facilities, hospitals, and shared living spaces, the accumulation of 2-Nonenal can contribute to overall air quality degradation, affecting not only the individual but also caregivers and cohabitants (Mendes et al., 2013).

At the same time, indoor air pollution and odor accumulation in enclosed spaces have become critical health concerns, particularly in environments where the elderly reside. Indoor odors stem from various sources, including volatile organic compounds (VOCs), hydrogen sulfide (H_2S), and ammonia (NH_3), which are released from cooking, microbial activity, waste decomposition, and inadequate ventilation (Kasozi et al., 2024). Studies have shown that prolonged exposure to VOCs and sulfur-based odors can contribute to respiratory issues, cognitive decline, and an overall reduction in indoor air quality, particularly for vulnerable populations such as the elderly (Li et al., 2019).

Despite the growing demand for effective odor management solutions, research on aging odor and indoor air odor has been largely conducted separately, with limited emphasis on their shared chemical properties, formation mechanisms, and potential for integrated removal strategies (Aduldejcharas, 2024). Existing solutions primarily focus on masking or temporary deodorization, rather than addressing the biochemical processes responsible for odor persistence (Zhou et al., 2023). Given the increasing number of elderly individuals living in enclosed spaces, there is an urgent need for a comprehensive, sustainable, and bio-based odor management approach that simultaneously targets both aging-related body odor and indoor air odor.

1.2. Research Purpose and Objectives

The primary objective of this study is to comparatively analyze the biochemical formation and environmental mechanisms of aging odor (2-Nonenal) and indoor air odor (VOCs, H_2S, NH_3) while exploring sustainable and innovative odor removal strategies. Despite the increasing interest in odor management, aging odor and indoor air odor have been studied in isolation, with limited research focusing on their commonalities and potential for integrated removal solutions.

Given the physiological, chemical, and environmental challenges associated with both odor types, this study aims to:

1) Analyze the physiological mechanisms underlying aging odor formation, with a focus on lipid peroxidation, sebaceous gland function, and the oxidative degradation of unsaturated fatty acids leading to 2-Nonenal production.
2) Examine the chemical and microbial processes contributing to indoor air odor, including the release of volatile organic compounds (VOCs), sulfur-based compounds (H_2S), and nitrogenous gases (NH_3) from food decomposition, bacterial metabolism, and poor ventilation.
3) Compare the transmission pathways and persistence of aging odor and indoor air odor, identifying factors such as hydrophobicity, adsorption onto textiles, and airborne diffusion rates that influence long-term odor accumulation.
4) Evaluate existing odor elimination techniques, focusing on plant-based antioxidants (e.g., green tea polyphenols, citrus flavonoids), marine bio-extracts (fucoidan, alginic acid), and microbial bio-filtration systems, assessing their effectiveness in neutralizing aldehydes, VOCs, and sulfur-based compounds.
5) Develop an integrated bio-based odor removal approach that combines plant-derived antioxidants, marine bio-adsorbents, and microbial degradation technologies, ensuring applicability in elderly care facilities, residential spaces, and indoor environments with persistent odor issues.

Through this study, we seek to bridge the gap between personal hygiene-related odor control and indoor air quality management, offering a comprehensive theoretical framework for the development of sustainable, long-term odor elimination solutions. The findings will contribute to the advancement of bio-based deodorization technologies and inform future research on multifunctional odor control strategies applicable to aging populations and indoor environments.

1.3. Current Research Trends and Limitations

Recent studies on aging odor have primarily focused on the

development of personal hygiene products such as deodorants, functional body washes, and skincare formulations designed to either mask or neutralize 2-Nonenal (Carini et al., 2004; Gao et al., 2023). While these products provide short-term relief, they fail to address the biochemical processes that lead to odor formation, including lipid peroxidation, sebaceous gland activity, and oxidative stress in aging skin (Eder et al., 2008).

Furthermore, aging odor is not limited to direct body emissions—due to the hydrophobic nature of 2-Nonenal, it tends to accumulate on textiles, bedding, and confined indoor environments, making conventional personal care solutions insufficient for long-term odor control (Haze et al., 2001).

Conversely, research on indoor air odor has largely focused on volatile organic compounds (VOC_s), sulfur-based compounds (H_2S), and ammonia (NH_3), which originate from synthetic materials, microbial decomposition, and food waste in enclosed spaces (Zhou et al., 2023; Kasozi et al., 2024). To mitigate these odors, advanced air purification technologies such as activated carbon filtration, photocatalytic oxidation, and biofiltration systems have been developed (Aduldejcharas, 2024). While these methods show effectiveness in reducing airborne pollutants, they do not specifically target aging-related body odor, which can be a significant contributor to indoor air pollution, particularly in elderly care facilities, shared living spaces, and medical institutions (Claverie et al., 2020).

Despite advancements in both personal hygiene and air purification technologies, these solutions remain fragmented, treating aging odor and indoor air odor as separate issues. There is currently no integrated approach that effectively addresses both odor sources simultaneously while considering their shared chemical composition, persistence, and long-term impact on indoor environments.

Given these limitations, this study emphasizes the need for a bio-based, integrative odor removal strategy that combines plant-derived antioxidants, marine bio-adsorbents, and microbial degradation systems. By utilizing antioxidant-rich botanical extracts (e.g., green tea polyphenols, citrus flavonoids), fucoidan-based marine bio-adsorbents, and probiotic biofiltration techniques, this research aims to propose a sustainable, long-lasting, and multifunctional odor management solution applicable to both personal care and indoor air quality control.

1.4. Research Scope and Methodology

To achieve the stated research objectives, this study employs a systematic literature review and theoretical analysis approach, examining existing research on the biochemical formation, environmental transmission, and removal strategies of aging odor and indoor air odor. Given the interdisciplinary nature of odor management, this study integrates findings from biochemistry, environmental science, microbiology, and material science to explore bio-based solutions for odor control.

This research covers the following areas:
1) Biochemical Formation of 2-Nonenal in Aging Skin → Investigation into the lipid peroxidation process, sebaceous gland activity, and oxidative stress in aging individuals, as well as how 2-Nonenal interacts with environmental factors such as humidity, temperature, and textiles (Carini et al., 2004; Eder et al., 2008).
2) Composition and Persistence of Indoor Air Odor → Analysis of volatile organic compounds (VOC_s), hydrogen sulfide (H_2S), and ammonia (NH_3), with a focus on their sources (microbial decomposition, waste accumulation, poor ventilation) and their relationship with aging odor persistence in confined environments (Zhou et al., 2023; Kasozi et al., 2024).
3) Comparative Analysis of Odor Transmission and Persistence → Examination of how aging odor and indoor air odor diffuse, adsorb onto surfaces, and interact with indoor air dynamics, considering factors such as hydrophobicity, volatility, and microbial transformation (Claverie et al., 2020).
4) Review of Existing Odor Control Strategies → Evaluation of current deodorization techniques, including plant-based antioxidants (green tea polyphenols, citrus extracts), marine bio-adsorbents (fucoidan, alginic acid), microbial degradation systems, and hybrid bio-filtration technologies, assessing their effectiveness, sustainability, and long-term applicability (Aduldejcharas, 2024).
5) Potential Integration of Bio-Based Solutions for Odor Management → Proposal of a multifunctional odor removal strategy that leverages plant-derived antioxidants, marine bio-adsorbents, and probiotic microbial systems to neutralize aging odor and indoor air pollutants simultaneously, offering a sustainable alternative to chemical-based deodorization.

Through this research, we aim to establish a scientific foundation for the development of bio-based, long-lasting odor elimination solutions that are applicable in elderly care facilities, residential environments, and other enclosed spaces where odor control is essential. By integrating biochemical insights with environmental and microbial technologies, this study seeks to bridge the gap between personal hygiene-based odor management and indoor air purification strategies.

2. Theoretical Background and Literature Review

2.1. Theoretical Background

With the global increase in aging populations, there is a rising concern regarding aging-related body odor, which is primarily attributed to the compound 2-Nonenal (C9H16O). This volatile aldehyde is generated through lipid peroxidation, a biochemical process in which unsaturated fatty acids degrade under oxidative stress, leading to the formation of persistent and unpleasant odors (Iitani et al., 2023). As individuals age, sebum composition shifts, particularly with an increase in palmitoleic acid and oleic acid, both of which are highly susceptible to oxidative degradation (Carini et al., 2004).

This oxidative process leads to the formation of 2-Nonenal, which is characterized by its hydrophobic nature, long-term adherence to surfaces, and resistance to conventional washing (Eder et al., 2008).

Furthermore, the aging process results in a decline in the activity of key antioxidant enzymes, such as glutathione peroxidase, catalase, and superoxide dismutase (SOD), further exacerbating lipid oxidation and increasing 2-Nonenal accumulation (Gao et al., 2023). In addition, skin microbiota, particularly Corynebacterium and Staphylococcus species, contribute to the modification and intensification of body odor by metabolizing sebaceous and sweat gland secretions, forming secondary volatile compounds (Mendes et al., 2013).

Unlike other body odors that are water-soluble and easily removable, 2-Nonenal is highly hydrophobic, making it difficult to eliminate from the skin, clothing, and surrounding environments, leading to persistent odor problems in enclosed spaces (Haze et al., 2001).

2.1.1. Aging Odor vs. Indoor Air Odor: Chemical and Environmental Considerations

At the same time, indoor air pollution and odor accumulation in enclosed environments have emerged as significant concerns, particularly in settings such as homes, elderly care facilities, and hospitals. Indoor air odor is primarily caused by volatile organic compounds (VOC_s), hydrogen sulfide (H_2S), ammonia (NH_3), and microbial activity, all of which arise from cooking, waste decomposition, human metabolic processes, and inadequate ventilation (Zhou et al., 2023). The interaction of microbial colonies with organic matter in enclosed spaces further contributes to the release of volatile odor compounds, affecting air quality and overall well-being (Kasozi et al., 2024).

Environmental factors such as temperature, humidity, and ventilation significantly influence the release, persistence, and transformation of indoor air odor compounds (Aduldejcharas, 2024). Unlike aging odor, which originates directly from human physiological processes, indoor air odor is often a result of complex biochemical and microbial interactions that continuously modify and amplify odor intensity.

Studies indicate that long-term exposure to indoor air pollutants, particularly VOC_s and sulfur-based compounds, can lead to respiratory irritation, cognitive decline, and reduced indoor comfort, especially for vulnerable populations such as the elderly and individuals with pre-existing health conditions (Claverie et al., 2020).

2.1.2. Common Characteristics of Aging Odor and Indoor Air Odor

Although aging odor and indoor air odor originate from distinct processes, they share several chemical and environmental characteristics, particularly in terms of persistence, molecular composition, and their impact on human comfort. Both types of odors contain volatile aldehydes, which contribute to long-lasting and unpleasant olfactory effects, making them difficult to neutralize using traditional deodorization methods. Additionally, their ability to adsorb onto various surfaces, including textiles, furniture, and walls, allows them to accumulate over time in enclosed environments, further exacerbating odor persistence (Wietstock et al., 2013).

These similarities suggest that aging odor and indoor air odor should not be treated as isolated problems. Instead, a comprehensive and integrative approach is required to effectively mitigate odor persistence and prevent long-term accumulation.

Sebum Production → Sebaceous glands secrete unsaturated fatty acids (e.g., palmitoleic acid, oleic acid).	**Lipid Oxidation** → Fatty acids undergo oxidation, forming hydroperoxides.	**2-Nonenal Formation** → Hydroperoxides degrade into volatile aldehydes	**Microbial Metabolism** → Bacteria (Corynebacterium, Staphylococcus) interact with 2-Nonenal, modifying odor intensity.	**Accumulation on Skin & Fabric** → Hydrophobic nature causes 2-Nonenal to adhere to skin, clothing, and bedding.

Figure 1: The Biochemical Pathway of 2-Nonenal Formation and Accumulation

Traditional fragrance-based masking agents and chemical deodorizers offer only temporary relief but fail to address the biochemical mechanisms underlying odor formation. Thus, there is a pressing need to develop sustainable, bio-based solutions capable of simultaneously neutralizing aging odor (2-Nonenal) and volatile indoor air pollutants(Henschel, 2011)

The following figure illustrates the biochemical formation of 2-Nonenal, highlighting its interaction with oxidative stress, sebaceous lipid oxidation, and microbial metabolism, all of which contribute to aging odor persistence.

The following Table 1 presents a comparison between aging odor (2-Nonenal) and indoor air odor (VOCs, H_2S, NH_3) based on their origin, chemical composition, persistence, and removal challenges

Table 1: Comparative Analysis of Aging Odor and Indoor Air Odor

Characteristic	Aging Odor (2-Nonenal)	Indoor Air Odor (VOCs, H_2S, NH_3)
Source	Lipid peroxidation in sebaceous glands	Cooking, microbial decomposition, waste accumulation
Key Chemicals	2-Nonenal (unsaturated aldehyde)	Aldehydes, sulfur compounds, ammonia
Persistence	Hydrophobic, adheres to skin and fabric	Highly volatile, disperses in air
Removal Challenges	Requires oxidation-resistant deodorants and enzymatic breakdown	Requires filtration, adsorption, and microbial degradation

2.2 Literature Review

2.2.1 Research on Aging Odor and 2-Nonenal Formation

Research on aging odor has primarily focused on identifying the biochemical mechanisms responsible for 2-Nonenal formation and exploring potential mitigation strategies, such as antioxidant intervention, microbiome modulation, and advanced textile technologies. Carini et al. (2004) were the first to identify 2-Nonenal as a key contributor to aging odor, demonstrating that its concentration increases significantly in individuals over 40 due to oxidative degradation of unsaturated fatty acids.

Building on this, Iitani et al. (2023) established a direct correlation between lipid peroxidation, decreased antioxidant defense, and persistent body odor, confirming that oxidative stress plays a pivotal role in 2-Nonenal formation and accumulation. More recently, Eder et al. (2008) examined the effects of dietary polyphenols and vitamin C supplementation on lipid peroxidation, suggesting that internal antioxidant enhancement may serve as a potential strategy for mitigating aging-related body odor.

Efforts to develop effective removal methods for 2-Nonenal have led to various approaches, including:
1) Plant-Based Antioxidants → Nirmal et al. (2024) analyzed the efficacy of green tea polyphenols, citrus extracts, and vitamin E derivatives in neutralizing 2-Nonenal.
2) Enzymatic Degradation → Studies on probiotic skin microbiome modulation have demonstrated that certain lactic acid bacteria and Bacillus species can reduce odor-producing bacterial activity (Gao et al., 2023).
3) Functional Textiles with Odor-Absorbing Properties → Haze et al. (2001) investigated fibers coated with metal oxides designed to adsorb and break down 2-Nonenal, highlighting the potential of textile-based deodorization technologies.

While these strategies offer promising results, they remain largely limited to personal hygiene applications, failing to address the environmental persistence of 2-Nonenal in enclosed indoor spaces, particularly in elderly care facilities, hospitals, and shared residential environments.

2.2.2. Research on Indoor Air Odor and VOC Accumulation

Parallel to studies on aging odor, research on indoor air odor has primarily focused on characterizing and mitigating volatile organic compounds (VOCs), sulfur-based compounds, and nitrogenous odors. Zhou et al. (2023) identified formaldehyde, acetaldehyde, hydrogen sulfide (H_2S), and ammonia (NH_3) as primary contributors to indoor odor pollution, emphasizing their negative impact on respiratory health and environmental quality. Similarly, Mendes et al. (2013) conducted air quality assessments in elderly care homes, revealing that poor ventilation significantly increases aldehyde and sulfur-based odor

concentrations, particularly in environments with high microbial activity.

Furthermore, Kasozi et al. (2024) demonstrated that temperature and humidity fluctuations influence VOC emissions, with higher temperatures accelerating aldehyde release, thereby exacerbating odor persistence in enclosed spaces.

To address indoor air odor problems, various odor removal technologies have been developed, including:
1) Activated Carbon Filtration and Photocatalytic Oxidation (TiO_2) → Hensche (2011) demonstrated the effectiveness of activated carbon and photocatalytic oxidation in reducing VOC concentrations, particularly in commercial and industrial settings.
2) Microbial Bio-Filtration Systems → Fazlzadeh et al. (2018) studied bacterial and algal bio-filtration methods for H_2S and ammonia removal, highlighting the potential of biological odor degradation in air purification applications.
3) Marine Bio-Waste-Derived Adsorbents → Aduldejcharas (2024) explored the adsorptive properties of chitosan and fucoidan, demonstrating that marine bio-based materials can enhance VOC removal efficiency, particularly in sustainable air filtration systems.

Despite these advancements, existing indoor air odor control technologies remain highly specialized, focusing predominantly on VOC removal, with limited application for aging odor (2-Nonenal) mitigation.

2.2.3. The Need for an Integrated Bio-Based Odor Removal Approach

A key limitation in current research is that aging odor and indoor air odor have been largely treated as separate problems, with little emphasis on their overlapping chemical properties, persistence, and environmental interactions. Both 2-Nonenal and VOC-based odors share common aldehyde structures, making them chemically persistent and difficult to eliminate through conventional means (Corsi, 2001). Additionally, both odor types accumulate in enclosed environments, suggesting the need for an integrated odor management strategy.

Given these research gaps, there is growing interest in bio-based solutions that combine plant-derived antioxidants, marine bio-adsorbents, and microbial bio-filtration technologies. Plant-based polyphenols have been shown to neutralize oxidative stress, while marine bio-extracts such as fucoidan and alginic acid have demonstrated strong aldehyde adsorption properties (Parthasarathy et al., 2011; Claverie et al., 2020). Meanwhile, probiotic and bacterial degradation systems offer long-term microbial control of odor compounds in both skin environments and enclosed spaces. Future research should explore:
- The synergistic effects of plant-based antioxidants and marine bio-adsorbents in neutralizing both 2-Nonenal and VOC-based odors.
- The feasibility of integrating enzymatic degradation and microbial bio-filtration into personal hygiene and air purification systems.
- Developing multifunctional odor management strategies applicable to both personal care and indoor environments.

By shifting from isolated deodorization methods to a unified, bio-based strategy, this research aims to establish a foundation for sustainable, long-term odor elimination solutions that address both aging odor and indoor air pollution simultaneously.

Plant-Based Antioxidants → Neutralize lipid peroxidation and reduce 2-Nonenal formation (green tea polyphenols, citrus extracts).	**Marine Bio-Adsorbents** → Alginates and fucoidan from seaweed adsorb volatile aldehydes and VOC_s.	**Microbial Degradation** → Probiotic bacteria break down 2-Nonenal, VOC_s, and sulfur compounds.	**Odor Reduction** → The combined approach effectively removes aging odor and indoor air pollution.

Figure 2: Integrated Bio-Based Odor Removal Mechanism

The Figure 2 as show above summarizes the proposed hybrid bio-based odor removal strategy, integrating plant antioxidants, marine bio-adsorbents, and microbial degradation.

3. Research Methods

Since this study is based on a literature review and theoretical analysis, the methodology will focus on systematic data collection, comparative analysis, and conceptual framework development rather than experimental procedures.

3.1. Research Design

This study employs a qualitative and comparative research approach based on a systematic literature review and theoretical analysis. The research design follows a structured process to ensure that the findings provide a comprehensive comparison between aging odor (2-Nonenal) and indoor air odor (VOC_s, H_2S, NH_3) while exploring bio-based odor removal solutions applicable to both personal

hygiene and indoor environments.

The study follows a step-by-step research framework, structured as follows:
1) Identifying Key Concepts → Defining the biochemical formation, environmental transmission, and persistence of aging odor and indoor air odor, emphasizing their shared aldehyde-based chemical properties.
2) Systematic Literature Review → Collecting and analyzing peer-reviewed academic papers, industry reports, patents, and case studies related to odor formation mechanisms and existing removal technologies. This involves searching for relevant literature in databases such as PubMed, ScienceDirect, and Google Scholar using keywords like "2-Nonenal removal," "aging odor reduction," "VOCs adsorption," and "bio-based deodorization."
3) Comparative Analysis → Conducting a side-by-side evaluation of aging odor and indoor air odor, focusing on:
- Chemical Composition → Examining the volatile aldehydes, sulfur compounds, and nitrogen-based compounds present in both odor types.
- Persistence Factors → Analyzing how odor compounds interact with textiles, air, and environmental surfaces, leading to long-term accumulation.
- Current Elimination Strategies → Comparing the effectiveness and limitations of chemical deodorizers, enzymatic oxidation, and bio-adsorbent technologies in odor mitigation.
4) Exploring Bio-Based Solutions → Evaluating the potential of sustainable, bio-based approaches for odor removal, including:
- Plant-Derived Antioxidants → Investigating the role of polyphenols (e.g., green tea, citrus extracts) in neutralizing oxidative stress and reducing 2-Nonenal production.
- Marine Bio-Adsorbents → Examining how fucoidan and alginic acid from seaweed can adsorb aldehydes and VOCs, contributing to long-term odor management.
- Microbial Degradation → Assessing probiotic bacteria and microbial bio-filtration systems for breaking down persistent odor molecules through biochemical conversion.
5) Developing an Integrated Odor Control Model → Proposing a conceptual framework that combines:
- Plant Antioxidants for preventing lipid oxidation in aging skin.
- Marine Bio-Adsorbents for trapping volatile odor compounds in the air and on surfaces.
- Microbial Degradation for long-term enzymatic breakdown of odor molecules.

This integrated approach will provide a scientific foundation for sustainable odor management, bridging personal care solutions with indoor air purification strategies.

3.2. Data Collection and Sources

Since this study is primarily a literature-based analysis, data is collected through academic, industrial, and regulatory sources to ensure a comprehensive review of odor formation mechanisms, chemical properties, and mitigation strategies. The data collection process follows a systematic approach to retrieving relevant and credible research materials.

The primary sources of data include:
1) Peer-Reviewed Journal Articles → Retrieved from scientific databases such as PubMed, ScienceDirect, and Web of Science, which provide biochemical, environmental, and microbiological insights into aging odor (2-Nonenal), VOC emissions, and bio-based deodorization technologies.
2) Patent Documents → Analysis of recent patents related to odor removal technologies, particularly in skincare formulations, air purification systems, and bio-adsorbent materials (e.g., functional textiles, enzymatic deodorization, and microbial bio-filtration).
3) Industry Reports → Reports from environmental agencies, fragrance technology firms, and consumer product manufacturers, detailing current market trends, regulatory standards, and industry innovations in odor control technologies.
4) Case Studies of Existing Deodorization Products → Examination of commercially available odor control solutions, including:
- Skincare formulations targeting 2-Nonenal reduction (e.g., antioxidant-enriched body washes, probiotic skincare).
- Functional textiles designed to adsorb and neutralize persistent odors.
- Air purification technologies, such as activated carbon filters, photocatalytic oxidation, and bio-based adsorption systems.

3.3. Systematic Literature Search Strategy

To ensure a structured and comprehensive data collection process, a systematic literature search is conducted using the following keywords:

1) "2-Nonenal removal" → Studies on biochemical pathways, lipid oxidation, and skin microbiome interactions related to aging odor formation.
2) "Aging odor control" → Research on topical treatments, functional textiles, and probiotic skincare interventions.
3) "VOCs adsorption" → Studies on volatile organic compound mitigation strategies, including marine bio-adsorbents and enzymatic degradation.
4) "Bio-based deodorization" → Research on natural odor control solutions, plant-derived antioxidants, and microbial

degradation systems.

Relevant studies are selected and analyzed based on:
- Odor formation mechanisms → The biochemical and microbial processes responsible for aging odor and indoor air odor.
- Chemical structures → The molecular properties of 2-Nonenal, VOC_s, and sulfur-based odorants, influencing their persistence and removal challenges.
- Effectiveness of removal methods → Evaluation of chemical deodorizers, enzymatic oxidation, bio-adsorbents, and hybrid filtration technologies

3.4. Analytical Framework

To structure the analysis, this study adopts a comparative evaluation framework that examines the biochemical, environmental, and technological aspects of aging odor (2-Nonenal) and indoor air odor (VOC_s, H_2S, NH_3). By comparing their formation mechanisms, persistence, current solutions, and challenges, this framework facilitates the identification of an integrated bio-based deodorization strategy.

Table 2: Comparative Analysis of Aging Odor, Indoor Air Odor, and Bio-Based Solutions

Criteria	Aging Odor (2-Nonenal)	Indoor Air Odor (VOC_s, H_2S, NH_3)	Bio-Based Solutions
Formation Mechanism	Lipid peroxidation in sebaceous glands	Environmental sources (food waste, bacterial activity)	Microbial and enzymatic breakdown
Persistence	Hydrophobic, accumulates on textiles	Volatile, airborne dispersion	Adsorption and neutralization
Current Solutions	Functional skincare, odor-absorbing fabrics	Air purifiers, activated carbon filters	Plant polyphenols, marine bio-adsorbents, microbial bio-filtration
Challenges	Long-lasting accumulation	Rapid diffusion in air	Scalability and stability

By applying this comparative framework, the study evaluates the feasibility of an integrated odor removal strategy that combines:
- Plant-Based Antioxidants → Neutralize lipid oxidation and reduce 2-Nonenal formation.
- Marine Bio-Adsorbents → Trap aldehydes and VOC_s, preventing airborne odor accumulation.
- Microbial Degradation → Use probiotic bacteria to break down 2-Nonenal and sulfur-based odors.

This holistic approach ensures both personal hygiene improvement and indoor air quality enhancement, addressing odor persistence at its biochemical and environmental sources.

3.5. Expected Research Contribution

The findings from this study will contribute to:
1) Bridging the gap between aging odor and indoor air odor research → Most existing studies focus on either personal odor or indoor air quality independently, without addressing their shared chemical and environmental persistence. This research highlights their common aldehyde-based mechanisms, suggesting an integrated approach for odor control.
2) Identifying limitations in existing odor removal technologies and proposing bio-based alternatives → Current odor control solutions, such as chemical deodorizers and air filtration systems, often fail to address long-term accumulation and persistence. This study evaluates bio-based materials such as plant-derived polyphenols, marine bio-adsorbents, and microbial enzymatic degradation, offering sustainable and multifunctional solutions.
3) Providing a scientific foundation for developing sustainable, multifunctional deodorization solutions applicable to both personal hygiene and indoor environments → The study proposes a novel odor management framework that integrates biochemical, environmental, and microbial approaches, setting the groundwork for future research and real-world applications in elderly care facilities, residential spaces, and enclosed environments.

By establishing a bio-based deodorization model, this research aims to enhance personal well-being, improve indoor air quality, and advance sustainable odor control technolog

4. Research Results and Discussion

This section presents the findings of the study based on the literature review, comparative analysis, and proposed bio-based odor removal strategies. Since this research is a literature-based study rather than an experimental investigation, the results are derived from systematic analysis and theoretical modeling rather than direct empirical data.

4.1. Comparative Findings on Aging Odor and Indoor Air Odor

Based on the literature review and analytical framework, aging odor and indoor air odor share common chemical components and removal challenges, yet they originate from

distinct biological and environmental processes. Aging odor primarily results from lipid oxidation in human sebum, while indoor air odor arises from microbial activity, food waste decomposition, and poor ventilation.

One of the key findings is that the persistence of both types of odors is largely due to the presence of volatile aldehydes, which are chemically stable and difficult to eliminate using conventional deodorization techniques. This similarity suggests that both 2-Nonenal and VOC-based odors require advanced oxidation, enzymatic degradation, or adsorption-based removal techniques for effective control. Traditional deodorization methods such as fragrances and chemical masking agents provide only temporary relief, while bio-based solutions show greater potential for long-term odor reduction.

Table 3: Comparative Evaluation of Aging Odor and Indoor Air Odor

Factor	Aging Odor (2-Nonenal)	Indoor Air Odor (VOC_s, H_2S, NH_3)
Primary Source	Lipid peroxidation in aging skin	Food waste, microbial decomposition, pollutants
Key Chemical Compounds	2-Nonenal (C9H16O)	VOCs (formaldehyde, acetone), sulfur compounds (H_2S)
Persistence	Hydrophobic, accumulates on fabric	Airborne, volatile, disperses quickly
Removal Challenges	Resistant to regular washing, penetrates textiles	Requires air purification and odor adsorption
Effective Bio-Based Solutions	Antioxidants, enzymatic breakdown, probiotic skincare	Activated biofilters, microbial odor degradation

This comparative analysis highlights the need for a hybrid odor control strategy that integrates plant-based antioxidants, marine bio-adsorbents, and microbial degradation technologies to effectively remove both aging odor and indoor air odor

4.2. Evaluation of Existing Odor Removal Technologies

Current odor removal methods, including chemical deodorants, activated carbon filtration, and synthetic antimicrobial agents, have limitations in terms of effectiveness, sustainability, and long-term usability. While chemical-based solutions can neutralize odors temporarily, they often fail to prevent the underlying biochemical reactions that generate odors, leading to recurring odor problems.

1) Chemical-Based Deodorizers
- Mask odors rather than eliminate them
- Limited effectiveness for long-term odor removal
- Potential skin and respiratory irritation from synthetic compounds

2) Activated Carbon and Synthetic Adsorbents
- Effective for air purification but limited application for skin-based odors
- Require frequent replacement and maintenance

3) Microbial and Enzymatic Deodorization
- Utilizes probiotic bacteria or enzymes to break down odor molecules
- More sustainable but requires optimization for specific odor types

The growing interest in bio-based solutions has led researchers to explore plant-derived antioxidants, marine bio-adsorbents, and microbial odor degradation as viable alternatives for sustainable odor removal.

4.3. Proposed Integrated Bio-Based Odor Removal Strategy

The integration of plant-based antioxidants, marine bio-adsorbents, and microbial odor degradation offers a comprehensive and sustainable approach to odor elimination.

1) Plant-derived polyphenols (from green tea, citrus extracts, rosemary) have been shown to neutralize oxidative stress in skin, reducing 2-Nonenal formation at the biochemical level.
2) Marine bio-extracts, including fucoidan and alginates from seaweed, have demonstrated high adsorption capacity for aldehydes and VOC_s, making them ideal for airborne odor removal applications.
3) Probiotic bacteria capable of degrading sulfur and nitrogen compounds have been successfully used in bio-filtration systems to eliminate persistent indoor odors.

The following diagram in Figure 3 illustrates how these three bio-based approaches can be combined to create an integrated odor removal solution.

Plant-Based Antioxidants → Reduce lipid oxidation and inhibit 2-Nonenal formation in aging skin	**Marine Bio-Adsorbents** → Trap VOCs and aldehydes, preventing airborne odor accumulation	**Microbial Degradation** → Use beneficial bacteria to break down 2-Nonenal and sulfur-based odors

Figure 3: Integrated Bio-Based Odor Removal Model

4.4. Practical Applications and Future Research Directions

The findings from this study suggest several key

applications for the proposed bio-based odor removal strategy:
- Personal Care Products → Development of probiotic skincare, antioxidant-enriched body washes, and functional textiles to prevent aging odor buildup.
- Indoor Air Quality Improvement → Implementation of marine bio-adsorbents in air filters to remove VOCs and persistent odors in enclosed environments.
- Elderly Care Facilities and Hospitals → Integration of microbial bio-filtration systems to reduce sulfur and nitrogen-based odors in medical and long-term care environments.

Future research should focus on optimizing the stability and efficiency of bio-based deodorization technologies, particularly how plant extracts, marine bio-adsorbents, and microbial degradation systems interact in real-world applications. Additionally, clinical and environmental testing will be necessary to evaluate the long-term effectiveness of bio-based odor removal products in aging populations and high-odor environments.

5. Conclusions and Research Limitations

5.1. Conclusion

This study explored the biochemical mechanisms and removal strategies for aging odor (2-Nonenal) and indoor air odor (VOC_s, H_2S, NH_3) through a comprehensive literature review and comparative analysis. The findings highlight that both aging odor and indoor air odor share volatile aldehydes as key contributors, making them persistent and challenging to eliminate using conventional deodorization methods. While aging odor originates from lipid oxidation and sebaceous gland activity, indoor air odor is primarily caused by microbial metabolism, food decomposition, and environmental pollutants.

The study also demonstrated that current odor removal solutions, such as chemical deodorizers, air purifiers, and activated carbon filters, provide only temporary relief and fail to address the underlying biochemical processes of odor formation. In contrast, bio-based solutions, including plant-derived antioxidants, marine bio-adsorbents, and microbial degradation technologies, offer a sustainable and long-term approach to odor management. A hybrid strategy integrating these bio-based solutions can effectively neutralize both aging odor and indoor air odor simultaneously, leading to improved personal hygiene and enhanced indoor environmental quality.

By developing an integrated bio-based odor removal system, this research contributes to bridging the gap between personal odor control and indoor air purification, paving the way for the creation of multifunctional, sustainable deodorization technologies.

This study establishes a theoretical foundation for an integrated odor removal strategy that combines plant-based antioxidants, marine bio-adsorbents, and microbial degradation technologies. While further experimental validation and real-world testing are required, the proposed bio-based solutions offer significant potential for long-term odor management in personal care, environmental health, and air purification industries. Future research should focus on scaling up these innovations for commercial applications to enhance human well-being and environmental sustainability.

5.2. Research Limitations

Although this study provides valuable insights, there are certain limitations that should be considered:
- Lack of Experimental Data → This study is based on literature review and theoretical analysis rather than empirical testing. Future research should include experimental validation of bio-based deodorization technologies.
- Limited Real-World Application Studies → While the proposed integrated odor removal strategy is conceptually sound, its practical effectiveness in real-world environments (homes, hospitals, elderly care facilities) requires further testing.
- Variability in Odor Formation → The formation and perception of odors vary based on individual skin microbiomes, environmental conditions, and personal habits, which should be accounted for in future studies.

Despite these limitations, this study provides a solid theoretical foundation for developing advanced, bio-based deodorization strategies.

5.3. Practical Applications and Future Research Directions

To further advance bio-based odor removal technologies, future research should focus on the following key areas:
1) Development of Functional Personal Care Products
- Formulation of antioxidant-rich skincare and probiotic-based body washes to prevent 2-Nonenal formation on aging skin.
- Integration of bioactive textiles with marine bio-adsorbents to neutralize odors in clothing and bedding.

2) Application of Marine Bio-Adsorbents in Indoor

Environments
- Use of fucoidan and alginates from seaweed in air filtration systems to remove VOCs, aldehydes, and sulfur-based odors in enclosed spaces.
- Development of odor-absorbing wall coatings and furniture materials enriched with marine bio-components.

3) Microbial-Based Odor Degradation Systems
- Engineering microbial biofilters that can effectively degrade 2-Nonenal, sulfur compounds, and nitrogen-based odors in elderly care homes and hospitals.
- Investigation into genetically optimized bacteria for targeted odor breakdown.

4) Pilot Testing in Real-World Settings
- Conducting clinical and environmental trials to validate the effectiveness of bio-based odor control solutions in aging populations and high-odor environments.
- Collaborating with cosmetic, textile, and air purification industries to develop market-ready bio-based deodorization products with sustainable and multifunctional applications.

By pursuing these research directions, bio-based solutions can be further optimized and commercialized, leading to a new generation of sustainable, multifunctional deodorization technologies applicable to both personal hygiene and indoor air quality improvement.

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