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Review

The Impact of Indoor Malodor: Historical Perspective, Modern Challenges, Negative Effects, and Approaches for Mitigation

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Abstract: Malodors, odors perceived to be unpleasant or offensive, may elicit negative symptoms via the olfactory system's connections to cognitive and behavioral systems at levels below the known thresholds for direct adverse events. Publications on harm caused by indoor malodor are fragmented across disciplines and have not been comprehensively summarized to date. This review examines the potential negative effects of indoor malodor on human behavior, performance and health, including individual factors that may govern such responses and identifies gaps in existing research. Reported findings show that indoor malodor may have negative psychological, physical, social, and economic effects. However, further research is needed to understand whether the adverse effects are elicited via an individual's experience or expectations or through a direct effect on human physiology and well-being. Conversely, mitigating indoor malodor has been reported to have benefits on performance and subjective responses in workers. Eliminating the source of malodor is often not achievable, particularly in low-income communities. Therefore, affordable approaches to mitigate indoor malodor such as air fresheners may hold promise. However, further investigations are needed into the effectiveness of such measures on improving health outcomes such as cognition, mood, and stress levels and their overall impact on indoor air quality.

Keywords: malodor; indoor air; human olfaction; volatile organic comound (VOC); microbial volatile organic compound (MVOC); VOC; MVOC; health effects; smell; malodor mitigation; air fresheners; fragrance

1. Introduction

The sense of smell is a fundamental means of navigating the sensory world and orienting ourselves to ecologically and socially appropriate behavior. Evolutionarily, this chemical sense was the original means by which the earliest organisms achieved adaptive regulation of action and can be considered the origin of behavior [1]. For humans today, volatile molecules can travel for long distances and thus can provide important information about people, places, food and things that cannot otherwise be immediately detected by other sensory systems. Beyond its informational content, odor can attract, intrigue, impress and entice, as well as repel, offend, disgust, or evoke pity. Malodors are odors perceived to be unpleasant or offensive and, while not necessarily occurring at the known thresholds for direct adverse events, may elicit negative symptoms via the olfactory system's connections to other cognitive and behavioral systems.

Malodors are sometimes depicted as an inconvenience or annoyance of relatively minor importance to human perception and experience [1]. An understanding of malodors as a merely "aesthetic" issue,

however, ignores their potential for negative impact on human health and social relations [2]. Malodors propagate a variety of psychological, social and economic disturbances, many of which are preventable. As defined at the International Health Conference, "health is a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity" [3]. Although crafted in 1946, this definition of health has remained in use by organizations such as the World Health Organization. Combating the sources and mitigating the impacts of malodors therefore represents an important public health undertaking.

Throughout history, people have used perfumes, incense, herbs and other means at their disposal to rid their indoor environments of the malodors that occur in the course of human life and industry. However, within a social structure where people cannot always remove the sources of malodors or move themselves to avoid odors, or where odors are the result of industries that sustain food and energy supplies, frequent and intense malodors that are left unchecked can contribute to larger challenges. Malodors can directly affect physical health if the malodorous chemical represents an irritant or harmful airborne substance and occurs at a high enough concentration to exceed observable adverse effect levels. Additionally, malodors may act indirectly, as a mediator of mood, performance and health symptoms, effects which are the focus of this review [4]. Negative effects of low-level chemical exposures (e.g., malodor exposure) are further discussed in Section 5. As the World Sanitation Foundation notes, malodors that result from poor sanitation can compound sanitation issues in under-resourced and developing areas [5]. In rural India, malodors resulting from poor sanitation in pit latrines can indirectly result in open defecation and thus spark a variety of new community-wide health hazards, including compounded malodor issues [6–8].

While eliminating the source of indoor malodor can be a direct mode of intervening in odorous environments, it is often not achievable with the resources at hand. Even in today's urbanizing societies, where malodors now concentrate indoors and in private spaces, people, especially those in low-income communities, may not have the resources to remove the sources of malodors or to relocate their residence. In this review, we examine and discuss the current state of understanding on the role of indoor malodors for impacting human behavior, performance and health, including the individual factors that may govern such responses and identify research priorities to address the data gaps where they exist. Malodors have been reported to have a number of negative psychological, physical, social and economic consequences, as will be discussed herein. Conversely, removal of malodor by increased ventilation or filtering has been reported to increase performance and subjective responses in workers (e.g., ratings of air freshness and air quality), highlighting the potential benefits of mitigating malodors in indoor spaces [9,10]. However, such interventions may not be feasible in many indoor environments. Malodor is an important part of indoor air quality, and accessible and affordable malodor solutions such as air fresheners should be studied to determine if similar benefits are observed.

2. A Historical Perspective

Throughout history and across different parts of the world, malodors have varied in intensity and cultural impact as has the use of perfumes to mitigate malodors. Influenced by the Egyptians, the ancient Romans used perfumes intensely and even applied them to domestic animals to mitigate malodors. In the 4th century, the use of perfumes and pleasant aromas was condemned as an indulgence and idolatry by the Christian church [11]. Partially as a result of this policy, the European cities of the medieval and renaissance ages are known to be among the most foul-smelling environments in human history. Without proper sanitation infrastructures, their close quarters and high population density led to high concentrations of malodors [12]. Rotten food, excrement and slaughtered animal remains frequently littered the streets [11]. To mitigate indoor malodors, Medieval Europeans scattered herbs throughout their homes, sewed aromatic leaves into pillows, or polished wood with myrrh. To perfume themselves, they sprinkled rose water on their clothes or wore pomanders.

Out of this environment emerged the beginnings of modern commercial perfumes. Perfumes with essential oils were made for royalty by Italian chemists in the 14th century. With Caterina de' Medici's marriage to Henry II in the mid-16th century, Renaissance Italy's perfumes traveled to France where they continued to flourish centuries later. Throughout these periods, fragrances were used to mitigate the negative impact caused by malodors and functioned as a social symbol of higher class [12]. Perspectives on odors have changed significantly since the Renaissance, though people today still seek out means of combating malodors and asserting control over unpleasant smells in their lives, often through the use of pleasantly scented products like air fresheners.

3. Modern Indoor Malodor Challenges Associated with Urbanization

As malodors in public spaces have generally decreased with post-industrialism sanitation improvements, the domestic household has become a prominent site for exposure to malodors. While malodors experienced in historical periods were concentrated in shared areas, contemporary experiences with malodors are frequently experienced in personal spaces [13]. Contemporary building and insulation techniques used in modern homes can allow malodors to concentrate within the household [14].

Household odors are a combination of external odors that enter the home and odors produced within the home. External odors that invade the home include emissions from industry and pollution. Odors produced within the home arise from aggregate effects of low concentrations of volatile organic compounds (VOC) caused by cooking, pet, and human body odors, and the use of personal and household cleaning products, among others. They can also arise from microbial volatile organic compounds (MVOC) formed by the metabolic processes of fungi and bacteria present on building materials [15]. Over time, these VOC will become absorbed by the porous surfaces in homes such as carpets, soft furnishings, curtains, wall paper and even the grout between tiles. The combination of the bouquet of VOC present in households imparts each home with its own unique smell [16].

Exposure to certain mixtures of MVOC and VOC has been shown to increase reports of poor air quality within indoor spaces [17]. However, it should be noted that VOC as a class of compounds are not inherently toxic or malodorous. With respect to establishing toxicity, one must measure the levels and refer to the known threshold for adverse effect for each specific VOC. Many indoor VOC are perceived to have a pleasant smell and can have positive associations, including the wide variety of VOC that are released during such activities as baking bread or cooking. Additionally, there is a certain amount of subjectivity in an individual's response to specific VOC, as one person may report a positive reaction to a certain VOC based on pleasant memories associated with that VOC while others may report it as a malodor.

The perception of VOC also differs with respect to concentration and context. For instance, the substance skatole (3-methylindole) is present in flowers and essential oils and is frequently used in fine fragrances at low concentrations. However, at higher concentrations, it is perceived as having a distinct fecal odor, pointing to the importance of concentration with respect to malodor perception [18]. The context in which a VOC is interpreted is also critical to how it is perceived. Participants who were told that isovaleric acid (a cheesy-smelling fatty acid) was a body odor rated it as far more unpleasant than participants who were told it was a food odor [19]. Finally, genetic variation across the population has resulted in a 'highly personalized inventory of functional olfactory receptors' that not only determine what any individual can smell but how pleasant or unpleasant an odorant is perceived to be [20–22].

In today's urban societies, people can spend nearly 90% of their time in indoor environments [23,24]. As such, there has been investigation into whether the experience of indoor malodors should be regarded as a health issue or a merely aesthetic one [2,25,26]. This line of inquiry has encompassed field studies of industries that emit high quantities of malodorous compounds in residential areas, surveys of workplace productivity in specific chemical environments, psychological laboratory tests of odor exposure and case studies of heightened olfactory sensitivity, in addition to genetic and neurophysiological studies

of olfaction and related biological systems. These types of studies have yielded important insights into understanding of the diverse effects of odors on health and social interactions.

4. The Human Perception of Malodors

Perception of a malodor occurs when a molecule activates receptor cells linked to one of several cranial nerves associated with chemoreception. The olfactory nerves of the nasal epithelium are the most significant in odor perception and transmit information from the nasal cavity to the olfactory bulb, which in turn transmits olfactory information to other areas of the brain. In addition, the trigeminal nerve transmits information about pungency from the mouth and eyes as well as the nose. The chorda tympani nerve, glossopharyngeal nerve or vagus nerve may additionally be activated if the compound enters via the mouth [27].

Pungency and odor perception have been determined to be separate chemical senses, as anosmics, who lack the ability to smell, can still sense chemicals through their pungency effects in the nose, mouth and elsewhere [28]. While unpleasant olfactory sensations define malodors, at sufficiently high concentrations these sensations can be further accompanied by unpleasant pungency sensations.

The chemical senses of odor and pungency perception vary in several significant ways. For one, the threshold detection for pungency is generally several orders of magnitude higher in concentration than what is required to perceive the odor; people most often perceive a smell before it becomes so strong as to sting their eyes [29]. Though people may adapt to a constant odor in a matter of minutes or hours, adaptation to the perception of pungency occurs over longer periods [30].

Detection thresholds for malodors vary dramatically depending on the specific chemical in question, with thresholds generally declining with the carbon chain length of the compound [28,29]. Humans can detect common indoor malodors like hexyl acetate at concentrations as low as 2.9 parts per billion [30]. Malodors from sulfur compounds like isoamyl mercaptan can be detected at concentrations as low as 0.77 parts per trillion (ppt) [31], and MVOC can be detected as low as 0.2 ppt (i.e., from 2-Isopropyl-3-methoxy-pyrazine) [15]. From an evolutionary point of view, this ability to detect extremely low concentrations of chemical compounds in the air affords identification of various sources of danger, such as spoiled food or harmful chemicals.

Like all senses, olfaction is a product of biological evolution whose features are linked to survival and adaptation [32]. To this end, major connections have been identified between the olfactory system and cognitive processes, such as associative learning [33] and emotional memory [34–36], as well as "fight or flight" response [37]. "Top-down" cognitive functions, such as risk and danger perception, can also influence "bottom-up" information from the odor stimulus by allocating greater attentional resources to malodors, thus increasing their negative impact [38].

While the perception of malodors across individuals follows the same physiological pathways, the intensity of and response to the perception can vary. Although there can be differences across individuals in their sensitivity to specific malodors, the more important drivers of an individual's hedonic response may be due to their expectations, past experiences and the context in which an odor is experienced. For instance, the smell of smoke around a campfire can evoke a positive scent experience. However, the smell of smoke within a home will evoke an entirely different response, as the smoke is a signal of danger in this context.

5. The Negative Effects of Malodors

Utilizing the search term "malodor harm" or variations thereof (e.g., synonyms of "malodor" and "harm") via publicly available databases such as ScienceDirect (https://www.sciencedirect.com/) revealed scientific research across an array of disciplines documenting various negative effects associated with malodors. These negative effects were observed to cluster into six categories as identified by the authors of this review (Figure 1).

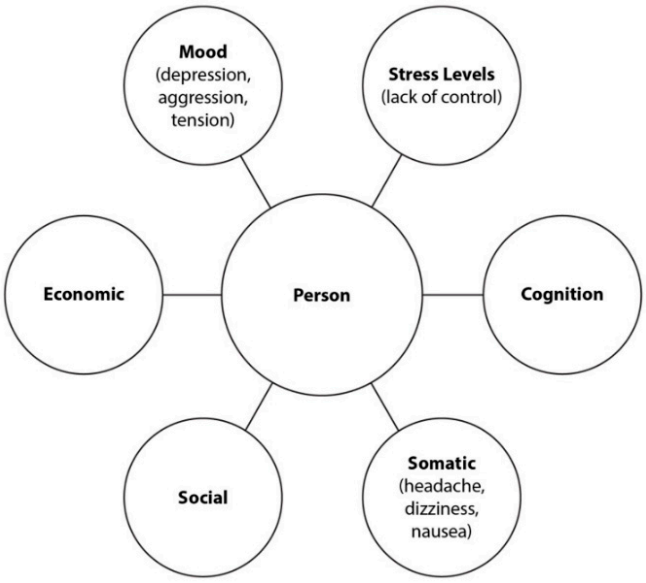

Figure 1. Reported negative effects associated with exposure to malodors.

Studies evaluating the negative effects of malodors have been conducted in both the field (observational) and the laboratory (experimental) employing a variety of dependent measures (Table 1).

Table 1. Measurement of malodor effects conducted in the field via observations and in the laboratory (Lab) via experimental methods.

Effect	Assessment Approaches Utilized	References
Mood	Profile of mood states (POMS) Mood scales Motivation on tasks	Field [39–42] Lab [33,43]
Stress levels	Heart rate Blood Pressure Salivary cortisol, alpha-amylase Anxiety/stress scales	Field [26,29,41]
Cognition	Cognitive tasks—simple and complex Creative problem solving	Lab [43–45]
Somatic	Symptom reports Pulmonary function Airway inflammation	Field [46–50] Lab [51]
Social	Self-reported behaviors/evaluations Pro-social behaviors (helping, friendliness)	Field [52,53] Lab [53–55]
Economic	Property valuation (homes, cars) Consumer choice behaviors (hotels, B&Bs)	Field [56–59]

Several studies have reported the negative effect of malodors on mood. Self-reported feelings of depression [39,40], fatigue [39,40], confusion [39,41], aggression [40,60,61], and tension [39,40] have all been positively correlated with malodor exposure, whereas subjective well-being [40] has been negatively correlated with such exposures. Even when no malodor is present, expectations of malodor exposure may cause negative effects on mood [43].

Malodors may cause individuals to feel a lack of control over their environment, adversely affecting stress levels. Indoor household malodors of external origin that are consistent and uncontrollable may produce feelings of helplessness [39,62]. Perceived control has also been shown to affect tolerance of a given malodor [44]. Individual coping style, however, may also affect odor annoyance and symptom

prevalence. Studies have suggested that those who have "palliative" or avoidance coping styles generally report less annoyance and symptoms than those with "instrumental" or problem-oriented coping styles [52]. Stress about the perceived toxicological effects of malodors may further allow odors to act as a trigger for other symptoms and behaviors [48–50].

Malodors have been shown to have detrimental effects on cognition. Rotton [44] has shown that exposure to malodor does not affect simple cognitive tasks, but that it has a detrimental effect on more complex tasks, such as proofreading. Cognitive deficits resulting from malodor exposure may be due to their negative effect on focus [45].

Malodors have been shown to elicit somatic symptoms. Somatic symptoms that have been reported with malodor exposure include vomiting, nausea, dizziness, headache, loss of appetite, sleep disorders and irritation of eyes, throat and nose [2,63]. Malodors can also cause somatic symptoms via "odor-worry" and stress [46]. Asthmatics, for example, may experience exacerbation of symptoms from non-irritating odors that are perceived as harmful [51]. Others may experience the stress effects of malodors because of "environmental worry" [46], an association with the odor as socially taboo or by perceiving possible property devaluation resulting from the odor [39]. Exposure to certain malodors has also been shown to affect the immune system, an effect probably mediated by perceived stress [47].

Social relations are also threatened by indoor malodors. Habituation to the odors of one's background can make people acutely aware of intrusive malodors, which may cause a variety of problems in social settings. Subjective ratings of odor unpleasantness have been shown to correlate with perception of socially undesirable traits [54]. Odor perception may also integrate with higher-order visual processes, such as facial perception. Unpleasant facial expressions paired with malodors have been shown to increase people's ratings of odor intensity and decrease their respiratory amplitude [53]. Judgments of interpersonal attraction are also influenced by the presence of malodor [64]. Indoor malodors can also reduce social interactions by causing inhabitants to experience shame or embarrassment about the malodor, even when they are external in origin [55]. It is reasonable to assume that this occurs with household odors as well.

Malodors can have economic effects. Unlike other "less visible" forms of pollution, malodors are readily identified and capitalized into property values [56]. Some industries, such as tanneries, paint factories, pulp mills and livestock operations, are regulated by legislated minimum "setback distances" that facilities must maintain from surrounding properties. Setbacks are used to minimize the economic effects of pollution, including malodors. Not only do properties surrounding these facilities decrease in value, but if the facilities' setback distance from surrounding properties is either unenforced or inaccurately determined [4,57], then malodors emitted from the facility can result in net economic loss, despite efficiency gains made by the offending firm [58]. Business and home owners alike can also suffer economic consequences. Malodors can affect car sales [59], worker productivity at call centers [9] and consumer satisfaction within the hospitality industry [65].

It is important to note that these negative effects are not necessarily independent measures and that individual effects can often act to compound economic ones. Levy and Yagil [66], for example, suggest that low Air Quality Index scores within stock exchanges may affect mood and risk aversion, thus resulting in lower stock returns. Fist, Black and Brunner [10] note that improvements to indoor environmental quality has a strong effect on workplace productivity and health, estimating a potential annual gain of $20 billion from improvements in office buildings in the United States.

6. Contemporary Approaches and Benefits of Mitigating Malodors

Efforts to protect the public from the adverse effects of outdoor malodors take the form of regulations in many jurisdictions. Regulations include concentration or exposure limits if the odors are produced by specific target pollutants, nuisance or annoyance laws and property setbacks. The odor impact criteria established by such regulations are most commonly based on field olfactometry-based concentration measurements, although instrumental concentration measurements or air dispersion models are also used [67].

In order to comply with odor regulations and to promote good relations with neighboring households, some facilities may install technology to control odors at the source. Control strategies include oxidation, adsorption, chemical reaction, chemical scrubbing, biofiltration/bioremediation and other methods [68].

To help households control indoor odors, product manufacturers often employ some of the same technical strategies used industrially to control odors. These include air filters and filter media, oxidizers, absorbents/adsorbents, surface and air sprays, and a variety of volatile ingredient diffusers. Air filtration to remove odors may be achieved with filters attached to heating, ventilation and air conditioning (HVAC) units or stand-alone filtering units. Such filters may utilize activated carbon or zeolite adsorbents, photocatalytic oxidants such as metal oxides (for example, patents US 8911670, US 8038935), or odor-reactive chemistry such as metallic salts or amine polymers (for example, patent US 4892719).

Household consumer goods products designed to eliminate household and automobile odors include air fresheners, pump and spray aerosols and diffusers. Such products may contain technologies designed to: capture or alter the molecular structure of VOC responsible for the underlying malodor; prevent perception of the malodorous VOC (MOVOC) by the olfactory system; and/or mask MOVOC via fragranced ingredients. Technologies used in air freshening sprays and diffusers that are designed to capture or alter specific types of malodor molecules are summarized in (Table 2). Spray products may utilize one or a variety of such technologies to eliminate the molecular source(s) and/or perception of MOVOC.

Table 2. Malodor classification and patented technologies that can be used in air fresheners to mitigate common indoor malodors.

Malodor	Common Molecular Components	Eliminated By	Reference
Smoke (Tobacco)	Cyclic compounds (e.g., methyl pyrole, pyridine)	Volatility reduction via complexation with cyclodextrin	[69–71]
Greasy Cooking Odors	Aldehydes (octanal, nonanal)	Capture via reaction with polyamine polymer	[72]
Body Odor	Acidic compounds (isovaleric acid); Thiols (methanthiol)	Salt formation by pH neutralization	[73]
Kitchen Odors	Amines (butylamine, trimethylamine)	Salt formation by pH neutralization; Reaction with carbonyl compounds	[74]
	Sulfur compounds (dipropyl sulfide)	Reaction with carbonyl compounds	[75]
	Amines; Fatty acids	Salt formation by pH neutralization; Reaction with carbonyl compounds	[76]
	2-Penethylfuran, Thiazoles, and Thiols (2-ethyl-1-hexanethiol)	Volatility reduction via complexation with cyclodextrin	[77]
	Sulfites; Amines (trimethylamine); Acid Compounds (acetic acid)	Salt formation by pH neutralization; Reaction with carbonyl compounds	[76]
	Fatty Acids; Amines; Thiols	Salt formation by pH neutralization; Reaction with carbonyl compounds	[78]
Bathroom Odors	Skatole; Morpholines; Acids (thioglycolic acid)	Olfactory receptor antogonists; Reaction with carbonyl compounds	[79]
	Bacterial VOC	Reaction with carbonyl compounds; Antimicrobial agents	[80]
Mold & Mildew	Fungal VOC	Reaction with carbonyl compounds + Antimicrobial	[80]
Pet Odor	Acidic Compounds; Sulfur Compounds; Amines	Salt formation by pH neutralization; Reaction with carbonyl compounds; Olfactory receptor antagonists	[74,79]

One such technology approach to mitigate indoor malodors is the use of cyclodextrin (CD) or cyclodextrin derivatives to trap MOVOC by complexation. Cyclodextrin has a macro-ring structure consisting of glucopyranose units. It is produced naturally by bacteria including *Bacillus macerana*

and *Bacillus circulans*, and is made industrially in bioreactors utilizing engineered glucosyl transferase enzymes [81]. The cavity of the cyclodextrin ring is apolar, so that less polar MOVOC readily displace water and become "trapped" upon interaction with aqueous cyclodextrin. Once complexed, the volatility of the MOVOC is significantly reduced and the malodors remain trapped in the CD cavity as long as the complex stays dry [69,82]. Patent documents indicate that consumer product companies make use of cyclodextrin technology in spray air freshening and other consumer products (for example, patents US 5760475, US 6077318, US 6248135 and US 6451065).

Spray air freshening products may also utilize pH buffers to neutralize acid or basic odors and convert them to non-volatile salts. Acidic odors include short chain fatty acids such as isovaleric acid, heptanoic acid and basic odors include amines such as ammonia, butyl amine, and trimethyl amine. Both types of neutralizable MOVOC are constituents of household odors such as food waste odors, and human odors [16]. Buffer systems used in spray air freshening products to neutralize odors may include for example, citrate or carbonate buffers. Neutralization of acid and amine odors to pH in the range of 5–8 by pH buffering converts these MOVOC to non-volatile salts, reducing or eliminating the odor [83].

Enzyme inhibitors may be used in consumer products, including air freshening products, to prevent production of odorous metabolites (patent US 9200269). For example, urease inhibitors and β-glucuronidase inhibitors have been described to prevent the formation MOVOC from urine by microorganisms on fibrous consumer products [84].

Unsaturated aldehydes are MOVOC components of household odors that are derived from the oxidation of skin oils or from oxidation of lipids during cooking [16,85,86]. Amine-functional polymers are known to bind with and capture aldehydes (including formaldehyde) through the formation of imine bonds [87,88], and have been used in air freshening products to bind with odors (patent US 9273427).

Additional technologies used in air freshening sprays include anti-microbial agents such as quaternary ammonium compounds to eliminate odor-causing microbes, which use salts of transition metals, particularly zinc and copper to complex with odors (for example, patents US 5783544, US 6503413), and oxidizing agents such as chloramine (patent US 6743420) that eliminate MOVOC through both antimicrobial and oxidative mechanisms.

Diffusion-type products, like heated or unheated fragrance diffusers, may typically contain reactive materials such as carbonyl compounds designed to react with nucleophilic or electrophilic malodorous molecules such as amines (for example, patents US 8992889, US 5795566, US 7998403) to form covalently bonded, non-odorous products.

Technologies designed to prevent the olfactory perception of malodors based on mechanisms such as olfactory receptor antagonism have also been explored by consumer product companies (for example, patents EP 2812316, US 9526680, US 9254248). Such approaches target specific olfactory receptors known to be activated by malodorous agonists with antagonistic agents to block activation of these receptors by the malodor.

Consumer products designed to control malodor often, but not always, contain fragrance in addition to the technologies described above, or may contain fragrance without additional technology. Fragrance can mitigate malodors by masking their smell. The mechanism by which fragrances mask malodors is not well understood and may be achieved through a combination of signal interference (such as by receptor antagonism as discussed above) and through top-down processing effects (e.g., blending malodor with other odors to create perception of a new, non-malodorous aroma). Additionally, as noted above, some fragrances may contain reactive materials, such as carbonyl compounds designed to react with nucleophilic or electrophilic malodorous molecules. Pleasant fragrances have also been shown to have beneficial effects by increasing positive emotions, decreasing negative mood states and reducing indices of stress [89,90]. It is postulated that fragrances exert these effects through emotional learning, conscious perception and belief/expectation [91].

While seeking solutions to mitigate malodors, consumers and regulators must balance the economic, environmental and health costs of indoor malodors against the benefits delivered by the odor mitigating approaches. Companies that manufacture odor control technologies that emit fragrance or odor mitigating molecules into the air follow safety assessment paradigms that are widely recognized to ensure consumer safety when used according to label instructions. These assessments are aligned with the process outlined by EU Scientific Committee on Consumer Safety and are based on an understanding of both the inherent hazards of any materials in a product formulation as well as the level of exposure to those materials based on usage scenarios including extreme consumer usage [76,92]. In addition, the Research Institute for Fragrance Materials (RIFM) has published extensive industry guidance for conducting safety assessments of fragrance ingredients [93]. A 2007 US Environmental Protection Agency (EPA) review found that 0.23% of reported air freshener exposures involved an adverse reaction and that the number of reported exposure incidents for air fresheners was relatively small when compared to the reported exposure incidents for other product categories [94].

Household consumer products designed to eliminate odors are widely used by consumers in the United States, with 75.9% of US households purchasing an air care product as of March 2019, according to Nielsen HomeScan panel data [95]. Air care products are broadly available at retail outlets at relatively low cost. Buying rates of air care products are highest in households with annual incomes less than $20,000 [96]. This may be due in part because lower-income households are disproportionately affected by environmental odors, odors arising from crowded conditions, and by economic limitations on their ability to deal with odor sources, such as those associated with sub-standard housing.

Despite the potential negative effects of malodors and the widespread use of consumer products designed to eliminate odors, the health and quality-of-life benefits of the use of such consumer products has not been widely studied. A review of published literature on the health impacts of using air cleaning devices was recently completed by Kelly and Fussell [97]. The studies reviewed focused mostly on indoor air cleaning devices that reduced particle and VOC concentrations by using filters, adsorbents, oxidative technologies or combinations thereof. The studies generally showed no or low levels of improvement in the health outcomes measured for households with good ambient air quality and modest improvements for households with very poor ambient air quality. However, none of these studies, and few other published studies, have specifically examined the impact of indoor malodor reduction on health outcomes such as cognition, mood, and stress levels, among others.

It may be inferred that eliminating the perception of malodor can reduce psychological effects of malodors, such as the feeling of a lack of control [41,44,47]. While studies have shown that people with problem-oriented coping strategies experience more stress and stress-related symptoms due to malodor exposure [52], air care and cleaning technologies offer a solution that allows people with problem-oriented coping styles to directly address the problems caused by malodors. Air care products designed to eliminate malodors can provide a more widely affordable solution compared to more costly alternatives such as home filtration systems, especially for low-income households who are economically unable to purchase such systems, replace malodorous household structures or items, or relocate away from substandard housing or industrial sources of malodor.

7. Conclusions

While there are complex issues at play in the distribution and effects of malodors (e.g., pollution concentrated near low-income communities, lack of access to proper sanitation), malodors are a general fact of daily human life. Indoor malodors are particularly challenging for people in developing countries or in low-income communities [2], which may lack the financial resources or opportunities to directly change the sources or living situations that harbor malodors. In these scenarios, malodors ultimately contribute to broad issues of structural inequality [41,98].

Viewing malodors as a merely "aesthetic" issue ignores their potential for negative impact on human health, previously defined as a "state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" [3]. Review of the current literature includes several studies

from a diverse range of disciplines reporting negative psychological, physical, social and economic consequences of indoor malodor. Conversely, removal of malodor has been reported to increase performance and subjective responses in workers [10], highlighting the potential benefits of mitigating malodors in indoor spaces. However, there are several gaps in the current research. Specifically, there is a lack of understanding regarding the mechanisms by which malodors can elicit any adverse effects, whether through an individual's experience or expectations that provide the interpretative context in which a VOC is experienced or through a more direct effect on human physiology and well-being. Thus, well-controlled studies examining the emotional, behavioral and performance-related outcomes induced by exposure to malodors are needed, as are studies that include a formal examination of the individual variables (i.e., personality, gender, age, culture) that may influence the magnitude and direction of malodor effects.

Eliminating the source of malodor can be a direct mode of intervening in odorous indoor environments, though it is often not achievable with the resources at hand, particularly in low-income communities. Therefore, easily accessible and affordable approaches to eliminate malodors such as air fresheners with odor eliminating technologies (Table 2) may hold promise for reducing some of the negative effects of indoor malodor. However, we found relatively few investigations into the effectiveness of such measures on improving health outcomes such as cognition, mood, and stress levels, among others. Therefore, further study is recommended on the impact of air fresheners and other odor mitigating products on health outcomes via malodor elimination and/or emission of pleasant fragrances, as well as their impact on measures of overall indoor air quality.

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