CTEH®

# HEALTH RISKS ASSOCIATED WITH SHORT- AND LONG-TERM EXPOSURE TO DIMETHYL SULFIDE (DMS)

Chiquita Canyon Landfill

Castaic, CA

CTEH

**Prepared By**

CTEH, LLC (A Montrose Environmental Group Company)
5120 North Shore Drive
North Little Rock, AR 72118

**Prepared For**

Chiquita Canyon, LLC
29201 Henry Mayo Drive
Castaic, California 91384

**Report Submittal Date**
January 15, 2024

**Version**
1.0

**CTEH Project #: PROJ-030205**

## Table of Contents



## List of Tables

## 1.0 Introduction

Condition 12 (b)(v) of the September 6, 2023, "Stipulated Order for Abatement" requires Chiquita Canyon, LLC to provide a report "*on the known health risks from acute and long-term exposure to DMS* [dimethyl sulfide; CAS# 75-18-3]*, including any action levels from other public health or government entities, and including a summary of recommended actions for persons exposed to DMS for acute and long-term durations.*" CTEH submits the following report to the South Coast Air Quality Management District ("South Coast AQMD") regarding the known health risks from acute and long-term exposure to DMS. This report summarizes the available scientific literature, including studies evaluating the toxicology of DMS in animal models and in humans, as well as health-based action levels and recommendations established by local, state and federal governmental public health agencies. In addition, this report provides action levels and actions as guidance for public health officials to adequately communicate health risks and precautions to the public. Recommendations for analysis of other constituents are also presented for future study.

## 2.0 General Overview of Dimethyl Sulfide

DMS is a clear to straw colored liquid that volatilizes at room temperature (Cameo Chemicals, n.d.; PubChem, 2023). As a volatile organic compound that contains sulfur, DMS is often described as having a pungent garlic or cabbage-like sulfuric smell of unpleasant or disagreeable character (PubChem, 2023). In contrast, DMS has also been reported to be a substantial contributor to the aroma of many lager-style beers resulting from the germination of barley, as well as from the breakdown of malt by yeast, with opinions varying on its desirability, affording a "*cooked corn*" aroma to beer (Bamforth, 2014). It is well documented that DMS occurs naturally in the environment from the decomposition of plant and animal materials (USEPA, 2005). It also occurs naturally in foods and is approved by the Food and Drug Administration (FDA) as a food additive with the designation as a Generally Recognized as Safe (GRAS) substance (PubChem, 2023; Sinki & Schlegel, 1990; US FDA, 2023). For example, DMS is naturally found in, produced during the cooking of, or added as a flavoring in the production of tomato paste; corn; cabbage; asparagus; clams and oysters; cheddar cheese; cheddar cheese powders; and beer (Casey et al., 1963; McGorrin, 2011).

### Natural Occurrence in the Environment and Anthropogenic Sources

DMS is produced by many living organisms, including algae, animals, microorganisms, plants, and humans (Bentley & Chasteen, 2004). An estimated 30 to 40 million metric tons per year are released from the ocean (Bentley & Chasteen, 2004; Kettle & Andreae, 2000), representing about 80% of total global DMS emissions to the atmosphere (Kappler & Schäfer, 2014). DMS is the most abundant biological sulfur compound emitted to the atmosphere (Bentley & Chasteen, 2004; Kappler & Schäfer, 2014; Simpson et al., 1999). DMS also occurs in soil, as a wide range of bacteria and cyanobacteria naturally present in

terrestrial environments generate DMS via methylation of methanethiol (methyl mercaptan) (Carrión et al., 2017).

Annual production of DMS in the United States is estimated to range from 10,000 to 15,000 metric tons primarily based on its use as a solvent and chemical intermediate for the production of organic chemicals such as dimethyl sulfoxide (OECD, 2007). Other industrial sources of DMS include wood pulp and papermills, petroleum processing plants and sewage treatment plants (USEPA, 2005). Given its low odor threshold, and relatively low toxicity, DMS is often added as a presulfiding agent for steam cracking, the process that turns hydrocarbons into ethylene and propylene (Chevron Phillips Chemical, 2023). It is also added, along with other reduced sulfur compounds, to natural gas to serve as an odorant for early leak detection (Barelli et al., 2015; Michanowicz et al., 2023). Because landfills contain decomposing organic matter, DMS can also be emitted from landfills along with other sulfur-containing compounds, such as mercaptans and hydrogen sulfide (Kim et al., 2006; Li et al., 2015; Long et al., 2017).

## Natural Occurrence in the Human Body and Biology

DMS is a byproduct of human metabolism of hydrogen sulfide, a colorless gas to which humans are exposed on a daily basis. The metabolism of hydrogen sulfide involving production of DMS is considered a detoxication process, in which hydrogen sulfide is detoxified by the enzymatic addition of a methyl group (methylation) into methanethiol, and further enzymatically methylated for detoxification into DMS by thiol-S-methyltransferase (Cao et al., 2019). DMS is produced in the body of mammals during metabolism of methionine and related substances, and by bacteria in the mammalian gut and mouth (Jervøe-Storm et al., 2019). This can result in elevated levels of DMS in human breath and has been documented at concentrations up to 345 parts per billion (ppb) in individuals with advanced liver disease (Tangerman et al., 1994).

## Odor Thresholds of DMS

The human olfactory system has the ability to sense an odor when an interaction occurs between volatile odorous chemicals and the olfactory epithelium tissue within the nasal cavity. Upon interaction, cellular changes lead to a set of neural signals that travel to the brain where interpretation of complex signals results in the detection and identification of an odor. Importantly, the capacity to detect odors varies across the population, due to multiple factors that can influence the process of odor detection. Factors that have been shown to influence odor detection and perception include lifestyle habits (i.e., smoking/alcohol consumption), age, health status (i.e., upper respiratory tract infections, neurodegenerative diseases), cognitive factors (Dalton, 1996; Rosenkranz & Cunningham, 2003), genetics, and even personality (i.e., assertiveness, impulsiveness) (Doty, 1989; Doty et al., 1984, 1985; Hoshika et al., 1993; Hummel, 2000; Kaneda et al., 2000; Larsson et al., 2000; Lehrner et al., 1997; Mesholam et al., 1998; Murphy et al., 2003; Simchen et al., 2006).

In addition to biological and lifestyle variability influencing odor detection, the identification of a numerical odor threshold (the concentration at and above which a person can perceive a smell) is further complicated by the varying methodologies used across scientific studies published in the literature to assess odor perception. This means that it is not uncommon to find a range of reported odor thresholds for a single chemical such as DMS. Recent studies have reported odor thresholds for DMS as low as 1 ppb and 2.5 ppb (Leonardos et al., 1969), whereas previous studies have reported odor thresholds ranging from 0.16 ppb to 63 ppb (Katz & Talbert, 1930; Nishida et al., 1979). Despite the variability in odor thresholds reported for DMS, there is a scientific consensus that DMS can be smelled by humans at levels well below concentrations known to cause adverse health effects in humans (Demchuk et al., 2018).

## 3.0 Summary of DMS Toxicity Studies in Humans

A summary of the available toxicological information for exposure to DMS is presented below in epidemiological studies and other studies using human or animal models. Overall, based on available data from peer reviewed publications and toxicological reports published by federal public health agencies such as the Agency for Toxic Substances and Disease Registry (ATSDR), the American Conference of Governmental Industrial Hygienists (ACGIH) and the USEPA, the mildest adverse health effects from short-term exposures (i.e., seconds to minutes) in humans are likely to present at concentrations of 44,000 ppb, resulting in possible nausea associated with strong odors, as documented by Katz & Talbert (1930). Notably, this concentration is hundreds of thousands of times above the concentrations at which DMS odors would be perceived in the general population. In the same study, Katz & Talbert noted that a stream of air containing pure grade DMS at 8,800,000 ppb flowing against the eye for 10 seconds produced faint irritation, while commercial grade DMS produced faint irritation at 6,200,000 ppb and moderate irritation at 24,000,000 ppb (Katz & Talbert (1930).

Although a few other studies have reported the toxicity of DMS in humans, such studies are case-reports that have limited information about exposure levels and are significantly confounded by co-exposures to other sulfur-containing gases. For example, Kangas et al. (1984) reported that cellulose mill workers were exposed to DMS concentrations ranging from 0 to 14,000 ppb. The authors reported that exposed workers complained of headaches more frequently than unexposed workers, but noted that co-exposures with hydrogen sulfide and methyl mercaptan in the exposed group made it difficult to ascertain how much the increased incidence of headaches reported could be directly attributed to DMS (Kangas et al.(1984)

More severe toxicity and life-threatening risks associated with exposure to DMS was reported by Terazawa et al., (1991), in a case-report where DMS concentrations possibly ranging from 5 to 55% (50,000,000 to 550,000,000 ppb) resulted in oxygen displacement within the confined space of a tank, leading to hypoxic (low oxygen) conditions, which resulted in a reported death from asphyxiation and DMS poisoning from inside the tank. Similarly, a case study by Vento (1966) reported on papermill workers that filled barrels with an odorant-sulfone mixture consisting of up to 80% DMS (as cited by Demchuk et

al., 2018). The low oxygen levels coupled with a lack of respiratory protection and non-functioning work area ventilation led to significant illness and death in these workers (Demchuk et al., 2018).

A review of evaluations conducted by governmental health agencies shows a consensus that DMS toxicity data in humans is scarce, with limited indication that it is of high toxicological significance. For example, in the absence of toxicity values in USEPA's Integrated Risk Information System (IRIS), Provisional Peer Reviewed Toxicity Values (PPRTVs) are developed following a review of the relevant scientific literature using the same methods, sources of data, and guidance for value derivation generally used by the USEPA IRIS program. In a report published by USEPA in which chronic and subchronic toxicity values for DMS were attempted to be derived, it was noted that:

> *"available data are inadequate for derivation of a provisional RfC for dimethyl sulfide directly from the inhalation data, by route-to-route extrapolation from the oral data, or by analogy to the potential surrogate chemicals, methyl mercaptan or dimethyl sulfoxide."* (USEPA, 2005: p. 7)
>
> And,
>
> *"no data regarding the toxicity of dimethyl sulfide to humans following chronic or subchronic oral exposure were located"* (USEPA, 2005: p. 3).
>
> And,
>
> *"no data regarding the possible carcinogenicity of dimethyl sulfide in humans were located"* (USEPA, 2005: p. 3).

Similarly, the American Conference of Governmental Industrial Hygienists (ACGIH) reported no findings of toxicity data in humans on exposure to DMS alone (ACGIH 2004: p. 2).

According to the Organization for Economic Co-operation and Development (OECD), Screening Information Database (SIDS) initial assessment report, DMS *"is currently of low priority for further work because of its low hazard profile"* (OECD, 2007). Similarly, Environment and Climate Change Canada/Health Canada ("Health Canada") published a screening assessment in 2018 for four sulfur-containing chemicals, including DMS. Health Canada's conclusion regarding the potential for ecological or human health risk associated with DMS exposure was that it "[did] *not meet the criteria under paragraph 64(c) of CEPA* as [DMS is] not entering the environment in a quantity of concentration or under conditions that constitute or may constitute a danger in Canada to human life or health*" (Health Canada, 2018).

---

**The Canadian Environmental Protection Act (CEPA) defines in Section 64(c) a substance as "toxic" if it is entering or may enter the environment in a quantity or concentration or under conditions that constitute or may constitute a danger in Canada to human life or health. https://laws-lois.justice.gc.ca/eng/acts/C-15.31/page-5.html#docCont*

According to the Emergency Response Planning Guidelines (ERPG) committee of the American Industrial Hygiene Association, as well as according to Demchuk et al. (2018) who conducted a comprehensive review of DMS toxicity in recent years, no studies on human developmental, reproductive, genotoxicity, or carcinogenicity effects following DMS exposure are available. Similarly, the ERPG committee noted no available data from human or animal studies evaluating subacute or chronic toxicity. CTEH conducted an independent evaluation of the available literature and similarly did not identify any human or animal studies evaluating long-term exposures to DMS.

### Human Physiological Effects of Odors

As discussed above, DMS has a low odor threshold compared to its relatively high concentration where toxicity is observed. This means that an individual may detect the odor of DMS at concentrations far below the concentration at which adverse health effects are anticipated. Nevertheless, the detection of odors in the environment is often associated with adverse health consequences by the public. Furthermore, risk perception by the public is often attributed to the assumption that environmental odor presence will result in a health hazard. Several studies have demonstrated that perception of a source of an odor as potentially hazardous is strongly correlated to the likelihood of a person reporting symptom complaints and attributing health problems to that odor or chemical (Dalton, 1996; Dalton & Wysocki, 1996; Rosenkranz & Cunningham, 2003).

Behavioral responses to environmental odors can also trigger odor responses associated with negative hedonic tone (i.e., unpleasant odors), such as nonspecific symptoms including nausea and headaches (ATSDR, 2017). These types of behavioral responses are also likely to vary among individuals exposed to the same odors, as they are largely dependent on an individual's history of detection of a specific odor and associating it with a particular event or health outcome, as well as contextual perspectives in which odors are detected.

## 4.0 Summary of DMS Toxicity Studies in Animals

Due to the lack of studies in humans investigating DMS exposure and the potential for adverse health effects, results from animal studies are used to predict human reactions to exposure. The use of animal models as surrogates for human exposure presents significant challenges in human health risk assessment due to differences in study objectives and design among other factors (Bracken, 2009). For example, it is difficult to predict clinically relevant outcomes for non-lethal, irritant effects in humans from studies that use high chemical concentrations in animals to determine a lethal dose. Despite the challenges of interpreting animal exposure and effect data for use in a human health risk model, animal studies are the next best proxy to estimate human reactions to exposure in the absence of human studies to evaluate the potential toxicity of a chemical. Described below are several animal studies involving DMS exposure in animals.

## Inhalation Animal Toxicity Studies

Demchuk et al. (2018) noted that time of exposure played a critical factor in DMS-induced lethality in animals exposed via inhalation. For example, Tansy et al. (1981) reported that no deaths following acute exposure to DMS upwards of 20,000,000 ppb were observed; however, 50% of the animals exposed to 40,250,000 ppb for four hours died following exposure. This toxicological endpoint (50% death across exposed animals via inhalation) is a standard toxicological endpoint referred to as the lethal concentration-50 or $LC_{50}$. Consistent with these observations, the European Chemical Agency (ECHA) reported that rats exposed for four hours via inhalation in a recent study, produced an $LC_{50}$ of 42,250,000 ppb, with 80% of the animals dying when exposed to 45,000,000 ppb and 90% dying when exposed to 48,000,000 ppb (ECHA 2023). Similarly, studies by Schoenig (1969a, 1967b, as cited by Demchuk et al., 2018) noted that Sprague-Dawley rats exposed to DMS via inhalation and dermally documented an $LC_{50}$ of 43,310,000 ppb after a 4-hour inhalation exposure. The authors further noted that animals began demonstrating symptoms of *"generalized inactivity"* beginning after 30 minutes of exposure to 18,500,000 ppb, with increasing severity in symptoms such as tremors, hyperpnea and unconsciousness, cyanosis and/or dyspnea at concentrations as high as 195,000,000 ppb for 1 minute. A summary of primarily non-lethal effects of DMS exposure via inhalation in rats is shown in Table. 1. Please note that concentrations reported in Table 1 are provided in parts per million (ppm).

**Table 1. Acute inhalation toxicity data for rats exposed to DMS up to 4 hr (Demchuck et al., 2018)**

| Concentration (ppm) | Time of Onset (min) | Duration (min) | Health Effect(s) |
|---|---|---|---|
| 18,500 | 10–15 | 45–70 | Generalized inactivity |
| | 30–45 | 30–50 | Tremors |
| | 60–-80 | 120–130 | Unconsciousness |
| 42,100 | 0–2 | 6–10 | Hyperactivity |
| | 8–10 | 10–20 | Generalized inactivity |
| | 10–15 | 250–260 | Hyperpnea |
| | 20–30 | 240–250 | Unconsciousness |
| | 120–200 | until death | Cyanosis – only in rats that died |
| | 310 | 60–120 | Tremors |
| 81,500 | 0–2 | 6–8 | Hyperactivity |
| | 6–8 | 10–15 | Generalized inactivity |
| | 8–12 | until death | Hyperpnea |
| | 10–20 | until death | Unconsciousness |
| | 15–20 | until death | Salivation |
| | 15–25 | until death | Frothy nasal discharge |
| | 15–25 | until death | Cyanosis |
| 195,000 | 0–1 | 1–4 | Generalized inactivity |
| | 1–2 | 5–8 | Hyperpnea |
| | 1–5 | until death | Unconsciousness |
| | 7–10 | until death | Dyspnea |

Source: adapted from Schoenig (1967b).

In a study by Dow Chemical (1957) the authors reported the inhalation $LC_{50}$, to be 218,500,000 ppb following a 9-minute exposure in rats. Similarly, a study by Ljunggren & Norberg (1943) reported no effect with inhalation of 1,100,000 ppb DMS and mortality at 54,000,000 ppb DMS in rats following a 15-minute exposure (Ljunggren & Norberg, 1943).

A study of rats by Zieve et al. (1974) calculated an approximate dose that induced coma in 50% of the test animals ($CD_{50}$) of 96,000,000 ppb via inhalation, or equivalent blood concentrations greater than 7 µmol/mL of DMS (as cited by Demchuk et al., 2018). Additional analysis by Demchuk et al. (2018) recalculated this $CD_{50}$ to be 95,089,000 ppb.

### Oral and Dermal Animal Toxicity Studies

A sub-chronic exposure study by Butterworth et al. (1975) administered daily oral doses of up to 250 mg/kg (equivalent to roughly 1,000,000 ppb inhalation exposure) of DMS in rats for 14 weeks. The authors noted no significant changes in any endpoints for exposed animals, including liver, kidney, or lung toxicity (ACGIH 2004; USEPA, 2005).

Additionally, in a study by Wood et al. (1971), rabbits received doses of approximately 2,000 mg/kg-day of DMS for 13 weeks in drinking water. The authors reported some congestion and hemorrhagic spots in the lungs as well as renal toxicity upon gross examination of the exposed animals (ACGIH, 2004; USEPA, 2005).

In addition to the previously discussed inhalation study by ECHA, they reported two additional key studies that indicated low toxicity of DMS via oral, or dermal routes in rodents (ECHA, 2023). For acute oral toxicity, ECHA reported on a study that orally exposed rats to 2,000 mg/kg body weight DMS. Animals were followed up through day 15 post bolus exposure. The authors reported no significant macroscopic findings nor any unscheduled deaths (ECHA 2023). From this, ECHA calculated a no deaths 2,000 mg/kg in rodents (ECHA 2023). Butterworth et al. (1975) conducted a repeated dose, subchronic study in rats fed doses of DMS in corn oil for 2, 6, or 14 weeks at doses of 0, 2.5, 25, or 250 mg/kg per day; from this study ECHA derived a no adverse effect level of 250 mg/kg per day (Butterworth et al., 1975; ECHA 2023).

For acute dermal toxicity, ECHA dermally exposed rats for 24 hours to doses up to 2,000 mg/kg body weight. Animals were observed through Day 15. The authors reported no macroscopic abnormalities nor any unscheduled deaths for the exposed animals. From this, ECHA calculated a dermal $LD_{50}$ of 2,000 mg/kg (ECHA 2023).

## 5.0 Basis and Considerations for the Use of Action Levels

Action levels, in the context of air quality, are typically set or proposed by public health agencies to limit potential exposures to constituents or to implement corrective action for exposures where applicable. Action levels may represent concentration thresholds that trigger a course of action to protect individuals in occupational and/or residential settings. In this regard, action levels are often times derived from

existing health-protective benchmarks like screening levels or occupational exposure limits. However, action levels do not replace exposure standards or guidelines intended to protect from exposure over longer periods of time.

Health-protective screening values are estimates of human exposure to hazardous substances at or below levels at which it is unlikely they would pose a meaningful risk to the general population. While the derivation of health-protective screening values varies depending on their intended application, they generally follow similar principles leading to values that are protective in nature. Health-protective values from which action levels may be developed are derived using reasonable maximum exposure assumptions that are intended to rule out risk under worst-case scenarios. Because of the conservative exposure parameters utilized in developing health-protective screening values, the intended usage of these is to account for a reasonable maximum exposure, as expressed by USEPA in the Federal Register (1998) which states:

> *"A legitimate use of worst-case scenarios is to determine if the exposure or risk is low enough even at this extreme so as to dismiss concern for this scenario. It is not legitimate to use a worst-case scenario to prove that there in fact exists a concern in a real population"* (USEPA, 1998).

The uncertainties associated with these worst-case scenarios and steps of risk assessment are well known. Regulatory agencies recognize this uncertainty and adopt assumptions that are conservative (meaning their exposure assumptions and toxicity constants ensure an overestimate of the true risk) to determine "*human-health protective*" exposure estimates - not to predict actual exposure outcomes. These precautionary assumptions are common for initial screening assessments, when the primary goal is to determine if the presence of a constituent represents a potential health risk and if further evaluation is necessary. In other words:

> *...the focus of federal agencies' "risk" assessments can sometimes be characterized more accurately as safety assessment [i.e., estimating an exposure level below which no significant risk will occur] rather than as risk assessment [i.e., simply describing the likelihood of a risk].* (GAO, 2001)

The risk assessment process is protective of human health on many levels. For example, the USEPA publishes toxicity values for hundreds of chemicals that serve as the toxicological underpinnings of regulatory human health risk assessments. These toxicity values are intended to protect even the most sensitive individuals in the general population and are derived by dividing the lowest levels at which adverse effects are observed (i.e., Lowest Observable Adverse Effect Level – LOAEL, or No Observable Adverse Effect Level - NOAEL) in the most sensitive laboratory animal species by "uncertainty factors" designed to account for differences in responses between animals and humans and other sources of uncertainty in the model. Therefore, these toxicity constants are health protective in nature and by design are likely to overestimate the hazard posed by a given dose of a chemical.

In this regard, utilizing established health-protective screening levels as the basis for action levels generally provides sufficient protection. However, given the limited risk presented by DMS at environmentally relevant concentrations, and the limited amount of toxicological data in humans or animals, there are very few established health protective benchmarks or action levels available for DMS.

## Community Health-Based Screening Levels of DMS

### *USEPA Reference Concentration (RfC)*

The USEPA establishes Reference Concentrations (RfC), which are estimates of continuous inhalation exposure concentration to people, including sensitive subgroups, that are likely to be without risk of deleterious effects during a lifetime. However, USEPA has not established an RfC for DMS.

### *USEPA Provisional Peer Reviewed Toxicity Values (PPRTVs)*

In the absence of an RfC, USEPA often publishes PPRTVs following a review of relevant scientific literature for derivation of chronic or subchronic values. In 2005, USEPA published a PPRTV document for DMS based on a review of the available literature. However, in this review, USEPA noted that there was a lack of available toxicity data for DMS (USEPA, 2005: p. 3-7). Importantly, in the absence of available data for DMS, USEPA considered the use of surrogate chemicals, such as dimethyl sulfoxide, but based on a lack of comparable doses in existing studies, equivalent doses for DMS could not be calculated. USEPA noted that "*the data do not support the use of dimethyl sulfoxide as a surrogate for derivation of a provisional [Reference Dose] for dimethyl sulfide by analogy*" (USEPA, 2005: p. 5). The USEPA ultimately concluded that data was insufficient to "*directly or by analogy*" derive a provisional RfD for DMS (USEPA, 2005: p. 5). Similarly, USEPA noted that exposure to DMS in human studies was unquantified and always in combination with other chemicals, and that animal studies were limited to acute studies and one inadequate study of subchronic duration. Whereas USEPA also considered deriving a RfC by analogy to the toxicity of other surrogate chemicals (i.e., methyl mercaptan), USEPA noted that significant differences in toxicity existed, thus precluding them from further consideration for derivation of a provisional RfC.

### *ATSDR Minimal Risk Levels (MRLs)*

ATSDR develops MRLs, which are estimated daily human exposure concentrations that a person could be exposed to for a specified duration of time (1-14 days, acute; 14 – 365 days, intermediate; 365 days or longer, chronic) without appreciable risk of adverse noncancer health effects. In conjunction with USEPA and in response to the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) [42 U.S.C. 9604 et seq.], ATSDR prioritizes the following:

1. *"a list of hazardous substances most commonly found at facilities on the CERCLA National Priorities List (NPL) (42 U.S.C. 9604(i)(2))*
2. *"prepare toxicological profiles for each substance included on the priority list of hazardous substances, and to ascertain significant human exposure levels (SHELs) for hazardous substances in*

*the environment, and the associated acute, subacute, and chronic health effects (42 U.S.C. 9604(i)(3))"*

3. *"assure the initiation of a research program to fill identified data needs associated with the substances (42 U.S.C. 9604(i)(5))"* (ATSDR, 2018).

ATSDR's Substance Priority List is comprised of substances most commonly found at facilities on the NPL and *"determined to pose the most significant potential threat to human health"* based on the frequency, toxicity, and potential for human exposure at these sites (ATSDR, 2023). Notably, DMS is not listed in the 2022 Substance Priority List and no prior list. In this regard, no MRLs are available for DMS.

### *Community Values from State Health Agencies*

State agencies, such as the California Office of Environmental Health Hazard Assessment (OEHHA) often develop health-protective values such as the Reference Exposure Levels (RELs) that are designed to provide protection over repeated exposures across various averaging periods (i.e., 1-hour, 8-hour, chronic); However, no RELs or other screening levels developed by State Agencies are available for DMS.

### *Protective Action Criteria (PAC) and Emergency Response Planning Guidelines (ERPG)*

The Protective Action Criteria (PAC) database includes hazardous exposure guidelines for the public in case of emergency response. PAC values consist of Emergency Response Planning Guidelines (ERPGs), published by the American Industrial Hygiene Association (AIHA), Acute Exposure Guideline Levels (AEGLs), and Temporary Emergency Exposure Limits (TEELs) (DOE/NNSA, n.d.; NOAA, 2023).

In the case of DMS, no AEGLs or TEELs have been developed; however, ERPGs serve as the basis for PAC values. ERPGs are classified into three levels, dependent on the health outcome (Cavender et al., 2008).

The Level One ERPG (ERPG-1) is defined as *"[t]he maximum airborne concentration below which nearly all individuals could be exposed for up to one hour without experiencing or developing health effects more severe than mild odor perceptions or irritation"* and is established by AIHA (Cavender et al., 2008). For DMS, the ERPG-1 has been established as 500 ppb (1.27 $mg/m^3$) (Cameo Chemicals, n.d.; DOE, 2018). The ERPG-1 value was based on odor data with the reported odor threshold. Humans detect an *"easily noticed odor"* after one inhalation at 1,900 ppb, and a *"faint"* odor at 84 ppb (AIHA, 2016: p. 5).

The Level Two ERPG (ERPG-2) is defined as *"[t]he maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to one hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action"*, and has been set at 1,000,000 ppb for DMS (Cameo Chemicals, n.d.; DOE, 2018). Whereas the supporting studies cited by the ERPG committee indicate no adverse health effects would be expected above 13,000,000 ppb in animals and 8,800,000 was only documented to cause eye irritation in humans, they noted that *"at 1,000 ppm [1,000,000 ppb] the odor could be very strong which may impede escape."*

The Level Three ERPG (ERPG-3) is defined as *"[t]he maximum airborne concentration below which is it believed that nearly all individuals could be exposed for up to one hour without experiencing or developing life-threatening health effects"* and has been set at 5,000,000 ppb for DMS. Whereas animal studies do not show lethality from exposure to DMS until several hours at concentrations greater than 40,000,000 ppb, the ERPG committee noted that the ERPG value of 5,000,000 represents 25% of the lower explosive limit (LEL) of DMS (Cameo Chemicals, n.d.; DOE, 2018). Of note, the lower explosive limit is the lowest concentration of a vapor or gas that will produce a flash of fire when presented with an ignition source. Thus, the risk of fire from the flammability of DMS presents a greater hazard than the toxicity of DMS. **Table 2** summarizes the above set ERPG values for each level.

**Table 2. ERPG values for Dimethyl Sulfide.**

| ERPG Level (1-hr value) | Concentration (ppb) |
|---|---|
| ERPG-1 (mild odor perceptions or irritation) | 500 |
| ERPG-2 (disabling or causing injury) | 1,000,000 |
| ERPG-3 (life-threatening health effects – flammability hazard) | 5,000,000 |

### *European Chemical Agency Derived No Effect Level (DNEL)*

ECHA provides values for the Derived No Effect Level (DNEL) as the level of exposure above which a human should not be exposed to a substance. ECHA published a DNEL for the general population of 850 ppb (ECHA 2023)The few U.S. agencies' attempts to establish health-based screening values for DMS are outlined below.

### *Other Proposed Health-Based Screening Values for DMS*

Demchuk et al. (2018) calculated three distinct exposure levels for DMS, noting that current short-term exposure recommendations for DMS were limited to 1-hour exposure ERPGs developed by AIHA. To extrapolate the 1-hour ERPGs to additional exposure durations for emergency response settings, the authors developed a novel chemical-specific toxic load exponent (TLE) framework and calculated the point of departure (POD) for each tier divided by its respective total uncertainty, referenced as uncertainty factors (UF). The POD is the dose or exposure level at which a biological response is first observed and serves as a basis for making extrapolations often necessary for risk assessment purposes. The exposure levels (referred to as Tiers) developed by Demchuk et al. are described in detail below.

Similar to the ERPG tiers developed by the AIHA described above, the authors derived Tier-1 based on human exposures that resulted in a detectable odor; Tier-2 was derived using the benchmark concentration (BMC) that resulted in a 10% incidence of coma in rats exposed for 15-minutes to inhaled DMS, specifically the lower 95% confidence bound of this BMC value ($BMCL_{10}$); and Tier-3 from $BMCL_{05}$ from mortality in rats. For each tier, Demchuk et al. (2018) calculated short-term inhalation exposure levels for 10-minute, 30-minute, 1-hour, 4-hour, and 8-hour durations.

For Tier-1, Demchuk et al. (2018) calculated 600 ppb as the short-term inhalation exposure level for 10 min, 30 min, 1 h, 4 h, and 8 h exposure durations. Demchuck et al. (2018) utilized 1,900 ppb, the value reported by Katz & Talbert (1930) as an easily noticed odor after one inhalation, as the highest experimental exposure level at which no adverse effects were observed (NOAEL). From there, an uncertainty factor of 3 was applied to the 1,900 ppb concentration to account for potential differences in susceptibility within the human population to achieve a final short-term inhalation exposure level of 600 ppb.

For Tier-2, the $BMCL_{10}$ was estimated at 47,409,000 ppb and used as the point of departure for the derivation of short-term inhalation exposure levels. The datasets from Zieve et al. (1974), Ljunggren and Norberg (1943) and Schoenig (1967) were pooled to estimate the $BMCL_{10}$ (as cited by Demchuk et al., 2018). The pooled $BMCL_{10}$ was based on a POD that was slightly higher than the NOAEL for incidence of coma in rats but below the LOAEL. Short-term inhalation exposure levels were calculated as 1,800,000 ppb, 1,200,000 ppb, 1,000,000 ppb, 600,000 ppb, and 500,000 ppb for 10 min, 30 min, 1 h, 4 h, and 8 h durations, respectively. An uncertainty factor of 10 was applied for interspecies extrapolation, multiplied by an uncertainty factor of 3 for intraspecies variability, resulting in a total uncertainty factor of 30.

For Tier-3, Demchuk et al. (2018) calculated the short-term inhalation exposure levels as 4,600,000 ppb, 4,600,000 ppb, 3,800,000 ppb, 2,600,000 ppb, and 2,000,000 ppb for 10 min, 30 min, 1 h, 4 h, and 8 h durations, respectively. The $BMCL_{05}$ of 25,895,000 ppb, modeled from a 4-hour rat mortality study by Tansy et al. (1981). The POD was selected between the exposure level of 24,000,000 ppb, where all rats survived, and 36,000,000 ppb, where two out of 10 rats died. An uncertainty factor of 3 was applied for interspecies extrapolation, multiplied by an uncertainty factor of 3 for intraspecies variability, resulting in a (rounded) uncertainty factor of 10. **Table 3** summarizes all the tiered screening values for DMS across various time scales, as proposed by Demchuk et al. (2018).

**Table 3. Summary of tiered screening values for DMS developed by Demchuk et al. (2018).**

| | Exposure duration | | | | |
|---|---|---|---|---|---|
| **Tier** | **10 min** | **30 min** | **1 h** | **4 h** | **8 h** |
| Tier-1 | 600 ppb | 600 ppb | 600 ppb | 600 ppb | 600 ppb |
| Tier-2 | 1,800,000 ppb | 1,200,000 ppb | 1,000,000 ppb | 600,000 ppb | 500,000 ppb |
| Tier-3 | 4,600,000 ppb | 4,600,000 ppb | 3,800,000 ppb | 2,600,000 ppb | 2,000,000 ppb |

## Occupational Health-Based Standards for DMS

Whereas no regulatory standards have been developed by the Occupational Safety and Health Administration (OSHA) for DMS, and no recommended exposure limits have been developed by the National Institute for Occupational Safety and Health (NIOSH) or other state occupational health agencies such as California OSHA (CalOSHA), the ACGIH has established an eight-hour time-weighted average (TWA) Threshold Limit Value (TLV) for DMS of 10,000 ppb, based on upper respiratory irritation (ACGIH 2004;

Alarie, 2015). Whereas no human studies of repeated exposure exist to derive a value that is intended to be protective from daily exposures up to 8 hours per day, for 40-hour workweeks over a lifetime, ACGIH reported on animal studies of repeated exposure in which rats did not show adverse effects following oral doses of 250 mg/kg for 14 weeks, described to be equivalent to an 8-hour inhalation exposure at approximately 1,000,000 ppb DMS. ACGIH further notes:

> *"Human experience has failed to identify any particular biologic endpoint that could be related to DMS exposure; however, at least one death has been associated with accidental exposure. The limited toxicological data, the low level of acute and subchronic toxicity, the lack of genotoxicity, and the absence of effects following low-level human exposure to DMS from nonindustrial sources suggests that 10 ppm [10,000 ppb] will be protective for workers. Because ethe TLV-TWA of 10 ppm [10,000 ppb] exceeds the odor threshold, perhaps by a thousandfold, it is doubtful that this concentration can be maintained in a workplace without causing a nuisance."* (ACGIH 2004).

In Europe, ECHA established a DNEL for workers of 4,840 ppb based on a repeated dose toxicity study in rats.

## 6.0 Summary of Action Levels for DMS

Overall, a limited number of health-protective benchmarks exist from which action levels could be derived. No such action levels have been promulgated by any public health agency based on our research. However, a relative consensus exists between the ERPG-1 value of 500 ppb, the Tier-1 value of 600 ppb proposed by Demchuk et al., (2018), and the DNEL of 850 ppb proposed by ECHA. A value of 600 ppb could be considered as the basis for a short-term action level of one hour intended for the protection of community members from odor nuisance, as this would be 1/3$^{rd}$ of the concentration of 1,900 ppb reported by Katz and Talbert (1930) to be *"easily noticed"*.

The Tier-2 and Tier-3 1-hour values developed by Demchuk et al. (2018) are also fairly consistent with the ERPG-2 and ERPG-3 values of 1,000,000 and 5,000,000 ppb, and they are based on the likelihood of eye irritation and other effects that could impair escape (i.e., flammability hazard), as detailed in the basis for the ERPG-2 and ERPG-3. However, concentrations this elevated are not anticipated to occur in the community.

Whereas no health-protective screening levels have been proposed by government public health agencies for longer-term action levels (i.e., 24-hour), a mathematical approach of extrapolating the ACGIH TLV-TWA protective over 8-hours, 40-hours per week for a working lifetime, can be considered. However, because the test data from which the ACGIH TLV-TWA was derived are not based on continuous exposure, a time-scale adjustment must be applied. The TLV-TWA of 10,000 ppb would need to be divided by 4.2. This factor is derived by dividing the usual work shift of 40 hours (8 hours/day, 5 days/week) by 168 hours (continuous exposure over 24 hours/day for a week). In addition, because the general workforce is

considered to be healthier than the general population (i.e., elderly, children, etc.), an additional safety factor of 10 should be applied to account for potential differences in human susceptibility.

Thus, 10,000 / 42 = 238 ppb as a 24-hour community screening level.

This methodology is consistent with how ambient air quality guidelines have been established for toxic air contaminants in the past (Air Management Services and The Ad Hoc Advisory Committee for Toxic Air Contaminants, 1983).

## 7.0 Actions to be Taken if Action Levels are Exceeded.

As stated above no action levels for either acute or long-term exposures to DMS have been established by public health agencies. Through the comprehensive review of the scientific literature conducted, CTEH toxicologists did not identify recommended actions established by public health agencies for individuals who may be exposed to DMS for acute or long-term exposure durations. Such recommendations would need to be developed by public health agencies. Ultimately, the actions triggered by established action levels should be proportional to the risk associated with the magnitude (i.e., duration and concentration) of the potential exposure.

For example, if an action level of **600 ppb for one hour** were to be selected, consistent with Demchuk et al., 2018 Tier-1 value, and in line with ERPG-1 value of 500 ppb, and the DNEL value of 850 ppb, public health officials could consider some of the following actions:

1. Collect additional DMS-specific data to characterize the spatial and temporal aspects of DMS emissions near the area where the exceedance was measured.

2. Evaluate recent odor complaint data to potentially expand or retract the areas in which to collect spatial and/or temporal data.

3. Prepare educational materials about DMS, including information about its odor threshold relative to concentrations at which adverse health effects could be anticipated.

4. Collect additional air monitoring or sampling data for other odorous compounds (e.g., methyl mercaptan, hydrogen sulfide, dimethyl disulfide, etc.) to rule out (or rule-in) alternate sources of odor complaints.

Similarly, in the event that DMS action levels exceed **600 ppb for one hour**, public health officials may consider the following actions for recommendation to the public:

1. Close windows and doors to reduce outdoor odors.

2. Consider the use of carbon-based air filtration systems in your home.

3. Report ambient odors to local health department or air quality management agencies. Document the time and date the odors were present, along with location of the odors and whether they persisted for any period of time.

4. Request follow-up information regarding the odor(s) to assess persistence across the community.

5. Stay apprised of changing ambient conditions via official agency websites, media, or social media sources and avoid reliance solely on individual social media feeds to ensure that you get the most accurate information available.

## 8.0 Conclusion

Based on initial information gathered during the identification of a sub-surface reaction taking place at the Chiquita Canyon landfill, DMS was identified as a constituent of landfill gas that was found at proportionally higher levels than others in the mixture within the reaction area, suggesting that DMS could present an emission concern for nearby community receptors. Due to its documented odor characteristics and apparent limited toxicological information available, condition 12 (b)(v) of the September 6, 2023, "*Stipulated Order for Abatement*" required that Chiquita Canyon and/or its consultants conduct an in-depth analysis of relevant and existing toxicological information on DMS to be compiled into the present report.

Whereas this report has not identified DMS to be a likely health risk driver at ambient air levels or within the communities near the Chiquita Canyon Landfill, the compilation of existing literature and proposal of action levels based on health-protective screening levels and guidance from public health agencies around the world is a step forward in helping identify (or rule-out) constituents of potential concern that could be associated with emissions from the reaction area of the Chiquita Canyon Landfill. Additional evaluations of odorous constituents and/or hazardous pollutants found to be emitted from the Chiquita Canyon Landfill detected in the community would be valuable in helping address public health concerns associated with landfill emissions.

## References

ACGIH (American Conference of Governmental Industrial Hygienists). (2004). *Dimethyl sulfide*. https://www.acgih.org/dimethyl-sulfide/

AIHA. (2016). *Emergency Response Planning Guidelines: Dimethyl Sulfide*.

Air Management Services and The Ad Hoc Advisory Committee for Toxic Air Contaminants. (1983). *Report on Recommended Ambient Air Quality Guidelines for Toxic Air Contaminants*. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.phila.gov/media/20181031153836/AMR-VI-Guidelines.pdf

Alarie, Y. (2015). *Table 2. List of Chemicals with Threshold Limit Values (TLV) Primarily Based on Sensory Irritation.* SOT. https://www.toxicology.org/education/docs/Alarie_Table_2_2015_List_of_TLVs_for_chemicals_with_URT_irr_basis_with_no_RD50_values.pdf

ATSDR. (2018). *Minimal Risk Levels (MRLs) - For Professionals*.

ATSDR. (2023). *ATSDR's Substance Priority List*. https://www.atsdr.cdc.gov/spl/index.html

ATSDR (Agency for Toxic Substances and Disease Registry). (2017). *Are Environmental Odors Toxic?* https://www.atsdr.cdc.gov/odors/docs/Are_Environmental_Odors_Toxic_508.pdf

Bamforth, C. W. (2014). Dimethyl Sulfide – Significance, Origins, and Control1. *Journal of the American Society of Brewing Chemists*, *72*(3), 165–168. https://doi.org/10.1094/asbcj-2014-0610-01

Barelli, L., Bidini, G., Desideri, U., Discepoli, G., & Sisani, E. (2015). Dimethyl sulfide adsorption from natural gas for solid oxide fuel cell applications. *Fuel Processing Technology*, *140*, 21–31. https://doi.org/10.1016/j.fuproc.2015.08.012

Bentley, R., & Chasteen, T. G. (2004). Environmental VOSCs—formation and degradation of dimethyl sulfide, methanethiol and related materials. *Chemosphere*, *55*(3), 291–317. https://doi.org/10.1016/j.chemosphere.2003.12.017

Bracken, M. B. (2009). Why animal studies are often poor predictors of human reactions to exposure. *Journal of the Royal Society of Medicine*, *102*(3), 120–122. https://doi.org/10.1258/jrsm.2008.08k033

Butterworth, K. R., Carpanini, F. M. B., Gaunt, I. F., Hardy, J., Kiss, I. S., & Gangolli, S. D. (1975). Short-term toxicity of dimethyl sulphide in the rat. *Food and Cosmetics Toxicology*, *13*(1), 15–22. https://doi.org/10.1016/0015-6264(75)90078-4

Cameo Chemicals. (n.d.). *Dimethyl Sulfide*. Retrieved December 15, 2023, from https://cameochemicals.noaa.gov/chemical/590

Cao, X., Ding, L., Xie, Z., Yang, Y., Whiteman, M., Moore, P. K., & Bian, J.-S. (2019). A Review of Hydrogen Sulfide Synthesis, Metabolism, and Measurement: Is Modulation of Hydrogen Sulfide a Novel Therapeutic for Cancer? *Antioxidants & Redox Signaling*, *31*(1), 1–38. https://doi.org/10.1089/ars.2017.7058

Carrión, O., Pratscher, J., Curson, A. R. J., Williams, B. T., Rostant, W. G., Murrell, J. C., & Todd, J. D. (2017). Methanethiol-dependent dimethylsulfide production in soil environments. *The ISME Journal*, *11*(10), 2379–2390. https://doi.org/10.1038/ismej.2017.105

Casey, J. C., Self, R., & Swain, T. (1963). Origin of Methanol and Dimethyl Sulphide from Cooked Foods. *Nature*, *200*(4909), 885–885. https://doi.org/10.1038/200885a0

Cavender, F., Phillips, S., & Holland, M. (2008). Development of emergency response planning guidelines (ERPGs). *Journal of Medical Toxicology*, *4*(2), 127–131. https://doi.org/10.1007/bf03160967

Chemical, D. (1957). *Results of range finding toxicological tests on dimethyl sulfide*.

Chevron Phillips Chemical. (2023). *Dimethyl Sulfide*. https://www.cpchem.com/what-we-do/solutions/specialty-chemicals/products/dimethyl-sulfide

Dalton, P. (1996). Odor Perception and Beliefs about Risk. *Chemical Senses*, *21*(4), 447–458. https://doi.org/10.1093/chemse/21.4.447

Dalton, P., & Wysocki, C. J. (1996). The nature and duration of adaptation following long-term odor exposure. *Perception & Psychophysics*, *58*(5), 781–792. https://doi.org/10.3758/bf03213109

Demchuk, E., Ball, S. L., Le, S. L., & Prussia, A. J. (2018). Concentration-time extrapolation of short-term inhalation exposure levels: dimethyl sulfide, a case study using a chemical-specific toxic load exponent. *Inhalation Toxicology*, *30*(11–12), 448–462. https://doi.org/10.1080/08958378.2018.1551444

DOE. (2018). *Table 3: Protective Action Criteria (PAC) Rev. 29a based on applicable 60-minute AEGLs, ERPGs, or TEELs*. https://edms3.energy.gov/pac/docs/Revision_29A_Table3.pdf

DOE/NNSA. (n.d.). *Definition of PACs (AEGLs, ERPGs or TEELs)*. Retrieved December 17, 2023, from https://edms3.energy.gov/pac/TeelDef

Doty, R. (1989). Influence of Age and Age-Related Diseases on Olfactory Function. *Annals of the New York Academy of Sciences*, *561*(1), 76–86. https://doi.org/10.1111/j.1749-6632.1989.tb20971.x

Doty, R. L., Applebaum, S., Zusho, H., & Settle, R. G. (1985). Sex differences in odor identification ability: a cross-cultural analysis. *Neuropsychologia*, *23*, 667–672.

Doty, R. L., Shaman, P., Applebaum, S. L., Giberson, R., Siksorski, L., & Rosenberg, L. (1984). Smell Identification Ability: Changes with Age. *Science*, *226*(4681), 1441–1443. https://doi.org/10.1126/science.6505700

ECHA (European Chemicals Agency). (2023). *Dimethyl Sulphide*. https://echa.europa.eu/registration-dossier/-/registered-dossier/13649/7/3/1

GAO (2001) Chemical Risk Assessment: Selected Federal Agencies' Procedures, Assumptions, and Policies, Washington, DC: United States General Accounting Office (GAO-01-810. Available at: https://books.google.com/books?id=MfWUWX0L814C&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false.

Health Canada (Environment and Climate Change Canada/Health Canada). (2018). *Screening assessment thiols group Chemical abstracts service registry numbers 75-18-3 150-60-7 25103-58-6 71159-90-5 Environment and Climate Change Canada Health Canada* (pp. 1–27). https://www.canada.ca/en/environment-climate-change/services/evaluating-existing-substances/screening-assessment-thiols-group.html

Hoshika, Y., Imamura, T., Muto, G., J., V. G. L., Don, J. A., & Walpot, J. I. (1993). International comparison of odor threshold values of several odorants in Japan and in The Netherlands. *Environmental Research*, *61*(1), 78–83. https://doi.org/10.1006/enrs.1993.1051

Hummel, T. (2000). Perspectives in Olfactory Loss Following Viral Infections of the Upper Respiratory Tract. *Archives of Otolaryngology--Head & Neck Surgery*, *126*(6), 802–803. https://doi.org/10.1001/archotol.126.6.802

Jervøe-Storm, P.-M., Schulze, H., & Jepsen, S. (2019). A randomized cross-over short-term study on the short-term effects of a zinc-lactate containing mouthwash against oral malodour. *Journal of Breath Research*, *13*(2), 026005. https://doi.org/10.1088/1752-7163/aaf401

Kaneda, H., Maeshima, K., Goto, N., Kobayakawa, T., Ayabe-Kanamura, S., & Saito, S. (2000). Decline in taste and odor discrimination abilities with age, and relationship between gustation and olfaction. *Chemical Senses*, *25*, 331–337.

Kangas, J., Jappinen, P., & Savolainen, H. (1984). Exposure to Hydrogen Sulfide, Mercaptans and Sulfur Dioxide in Pulp Industry. *American Industrial Hygiene Association Journal*, *45*(12), 787–790. https://doi.org/10.1080/15298668491400647

Kappler, & Schäfer. (2014). Transformations of Dimethylsulfide. In Kroneck & Torres (Eds.), *The Metal-Driven Biogeochemistry of Gaseous Compounds in the Environment. Metal Ions in Life Sciences*. https://doi.org/10.1007/978-94-017-9269-1_11

Katz, S. H., & Talbert, E. J. (1930). *Intensities of odors and irritating effects of warning agents for inflammable and poisonous gases*. Bureau of Mines; Government Printing Office.

Kettle, A. J., & Andreae, M. O. (2000). Flux of dimethylsulfide from the oceans: A comparison of updated data sets and flux models. *Journal of Geophysical Research: Atmospheres*, *105*(D22), 26793–26808. https://doi.org/10.1029/2000jd900252

Kim, K.-H., Choi, Y.-J., Oh, S.-I., Sa, J. H., Jeon, E.-C., & Koo, Y. S. (2006). Short-term Distributions of Reduced Sulfur Compounds in the Ambient Air Surrounding a Large Landfill Facility. *Environmental Monitoring and Assessment*, *121*(1–3), 343–354. https://doi.org/10.1007/s10661-005-9128-y

Larsson, M., Finkel, D., & Pedersen, N. L. (2000). Odor IdentificationInfluences of Age, Gender, Cognition, and Personality. *The Journals of Gerontology: Series B*, *55*(5), P304–P310. https://doi.org/10.1093/geronb/55.5.p304

Lehrner, J. P., Brucke, T., Dal-Bianco, P., Gatterer, G., & Kryspin-Exner, I. (1997). Olfactory functions in Parkinson's disease and Alzheimer's disease. *Chemical Senses*, *22*, 105–110.

Leonardos, G., Kendall, D., & Barnard, N. (1969). Odor Threshold Determinations of 53 Odorant Chemicals. *Journal of the Air Pollution Control Association*, *19*(2), 91–95. https://doi.org/10.1080/00022470.1969.10466465

Li, D., Lu, W., Liu, Y., Guo, H., Xu, S., Ming, Z., & Wang, H. (2015). Analysis of Relative Concentration of Ethanol and Other Odorous Compounds (OCs) Emitted from the Working Surface at a Landfill in China. *PLoS ONE*, *10*(3), e0119305. https://doi.org/10.1371/journal.pone.0119305

Ljunggren, G., & Norberg, B. (1943). On the Effect and Toxicity of Dimethyl Sulfide, Dimethyl Disulfide and Methyl Mercaptan. *Acta Physiologica Scandinavica*, *5*(2-3), 248–255. https://doi.org/10.1111/j.1748-1716.1943.tb02053.x

Long, Y., Zhang, S., Fang, Y., Du, Y., Liu, W., Fang, C., & Shen, D. (2017). Dimethyl sulfide emission behavior from landfill site with air and water control. *Biodegradation*, *28*(5–6), 327–335. https://doi.org/10.1007/s10532-017-9799-4

McGorrin, R. J. (2011). Volatile Sulfur Compounds in Food. *ACS Symposium Series*, 3–31. https://doi.org/10.1021/bk-2011-1068.ch001

Mesholam, R. I., Moberg, P. J., Mahr, R. N., & Doty, R. L. (1998). Olfaction in neurodegenerative disease: a meta-analysis of olfactory functioning in Alzheimer's and Parkinson's diseases. *Archives of Neurology*, *55*, 84–90.

Michanowicz, D. R., Leventhal, O. M., Domen, J. K., Williams, S. R., Lebel, E. D., Hill, L. A. L., Buonocore, J. J., Nordgaard, C. L., Bernstein, A. S., & Shonkoff, S. B. C. (2023). Natural gas odorants: A scoping review of health effects. *Current Environmental Health Reports*, *10*(3), 337–352. https://doi.org/10.1007/s40572-023-00403-w

Murphy, C., Doty, R. L., & Duncan, H. J. (2003). Clinical disorders of olfaction. *Handbook of Olfaction and Gustation*, 461–478.

Nishida, K., Yamakawa, M., & Honda, T. (1979). Experimental investigations on the combined actions of components of mixed odorous gas. *Memoirs of the Faculty of Engineering, Kyoto University*, *41*, 552–565.

NOAA. (2023). *Protective Action Criteria for Chemicals (PACs)*. https://response.restoration.noaa.gov/oil-and-chemical-spills/chemical-spills/resources/protective-action-criteria-chemicals-pacs.html

OECD (Organisation for Economic Co-operation and Development). (2007). *SIDS Initial Assessment Report For SIAM 22 (Dimethyl sulfide)* (pp. 1–85). https://hpvchemicals.oecd.org/UI/SIDS_Details.aspx?id=51985be5-6f1c-490e-9c02-e63fe390a9f2

PubChem. (2023, December 9). *Dimethyl Sulfide*. https://pubchem.ncbi.nlm.nih.gov/compound/Dimethyl-sulfide

Rosenkranz, H. S., & Cunningham, A. R. (2003). Environmental odors and health hazards. *Science of The Total Environment*, *313*(1–3), 15–24. https://doi.org/10.1016/s0048-9697(03)00330-9

Schoenig, G. (1967). *Acute oral toxicity of dimethyl sulfide*. Industrial Bio-Test Laboratories, Inc.

Simchen, U., Koebnick, C., Hoyer, S., Issanchou, S., & Zunft, H.-J. (2006). Odour and taste sensitivity is associated with body weight and extent of misreporting of body weight. *European Journal of Clinical Nutrition*, *60*(6), 698–705. https://doi.org/10.1038/sj.ejcn.1602371

Simpson, D., Winiwarter, W., Börjesson, G., Cinderby, S., Ferreiro, A., Guenther, A., Hewitt, C. N., Janson, R., Khalil, M. A. K., Owen, S., Pierce, T. E., Puxbaum, H., Shearer, M., Skiba, U., Steinbrecher, R., Tarrasón, L., & Öquist, M. G. (1999). Inventorying emissions from nature in Europe. *Journal of Geophysical Research: Atmospheres*, *104*(D7), 8113–8152. https://doi.org/10.1029/98jd02747

Sinki, G. S., & Schlegel, W. A. F. (1990). Flavoring agents. *Food Additives*, 195-258.

Tangerman, A., Meuwese-Arends, MariaT., & Jansen, JanB. M. J. (1994). Cause and composition of foetor hepaticus. *The Lancet*, *343*(8895), 483. https://doi.org/10.1016/s0140-6736(94)92729-4

Tansy, M. F., Kendall, F. M., Fantasia, J., Landin, W. E., Oberly, R., & Sherman, W. (1981). Acute and subchronic toxicity studies of rats exposed to vapors of methyl mercaptan and other reduced-sulfur compounds. *Journal of Toxicology and Environmental Health*, *8*(1–2), 71–88. https://doi.org/10.1080/15287398109530051

Terazawa, K., Mizukami, K., Wu, B., & Takatori, T. (1991). Fatality due to inhalation of dimethyl sulfide in a confined space: A case report and animal experiments. *International Journal of Legal Medicine*, *104*(3), 141–144. https://doi.org/10.1007/bf01369718

USEPA. (1998). *Linear Low dose Extrapolation for Cancer Risk Assessments: Sources of Uncertainty and How They Affect the Precision of Risk Estimates*. U.S. Environmental Protection Agency. https://archive.epa.gov/scipoly/sap/meetings/web/pdf/session2.pdf

USEPA. (2005). *Provisional Peer Reviewed Toxicity Values for Dimethyl Sulfide: Derivation of Subchronic and Chronic Oral RfDs*. https://cfpub.epa.gov/ncea/pprtv/documents/DimethylSulfide.pdf

US FDA. (2023, November 15). *Substances Added to Food: Dimethyl Sulfide*. https://www.cfsanappsexternal.fda.gov/scripts/fdcc/index.cfm?set=FoodSubstances&id=METHYLSULFIDE

Vento, R. (1966). Sluchai otravlenia odorant-sulfanom (Incident of odorant-sulfane poisoning). *Sbornik nauchno-prakticheskih rabot sudebnyh medikov i kriminalistov (Compendium of applied and research reports of forensic physicians and criminologists)*, 129–132.

Wood, D. C., Wirth, N. V., Weber, F. S., & Palmquist, M. A. (1971). Mechanism considerations of dimethyl sulfoxide (DMSO)-lenticular changes in rabbits. *The Journal of Pharmacology and Experimental Therapeutics*, *177*(3), 528–535.

Zieve, L., Doizaki, W. M., & Zieve, J. (1974). Synergism between mercaptans and ammonia or fatty acids in the production of coma: a possible role for mercaptans in the pathogenesis of hepatic coma. *The Journal of Laboratory and Clinical Medicine*, *83*(1), 16–28.