

Review

Removal of Taste and Odor Compounds from Water: Methods, Mechanism and Prospects

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Abstract: In recent years, taste and odor (T&O) compounds in drinking water are becoming a serious problem, which has brought many challenges to drinking water treatment plants. Due to global concerns about the emergence of T&O compounds, researchers have proposed various water treatment technologies to ensure the quality of drinking water. In this paper, abiotic and biotic methods for the treatment of T&O compounds are reviewed, including process parameters, advantages and disadvantages, removal efficiency and mechanism. Geosmin (GSM) and 2-methylisoborneol (2-MIB) are the most common odorous substances with earthy and musty smells. The chemical and biological methods for the possible degradation pathways of these two compounds are summarized. Furthermore, suggestions and approaches are provided for efficient and safe strategies for T&O compound treatments and their future applications.

Keywords: taste and odor (T&O) compounds; drinking water; water treatment; removal technologies; degradation pathway



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1. Introduction

Taste and odor (T&O) compounds have become a universal problem in the water quality control of lakes due to increasing eutrophication [1]. T&O compounds are produced during the secondary metabolism of actinomycetes, algae and other living organisms, and also during the decay of aquatic plants and other organic matter [2]. There are different kinds of T&O compounds in water, such as geosmin (GSM), 2-methylisoborneol (2-MIB), 2-isopropyl-3-methoxypyrazine (IPMP), 2-isobutyl-3-methoxypyrazine (IBMP) and 2,4,6-trichloroanisole (TCA) [1–4]. Among them, GSM and 2-MIB are representative T&O compounds that are derived from the metabolism and biodegradation of certain types of cyanobacteria and actinomycetes [4]. Research has shown that from a toxicological perspective, T&O compounds in water pose no risk. However, long-term exposure to odors can have negative health effects, including emotional stress (anxiety or depression) and physical symptoms (eye irritation, headaches, respiratory problems, nausea or vomiting) [3,5]. In addition, these compounds possess a strong musty or earthy taste even at low concentrations of 10 ng/L [1,6]. T&O compounds in drinking water are direct sensory inducements causing consumer complaints, which have brought many challenges to drinking water treatment plants and have become major issues of global concern [7]. Therefore, it is necessary to explore effective treatment methods to ensure that the concentration of T&O compounds is below the odor threshold concentration (OTC) [1].

T&O compounds can be classified into four flavor categories or eight odor categories. The eight odor categories are the earthy/musty/moldy category, the grassy/hay/straw/woody category, the marshy/swampy/septic/sulfurous category, the chemical/hydrocarbon category, the fishy/rancid category, the medicinal/phenolic category, the chlorinous/bleachy category, and the fragrant/vegetable/fruity/floral category [8]. Different T&O compounds possess different physical and chemical properties. Microbial metabolism produces T&O compounds including terpenes, aldehydes, polyunsaturated fat derivatives, ethers and carotenoid derivatives [9]. However, they are a class of semivolatile substances and have a low molar mass of less than 1000 g/mol [10]. T&O compounds with very low OTC can cause taste and odor problems in drinking water [11]. Among T&O compounds, 2-MIB is a monoterpene while GSM is an irregular sesquiterpene [12]. However, they both contain a tertiary alcohol group, which makes them extremely stable and resistant to natural degradation and they have relatively low molecular weights of 182.31 g/mol and 168.28 g/mol, respectively. GSM and 2-MIB have small Henry's law constants (low volatility), are moderately soluble and hydrophobic with octanol/water partition coefficients of 3.57 and 3.31 ($\log K_{ow}$), respectively [9,10,12–17]. The physicochemical properties of T&O compounds such as IPMP, IBMP and TCA have also been described in the literature [18,19]. The presence of an unpleasant taste or odor of T&O compounds in drinking water can be an early warning that the water is contaminated. And GSM and 2-MIB, the two main T&O compounds, are both indicator compounds of possible water contamination [9].

At present, many studies have focused on the effective removal of T&O compounds from water. The removal of T&O compounds is an extremely complex problem. The treatment methods for T&O compounds are divided into three types: physical methods (conventional water treatment processes, adsorption, etc.), chemical methods (catalytic oxidation, ozonation, etc.) and biological methods (microbial degradation, biological contact oxidation, biological filter, ecological coupling, etc.) [11,20,21]. Physical and chemical technologies are widely used. However, conventional water treatment processes (coagulation, precipitation, filtration) or common oxidants such as chlorine, chlorine dioxide and $KMnO_4$ cannot effectively remove T&O compounds alone [4,21,22]. Activated carbon adsorbent is an effective removal method and has been widely used in water treatment processes. However, reducing the concentration of T&O compounds to OTC requires a large amount of activated carbon, and high costs are associated with frequent carbon renewal and regeneration [23]. In natural water, activated carbon adsorption is susceptible to natural organic matter (NOM), which leads to the decline of its adsorption capacity [22]. In order to explore more effective water treatment methods, researchers have focused on the treatment of T&O compounds using advanced oxidation processes in various water conditions [11]. Ozone oxidation and photocatalytic degradation (usually refers to UV/chlorine, UV/ H_2O_2 , UV/ TiO_2) are the most commonly used advanced oxidation processes. The reaction principle of the advanced oxidation process is to use highly active hydroxyl radicals to degrade T&O compounds [11,24]. It has many advantages, such as a fast reaction speed, no selectivity, a high removal rate and the ability to handle multiple pollutants at the same time [11,25]. However, the degradation of T&O compounds through advanced oxidation processes that include chlorination may produce chlorination by-products when chlorine is in excess and organic substances are present in the water [26]. In recent years, the biological treatment of T&O compounds has also become a research hotspot. Studies have showed that biological treatment has been used to remove pollutants from drinking water and wastewater, but unlike wastewater, the application of biological methods for drinking water is limited [24]. Biotechnology is currently recognized as the best treatment technology for T&O compounds. Compared to physical and chemical methods, biological methods have the advantages of low cost, simple operation, no toxic by-products and high efficiency [20]. Therefore, biodegradation technology has broad application prospects in drinking water treatment and may become a cost-effective method for treating T&O compounds [25]. However, biological methods have the disadvantages of long treatment cycles, difficulty in controlling pH and humidity and the inability to effectively treat high-concentration

pollutants [20]. In addition, it is also a big problem to select the right strains [20]. Membrane separation technology possessed a lot of advantages, such as higher separation efficiency, environmental friendliness, low energy consumption and simple operation [27]. Due to its priority, ceramic membrane ultrafiltration was combined ozone oxidation for the removal of 2-MIB and GSM, where the removal efficiencies reached 96% and 88%, respectively [28]. The ozone-bioactivated carbon-ultrafiltration process provided good removal of GSM and 2-MIB with the removal efficiencies of 92.2% and 92.5%, respectively [29].

This review paper summarizes the sources of T&O compounds and their impacts on health and drinking water management. The methods of removing T&O compounds from drinking water and their advantages and disadvantages are also reviewed. In addition, this paper deduces possible degradation pathways of 2-MIB and GSM.

2. Degradation of T&O Compounds Using Abiotic Methods

2.1. Physical Methods

In previous studies, there were many physical methods for removing T&O compounds, such as conventional water treatment processes and adsorption (activated carbon, graphene oxide metal doped TiO_2 , fly ash-bentonite composite adsorbent, etc.) [22,30,31]. Physical methods used for the removal of T&O compounds and the degradation effect are listed in Table 1. Activated carbon adsorption is the most widely studied method for T&O compound removal and is often used in water treatment plants. Its porous structure combines with the positively charged hydrophobic surface to create the adsorption of organic matter and many micropollutants [23]. According to the particle size, activated carbon can be divided into three types: granular activated carbon (GAC), powdered activated carbon (PAC) and super-powdered activated carbon (S-PAC) [32,33]. As shown in the table, when GAC is used alone for the removal of T&O compounds, a large amount of activated carbon is required and only 70–80% of 2-MIB or GSM can be removed [22]. It has also been reported that GAC could absorb more than 90% of IPMP or IBMP when the reaction time is slightly longer [32]. Compared to GAC, PAC has a better removal effect on T&O compounds. After coagulation of 27 mg/L polyaluminum chloride and adsorption of 20 mg/L PAC treatments, the removal efficiency of GSM and 2-MIB with the initial dose of 100 ng/L reached 80% and 60%, respectively [34]. In another study, the removal efficiency of GSM and 2-MIB with an initial dose of 100 ng/L was greater than 80% using 32.14 mg/L of C-PAC [35]. The combination of PAC and membrane filtration processes can be also an effective alternative for T&O compounds [36]. Studies have shown that the combined use of PAC adsorption and gas stripping can increase the removal efficiency of GSM to over 93% [31]. Although PAC or S-PAC has a large specific surface area and a high adsorption capacity for GSM and 2-MIB, their adsorption time is long, and it takes about one week to reach the adsorption equilibrium [37]. In addition, the particle size and concentration of natural organic matter (NOM) are higher than T&O compounds in natural water, which greatly reduces the adsorption capacity of GAC or PAC [21,22,38]. Therefore, some researchers have explored pretreatment methods for the removal of NOM followed by a combination of adsorption to remove T&O compounds [39]. Due to the long adsorption time of activated carbon, some studies have applied graphene oxide (GO) to GSM and 2-MIB adsorption. Although GO can reach adsorption equilibrium quickly, its adsorption capacity is much smaller than activated carbon [37]. In addition, some studies have used composite adsorbents to remove T&O compounds such as fly ash-bentonite and metal-doped TiO_2 nanoparticles [22,30]. Compared to activated carbon, fly ash-bentonite composite adsorbent has a lower cost; however, its removal efficiency is very low [33]. Metal-doped TiO_2 is not only less susceptible to natural organic matters but has a higher removal rate [22]. Table 1 shows that Pt- TiO_2 nanoparticles can remove 98% GSM within one hour, and Fe- TiO_2 nanoparticles also have a removal rate of more than 90% for both 2-MIB and GSM [22]. Therefore, the composite adsorbent has certain application potential in removing GSM and 2-MIB.

Table 1. Summary of physical methods for degradation of T&O compounds.

Material	Adsorbent Dose (mg/L)	Specific Surface Area (m ² /g)	Iodine Value (mg/g)	Condition	Adsorption Substrate	Initial Concentration (µg/L)	Degradation Rate	References
Granular activated carbon	160	274	--	T = 25 ± 1 °C, React Time [R.T.] = 1 h	2-MIB	0.7	73%	[22]
Granular activated carbon	160	274	--	T = 25 ± 1 °C, [R.T.] = 1 h	GSM	0.7	82%	[22]
Granular activated carbon	200	--	1046	pH = 3.0–11.0, [R.T.] < 12 h	IPMP	150	>90%	[32]
Granular activated carbon	200	--	1046	pH = 3.0–11.0, [R.T.] < 12 h	IBMP	150	>90%	[32]
Powdered activated carbon	15	1256	950	[R.T.] = 15 min	GSM	0.08	45%	[40]
Powdered activated carbon	15	1256	950	[R.T.] = 15 min	2-MIB	0.08	45%	[40]
Powdered activated carbon	15	--	1115	[R.T.] = 60 min				
Powdered activated carbon	15	--	1115	aeration flow rate of 15 L/min	2-MIB	--	74%	[31]
Powdered activated carbon	20	830–850	--	[R.T.] = 50 min	2-MIB	1	60%	[34]
Powdered activated carbon	20	830–850	--	[R.T.] = 50 min	GSM	1	80%	[34]
Powdered activated carbon	15	--	1115	[R.T.] = 30 min				
Powdered activated carbon	15	--	1115	aeration flow rate of 15 L/min	GSM	--	93%	[31]
C-powdered activated carbon	32.14	1216	--	[R.T.] = 20 min	2-MIB	0.1	>80%	[35]
C-powdered activated carbon	32.14	1216	--	[R.T.] = 20 min	GSM	0.1	>80%	[35]
Wood-powdered activated carbon	2	--	--	[R.T.] = 30 min	GSM	0.024	62.5%	[41]
Wood-powdered activated carbon	2	--	--	[R.T.] = 30 min	2-MIB	0.968	37%	[41]
Graphene oxide	100	478	--	pH = 7.4–7.5, [R.T.] = 15 min	2-MIB	1	15%	[37]
Graphene oxide	100	478	--	pH = 7.4–7.5, [R.T.] = 15 min	GSM	1	22%	[37]

Table 1. Cont.

Material	Adsorbent Dose (mg/L)	Specific Surface Area (m ² /g)	Iodine Value (mg/g)	Condition	Adsorption Substrate	Initial Concentration (μg/L)	Degradation Rate	References
Fly ash-bentonite (fly ash to bentonite ratio of 0.4:0.6)	15	63.5	--	pH = 8.0, [R.T.] = 60 min	2-MIB	0.042–0.234	59.9%	[30]
Fly ash-bentonite (fly ash to bentonite ratio of 0.4:0.6)	15	63.5	--	pH = 8.0, [R.T.] = 60 min	GSM	0.042–0.234	63.7%	[30]
Alginate-based carriers	35	--	--	[R.T.] = 24 h	GSM	1	90%	[42]
Alginate-based carriers	35	--	--	[R.T.] = 24 h	2-MIB	1	80%	[42]
Pt-TiO ₂	125	567	--	T = 25 ± 1 °C, [R.T.] = 1 h	GSM	0.7	98%	[22]
Fe-TiO ₂	125	423	--	T = 25 ± 1 °C, [R.T.] = 1 h	2-MIB	0.7	93%	[22]
Fe-TiO ₂	125	423	--	T = 25 ± 1 °C, [R.T.] = 1 h	GSM	0.7	95%	[22]

Adsorption is a basic surface phenomenon that selectively removes contaminants from aqueous solutions by attaching solutes to solid surfaces (adsorbents) [43]. During the adsorption of T&O compounds (mainly GSM and 2-MIB) by the adsorbent, hydrogen bonding, hydrophobic force and van der Waals force work together or one of them works between each T&O compound and the adsorbent [37]. Due to the hydrophobicity of GSM and 2-MIB, both activated carbon and nanoparticles may be based on hydrophobic interaction to remove T&O compounds [22]. Compared to activated carbon, nanomaterials have a larger specific surface area and more surface atoms, thus showing stronger adsorption properties [22,43]. However, if GO is used as an adsorbent, these mechanisms may work together. Studies have shown that the chemical structures of GO, GSM, and 2-MIB have oxygen-containing functional groups and hydroxyl groups, respectively, which indicates that hydrogen bond interaction may be one of the reasons that GO can adsorb these two T&O compounds [37]. In addition, since the adsorption capacity and hydrophobicity of GSM are higher than 2-MIB, many studies have found that GSM was better adsorbed by the adsorbent than 2-MIB, indicating that hydrophobicity may play a leading role in T&O removal through adsorption, and it is also affected by its own structure and other properties [37,44].

2.2. Chemical Methods

Compared to physical methods, chemical methods can degrade T&O compounds faster and have better degradation effects. However, common oxidants, such as chlorine, chlorine dioxide and KMnO_4 , are not effective in removing T&O compounds alone [1]. There are two reasons: one is that GSM and 2-MIB do not have functional groups, like double bonds, that can easily react with oxidants. The other is that GSM and 2-MIB have antioxidation tertiary alcohol structures [4]. Many studies have shown that advanced oxidation methods (AOPs) can effectively remove T&O compounds and have been widely used in drinking water treatment in recent years. However, it should be noted that AOP can lead to cell lysis and intracellular T&O release. Thus, elimination treatments for the residual oxidant and toxic by-product should be considered [9]. Coagulation-flocculation-decanting is a process that uses a coagulant or flocculant to aggregate smaller particles (e.g., microbial cells) into a larger substance and remove it by settling or floating. Coagulants were often used in the treatment of drinking water, including ferric chloride, aluminum sulfate and polymeric compounds [9]. Preoxidation can cause a reduction in algal cell stability and survival, thereby increasing the algal removal efficiency in the subsequent coagulation and filtration processes in water purification plants [45]. Therefore, preoxidation with oxidant and AOP were often used in conjunction with coagulation-flocculation-decantation to remove algal cells and odorants. Algal removal through ozone preoxidation combined with the coagulation of polyaluminium chloride and polyacrylamide increased from 43.3% to 75.5% and 80.2%, respectively, and the removal of 2-MIB approached 100% using a post-peroxide process with 2.0 mg/L of O_3 and 2.0 mg/L of H_2O_2 [46]. Preoxidation of 1 mg/L KMnO_4 , coagulation of 20–60 mg/L polyaluminum chloride and adsorption of 20 mg/L PAC were combined to treat GSM and 2-MIB, achieving 88% and 66% removal efficiency for GSM and 2-MIB, respectively [34]. In addition, a new coagulant plant–mineral composite (PMC) was developed, where coagulation process with 20 mg/L of PMC removed 94% of turbidity and 99% of algae and the concentrations of 2-MIB and GSM were reduced by 37% and 45%, respectively [47]. The results of studies on the degradation of T&O compounds by various AOPs in aqueous media are shown in Table 2. GSM and 2-MIB are the most common T&O compounds in water bodies, so many studies have focused on the removal effect of these two compounds. However, rare studies are found related to the reaction mechanism of AOPs, intermediate structure, degradation mechanism and degradation pathway of GSM and 2-MIB [11]. The removal of T&O compounds through ozonation and ozone-based AOPs (e.g., $\text{O}_3/\text{H}_2\text{O}_2$ and UV/O_3) has been investigated [48–50]. Ozone oxidation is one of the AOPs commonly used to degrade 2-MIB and GSM [11,51,52]. The removal rate of 2-MIB and GSM through ozone oxidation depends on reaction parameters,

such as the pH, ozone dose, reaction time, water quality parameters, temperature and initial concentration [52]. The main water quality parameters include NOM, alkalinity and micropollutants [51]. It has been reported that when the dose of O_3 was increased from 0.5 mg O_3 /mg DOC (dissolved organic carbon) to 2.5 mg O_3 /mg DOC, the removal efficiency of 2-MIB and GSM increased from 7% and 15% to 46% and 50%, respectively [48]. However, as the initial concentration of 2-MIB and GSM increases, the removal rate shows a downward trend. As Yuan et al. reported, when the initial concentration of 2-MIB and GSM increased from 100 ng/L to 500 ng/L, the removal rate of 2-MIB and GSM decreased from 93.6% and 97.9% to 66.4% and 72.6%, respectively [52]. GSM is more hydrophobic and volatile than 2-MIB and easily enters the gas phase from the liquid phase to react with ozone, resulting in better reaction kinetics [52–54]. Although increasing the dose of ozone could reduce the content of 2-MIB and GSM, this method resulted in the formation of bromate [48,50]. Bromate is a potential human carcinogen and poses a serious threat to human health [55]. It has been reported that long-term exposure to bromate can cause tumor development in different organs, kidney failure, hearing loss, etc. [55,56]. To overcome this dilemma, H_2O_2 , catalysts, UV and electrochemistry are combined with ozone oxidation. At the same O_3 concentration of 15.84 mg/L, 99% of GSM and 95% of 2-MIB were removed under UV radiation while 2-MIB and GSM were removed by 63% and 65.7% without UV radiation, respectively [57]. This could be mainly due to the decomposition of ozone and the production of $\bullet OH$ radicals when ozone was exposed to UV radiation [11]. However, there are many problems and shortcomings in the UV/ O_3 and H_2O_2 / O_3 treatment of T&O compounds, including a high cost, narrow application range, difficult storage and transportation and low safety [48–50]. To overcome those limitations, researchers used electrochemical methods to generate H_2O_2 on-site combined with UV for T&O removal [58]. In addition, the electro-peroxone (E-peroxone) process has been applied to water treatment, which combines electrochemistry and ozone technology to produce H_2O_2 from oxygen reduction [59,60]. Traditional ozonation can be easily upgraded to an electrochemical oxidation process, which greatly increases the generation of hydroxyl radicals [60]. Compared to traditional ozonation, the electrochemical oxidation process realizes the rapid removal of 2-MIB and GSM while also reducing the formation of bromate [48,61]. Although the E-peroxone process can significantly accelerate 2-MIB and GSM abatement, it can only moderately increase the removal efficiency when O_3 is completely decomposed in the conventional ozone oxidation process [48]. The effectiveness of 2-MIB removal by alumina (γ -AlOOH and γ -Al₂O₃) catalyzed ozonation was investigated [62]. The results showed that γ -AlOOH had no significant effect on the removal efficiency of 2-MIB with a final removal efficiency of 27.5%, which was almost close to that of ozonation alone. However, the treatment of γ -Al₂O₃-catalyzed ozonation showed 98.4% 2-MIB removal with 30 min. γ -AlOOH-catalyzed ozonation was reported to provide the TCA removal of 79.3% while only 29.1% removal was achieved with ozonation alone. In this case, the removal efficiency of 2-MIB through ozonation also did not change significantly when γ -AlOOH was applied [63]. Besides the conventional catalysts, studies could explore novel types of catalysts to treat T&O compounds. It was believed that chemical catalysts with enzyme-active center characteristics were promising due to good catalytic efficiency and stability. An adjacent metal complex of Pt^{II} was fabricated as a metal-dependent esterase mimic and it effectively catalyzed the degradation of thiophosphate pesticides [64]. The cyclic platinum compounds with ligand oximes may be used to prepare specific and reactive catalysts for the treatment of T&O compounds.

Table 2. Summary of chemical methods for degradation of T&O compounds.

Materials and Methods	Condition	Degradation Substrate	Initial Concentration ($\mu\text{g/L}$)	Degradation Rate	Possible Intermediate	References
UV (254 nm) UV fluence = 3348 mJ/cm^2	T = 25–31 °C, pH = 5.0 [R.T.] = 1 h	2-MIB	0.1	34.08%	--	[65]
UV (254 nm) UV fluence = 3348 mJ/cm^2	T = 25–31 °C, pH = 5.0 [R.T.] = 1 h	GSM	0.1	21.19%	--	[65]
UV fluence = 1200 mJ/cm^2	--	2-MIB	0.108	20%	--	[66]
UV fluence = 1200 mJ/cm^2	--	GSM	0.04	20%	--	[66]
UV (254 nm)/chlorine [chlorine] = 0.5 mg/L	T = 25 °C, pH = 7.0 [R.T.] = 1 h	2-MIB	5	100%	2-methylenebornane and 2-methyl-2-bornene	[4]
UV (254 nm)/chlorine [chlorine] = 0.5 mg/L	T = 25 °C, pH = 7.0 [R.T.] = 40 min	GSM	5	100%	1,4-dimethyl-adamantane and 1,3-dimethyl-adamantane	[4]
UV/chlorine UV = 250 mJ/cm^2 , [chlorine] = 0.5; 1.2 mg/L	pH = 5.0	2-MIB	0.06	>97%	--	[67]
UV/chlorine UV = 250 mJ/cm^2 , [chlorine] = 0.5; 1.2 mg/L	pH = 5.0	GSM	0.06	>97%	--	[67]
UV (210 nm)/chlorine, [chlorine] = 100 mg/L	T = 25 °C, pH = 7.0	IPMP	1×10^4	95.6%	--	[68]
UV-LED (275 nm)/chlorine UV-LED = 420 mJ/cm^2 [Chlorine] ₀ = 200 μM ,	T = 25 \pm 1 °C pH = 7.0 \pm 0.1	TCA	20	80%	--	[69]
UV/ H_2O_2 UV fluence = 1200 mJ/cm^2 , [H_2O_2] = 6 mg/L	--	2-MIB	0.306	65%	--	[66]
UV/ H_2O_2 UV fluence = 1200 mJ/cm^2 , [H_2O_2] = 6 mg/L	--	GSM	0.183	90%	--	[66]
UV (254 nm)/ H_2O_2 UV fluence = 3348 mJ/cm^2 , [H_2O_2] = 20 mg/L	T = 25–31 °C, pH = 5.0 [R.T.] = 1 h	2-MIB	0.1	52.1%	--	[65]
UV (254 nm)/ H_2O_2 UV fluence = 3348 mJ/cm^2 , [H_2O_2] = 20 mg/L	T = 25–31 °C, pH = 5.0 [R.T.] = 1 h	GSM	0.1	38.28%	--	[65]

Table 2. Cont.

Materials and Methods	Condition	Degradation Substrate	Initial Concentration ($\mu\text{g/L}$)	Degradation Rate	Possible Intermediate	References
UV/ H_2O_2 UV fluence = 350 mJ/cm^2 , [H_2O_2] = 6 mg/L	--	2-MIB	0.275	96.58%	--	[70]
UV/ H_2O_2 UV fluence = 600 mJ/cm^2 , [H_2O_2] = 4 mg/L	--	2-MIB	0.219	>80%	--	[6]
UV/ H_2O_2 UV fluence = 600 mJ/cm^2 , [H_2O_2] = 4 mg/L	--	GSM	0.231	> 80%	--	[6]
UV (238 nm)/persulfate $I_0/V = 1.26 \mu\text{E s}^{-1} \text{L}^{-1}$, [PDS] ₀ = 10 μM	T = 20 °C, pH = 7.0 [R.T.] = 10 min	2-MIB	40	86%	--	[71]
UV (219 nm)/persulfate $I_0/V = 1.26 \mu\text{E s}^{-1} \text{L}^{-1}$, [PDS] ₀ = 10 μM	T = 20 °C, pH = 7.0 [R.T.] = 10 min	GSM	40	94.5%	--	[71]
UV (365 nm)/ $\text{SiW}_{12}\text{O}_{40}^{4-}$ ($7 \times 10^{-4} \text{ M}$, 200 mg/L)	[R.T.] = 100 min	2-MIB	1×10^3	100%	1,2,7,7-tetramethyl-bicyclo [2.2.1]hept-2-ene and 1,7,7-trimethyl-bicyclo [2.2.1] heptan-2-one (d-camphor)	[72]
UV (365 nm)/ $\text{SiW}_{12}\text{O}_{40}^{4-}$ ($7 \times 10^{-4} \text{ M}$, 200 mg/L)	[R.T.] = 120 min	GSM	1×10^3	100%	8a-hydroxy-4a-methyl- octahydro-naphthalen-2-one and 8,8a-dimethyl-decahydro- aphthalen-1-ol	[72]
UV (365 nm)/ TiO_2 [TiO_2] = 200 mg/L	[R.T.] = 25 min	2-MIB	1×10^3	100%	1,2,7,7-tetramethyl-bicyclo [2.2.1]hept-2-ene and 1,7,7-trimethyl-bicyclo [2.2.1]heptan-2-one (d-camphor)	[72]
UV (365 nm)/ TiO_2 [TiO_2] = 200 mg/L	[R.T.] = 30 min	GSM	1×10^3	100%	8a-hydroxy-4a-methyl- octahydro-naphthalen-2-one and 8,8a-dimethyl-decahydro- naphthalen-1-ol	[72]

Table 2. Cont.

Materials and Methods	Condition	Degradation Substrate	Initial Concentration ($\mu\text{g/L}$)	Degradation Rate	Possible Intermediate	References
Simulated sunlight/ Zn-Al-La-MMO (1 g/L)	I = 10 A	2-MIB	0.2	95%	--	[73]
UV/TiO ₂ I = 600 W/m ² , [TiO ₂] = 100 mg/L	[R.T.] = 20 min	IPMP	1×10^4	95%	--	[3]
UV (365 nm)/ TiO ₂ /PAC = 3 mg/L	T = 20 \pm 1 $^{\circ}\text{C}$, pH = 7.5 [R.T.] = 3 h	2-MIB	1	97.8%	--	[74]
UV (254 nm)/NaCl [NaCl] = 60 mmol/L I = 15 mA/cm ²	T = 25 $^{\circ}\text{C}$, pH = 7.0 [R.T.] = 25 min	2-MIB	1	95%	--	[75]
UV (254 nm)/NaCl [NaCl] = 60 mmol/L I = 15 mA/cm ²	T = 25 $^{\circ}\text{C}$, pH = 7.0 [R.T.] = 25 min	GSM	1	96%	--	[75]
Photo-Fenton UV fluence = 3348 mJ/cm ² , [Fe ²⁺] = 2 mg/L, [H ₂ O ₂] = 20 mg/L	T = 25–31 $^{\circ}\text{C}$, pH = 5.0 [R.T.] = 1 h	GSM	0.1	48.38%	nonanoic acid and butyl butyrate (or isobutyl isobutyrate)	[65]
Photo-Fenton UV (365 nm)/rGOF, [rGOF] = 1 g/L	T = 25–31 $^{\circ}\text{C}$, pH = 3.0 [R.T.] = 3 h	2-MIB	5	99%	nonanoic acid and butyl butyrate (or isobutyl isobutyrate) from GSM	[45]
[O ₃] = 0.5–2.5 mg O ₃ /mg DOC	T = 23 \pm 1 $^{\circ}\text{C}$ pH = 7.9–8.1, [R.T.] = 40 min.	2-MIB	10	7–46%	--	[48]
[O ₃] = 0.5–2.5 mg O ₃ /mg DOC	T = 23 \pm 1 $^{\circ}\text{C}$ pH = 7.9–8.1 [R.T.] = 40 min.	GSM	10	14–50%	--	[48]
[O ₃] = 2 mg O ₃ /mg DOC (E-preoxoen)	T = 23 \pm 1 $^{\circ}\text{C}$, pH = 7.9–8.1 I = 40 mA, [R.T.] = 5 min	2-MIB	10	48%	--	[48]
[O ₃] = 2 mg O ₃ /mg DOC (E-preoxoen)	pH = 7.9–8.1, I = 40 mA, [R.T.] = 5 min	GSM	10	54%	--	[48]

Table 2. Cont.

Materials and Methods	Condition	Degradation Substrate	Initial Concentration ($\mu\text{g/L}$)	Degradation Rate	Possible Intermediate	References
$[\text{O}_3]_0 = 2.2 \text{ mg/L}$	pH = 7.0 [R.T.] = 30 min	2-MIB	1	31%	--	[52]
$[\text{O}_3]_0 = 2.2 \text{ mg/L}$	pH = 7.0 [R.T.] = 30 min	TCA	1	49%	--	[52]
$[\text{O}_3] = 4.19 \text{ mg/L}$	T = $25 \pm 1 \text{ }^\circ\text{C}$, pH = 7.3 [R.T.] = 20 min	2-MIB	0.1	93.6%	2-methylenebornane and 2-methyl-2-bornene	[53]
$[\text{O}_3] = 4.19 \text{ mg/L}$	T = $25 \pm 1 \text{ }^\circ\text{C}$, pH = 7.3 [R.T.] = 20 min	2-MIB	0.5	66.4%	--	[53]
$[\text{O}_3] = 4.19 \text{ mg/L}$	T = $25 \pm 1 \text{ }^\circ\text{C}$, pH = 7.3 [R.T.] = 20 min	GSM	0.1	97.9%	cis-1,4- dimethyladamantane and 1,3-dimethyl-adamantane	[53]
$[\text{O}_3] = 4.19 \text{ mg/L}$	T = $25 \pm 1 \text{ }^\circ\text{C}$, pH = 7.3 [R.T.] = 20 min	GSM	0.5	72.6%	--	[53]
UV = 250 mJ/cm^2 $[\text{O}_3]_0 = 15.84 \text{ mg/L}$	--	GSM	--	99%	--	[57]
UV = 250 mJ/cm^2 $[\text{O}_3]_0 = 15.84 \text{ mg/L}$	--	2-MIB	--	95%	--	[57]
$[\text{O}_3]_0 = 0.5 \text{ mg/L}$ [γ -AlOOH] = 500 mg/L	pH = 7.05 [R.T.] = 10 min	IPMP	38	94.2%	--	[76]
$[\text{O}_3]_0 = 0.5 \text{ mg/L}$ [γ -AlOOH] = 200 mg/L	T = $25 \text{ }^\circ\text{C}$, pH = 6.7	TCA	23.2	79.3%	--	[63]
$[\text{O}_3]_0 = 0.5 \text{ mg/L}$ [γ -AlOOH] = 200 mg/L	T = $25 \text{ }^\circ\text{C}$, pH = 6.7	2-MIB	23.2	27.5%	--	[63]
$[\text{O}_3]_0 = 0.5 \text{ mg/L}$ [γ -Al ₂ O ₃] = 200 mg/L	T = $25 \pm 2 \text{ }^\circ\text{C}$, pH = 6.7, [R.T.] = 30 min	2-MIB	23.2	98.4%	--	[62]
[K ₂ FeO ₄] = 50 mg/L	pH = 9.0	2-MIB	--	31.9%	--	[77]
[K ₂ FeO ₄] = 50 mg/L	pH = 9.0	GSM	--	22.5%	--	[77]
peroxide/Fe ²⁺ -based Fe ²⁺ = 0.1 mmol/L, Peroxide = 0.05 mmol/L	pH = 6.5	TCA	10	77.9%	--	[78]
Fenton [Fe ²⁺] = 2 mg/L, [H ₂ O ₂] = 20 mg/L	T = 25–31 $^\circ\text{C}$, pH = 5.0 [R.T.] = 1 h	2-MIB	0.1	16%	--	[65]

Table 2. Cont.

Materials and Methods	Condition	Degradation Substrate	Initial Concentration ($\mu\text{g/L}$)	Degradation Rate	Possible Intermediate	References
Fenton [Fe ²⁺] = 2 mg/L, [H ₂ O ₂] = 20 mg/L	T = 25–31 °C, pH = 5.0 [R.T.] = 1 h	GSM	0.1	17%	--	[65]
Ultrasound (640 kHz)	T = 4 °C [R.T.] = 40 min	2-MIB	10	>90%	2-methylenebornane and 2-methyl-2-bornene	[54]
Ultrasound (640 kHz)	T = 4 °C [R.T.] = 40 min	GSM	10	>90%	(1S, 4aR)-1, 4a-dimethyl-1, 2, 3, 4, 4a, 5, 6, 7-octahydronaphthalene and (R)-4a, 8-dimethyl-1, 2, 3, 4, 4a, 5, 6, 7-octahydronaphthalene	[54]

Photocatalytic degradation (usually refers to UV/chlorine, UV/H₂O₂, UV/TiO₂) is also one of most common AOPs. Among various photocatalytic degradation technologies, the combined use of UV and H₂O₂ is one of the most widely studied methods. UV/H₂O₂ has mild reaction conditions and can eventually mineralize organic matter into water, carbon dioxide and inorganic salts without other by-products [70]. However, in the actual process of treating water, the reaction is easily affected by water quality parameters such as total organic carbon (TOC), alkalinity and nitrate, which leads to the reduction of degradation efficiency [6]. In addition, another problem is the photolysis of nitrate to form nitrite during the UV treatment, which is harmful to human health [6]. To reduce the utilization dose of UV, the combination of UV and electrochemistry was studied and it greatly improved the removal efficiency of T&O compounds, resulting in a 95% removal efficiency for both 2-MIB and GSM [75]. Some studies show that the UV/chlorine method is more economical and effective than the UV/H₂O₂ method, and one of the reasons is that residual chlorine can be used as a secondary disinfectant [4]. In addition, the survival of H₂O₂ in the application occurred due to the different light absorption coefficients, and the removal of H₂O₂ increased the overall cost as well as the lower scavenging of •OH by HOCl [26]. In the UV/chlorine reaction, GSM and 2-MIB can be completely removed within one hour, and the degradation efficiency of GSM is higher due to its smaller steric hindrance [4]. Similarly, the process is effective for the removal of IPMP in both ultrapure water and drinking water, with a removal efficiency of 95.6% [68]. However, it might produce chlorination by-products. For example, chloroform is an intermediate of GSM and 2-MIB that which is found in the UV/chlorine reaction [4]. In addition, photocatalytic technology using TiO₂ as the catalyst has been proven to have a good effect in degrading T&O compounds in recent years. Among them, the photocatalytic removal of 2-MIB and GSM has been reported, as well as IPMP [67,72]. In addition, the effectiveness of using UV/chlorine and UV/H₂O₂ to remove IPMP, IBMP and TCA was compared [79]. Studies have shown that the UV/TiO₂ method can completely remove GSM and 2-MIB in 30 min. Moreover, the removal rate of IPMP is more than 95% and no by-products are generated in the process [67,72]. Apart from the above three most common photocatalytic processes, polyoxometalates (POM) and persulfates could also be used as the catalyst for the photocatalytic degradation of 2-MIB and GSM [3,67]. It is worth mentioning that POM has similar functions to TiO₂ and is a highly efficient photocatalyst that can degrade and mineralize many organic pollutants [67]. Studies have shown that POM can completely degrade GSM and 2-MIB into carbon dioxide, water and inorganic anions under the action of UV [67]. Therefore, photocatalytic removal of T&O compounds has wide application prospects in water treatment processes.

According to the different ways of generating •OH radicals and reaction conditions, the advanced oxidation processes used for the treatment of odor substances also include heterogeneous photocatalysis, ultra-sonication, Fenton (Fe²⁺/H₂O₂) and photo-Fenton process [45,54,65,68]. Park et al. compared the removal of GSM and 2-MIB through various oxidation processes (UV, UV/H₂O₂, Fenton and photo-Fenton) [65]. Research shows that 21.19% of GSM and 34.08% of 2-MIB are removed, respectively, in the process of using UV [65]. Similarly, the research of Jo et al. showed that about 20% of GSM and 2-MIB was degraded by the UV process [66]. This means that GSM and 2-MIB can be directly degraded by the UV process; however, it is not an effective method. H₂O₂ can be added into the UV process to become UV/H₂O₂ process, and Fe²⁺ can be added into the UV/H₂O₂ process to transform into the photo-Fenton process. The results showed that the addition of H₂O₂ can increase the degradation efficiency of GSM and 2-MIB. On the basis of the UV/H₂O₂ process, the addition of Fe²⁺ further improved the degradation efficiency [65]. However, the Fenton process was the least effective method due to it producing the least hydroxyl radicals [65]. In recent years, many researchers have made efforts to prepare new photocatalytic materials, which were applied to the treatment of T&O compounds to provide an effective method for removing T&O compounds. Moztahida et al. prepared a heterogeneous catalyst material (reduced graphene oxide supported magnetite—rGOF)

similar to the Fenton system for photocatalytic degradation of 2-MIB, with a degradation efficiency of 99% [45]. TiO₂/PAC was fabricated by loading TiO₂ nanoparticles on the surface of PAC, and its degradation efficiency of 2-MIB reached 97.8% in combination with UV [74]. Ultrasonication is also an advanced oxidation process used to induce the degradation of T&O compounds. Song et al. reported the ultrasonic-induced degradation of 2-MIB and GSM for the first time [54]. The research showed that the degradation efficiency of these two compounds was above 90% after 40 min of ultrasonic irradiation [54]. However, it is difficult to control the conditions of the ultrasonic reaction, and the processing equipment is complicated, expensive and difficult for large-scale applications.

2.3. Degradation Pathway Using Chemical Methods

Some studies have identified the intermediates in the degradation process of 2-MIB and GSM by using gas chromatography-mass spectrometry (GC-MS) [24,50]. The degradation pathways of 2-MIB and GSM under different processes are shown in Figures 1 and 2, respectively, in which a number of reactions took place, such as dehydration, ring opening and bond scission. Degradation of 2-MIB and GSM using different methods could lead to different intermediates. Figure 1 shows the formation and decay of various degradation products of 2-MIB during photocatalysis or ozonation. Among them, 2-MIB is dehydrated to form 2-Methyl-2-bornene and 2-Methylenebornane in the process of ozonation and UV/chlorine and 1,2,7,7-Tetramethyl-bicyclo [2.2.1]hept-2-ene in the process of UV/TiO₂ or UV/SiW₁₂O₄₀⁴⁻ [4,52,72]. The UV/H₂O₂ process generated similar intermediates in 2-MIB degradation as those in UV/chlorine [80]. At the same time, 2-MIB generates primary degradation products such as alcohols, alkenes and ketones through demethylation, ring opening, bond breaking and other reactions [4,52,72]. Finally, chloroform is produced as a by-product during the UV/chlorine process [4]. Similarly to the 2-MIB degradation process, GSM also dehydrates first, and its dehydration products include 1,4-Dimethyladamantane, 8a-Hydroxy-4a-methyl-octahydro-naphthalen-2-one, 1,3-Dimethyl-Adamantane, 8,8a-Dimethyl-decahydro-naphthalen-1-ol, etc. [4,52,72]. Then GSM or the primary degradation products of GSM are further degraded by ring opening, bond breaking, rearrangement, hydroxylation, etc. [4,52,72]. Tan et al., identified and compared the transformation products of GSM under four UV-based AOPs in phosphate-buffered saline (PBS) and demonstrated that their degradation intermediates were partially identical [81].

In conclusion, the intermediates of 2-MIB are composed of its alcohols, ketone and diketone derivatives, ring compounds and open-chain aliphatic compounds [72]. The intermediates of GSM are composed of cyclic ketone, which leads to the generation of linear saturation and unsaturated products when the ring is opened [72]. Although the intermediates produced after the degradation of 2-MIB and GSM are quite different, the mechanisms of degradation are almost the same through different processes. Their possible mechanisms of degradation are dehydration, ring opening and bond breaking, followed by hydroxylation from •OH radical attack and the formation of ketones [72]. Finally, the cyclic ketone can be further decomposed through a ring-opening reaction. Among them, hydroxyl radical plays an important role in the degradation mechanism [72]. This conclusion has been proven by experiments in the literature. It was mentioned in the literature that the addition of •OH radical scavengers delayed the ozonation or photodegradation rate of these two compounds, indicating that the degradation mechanism was caused by •OH radical [60,82]. In addition, the presence of most oxygen-containing degradation products suggests that the mechanism involved in the production of most intermediates is indeed hydroxyl radical oxidation, driven by electrophilic substitution reactions [72].

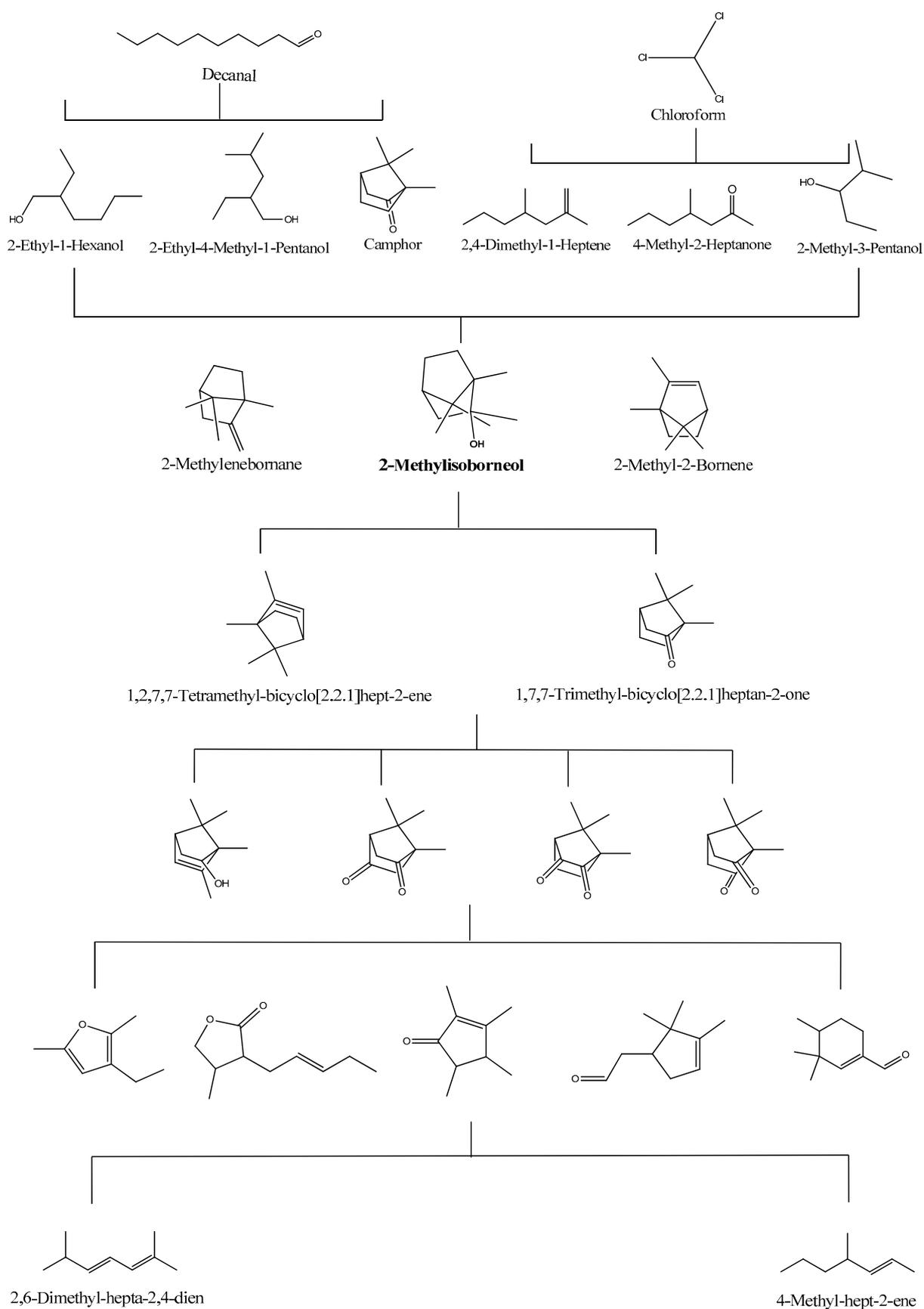


Figure 1. Proposed degradation pathway of 2-MIB [4,52,65,72].

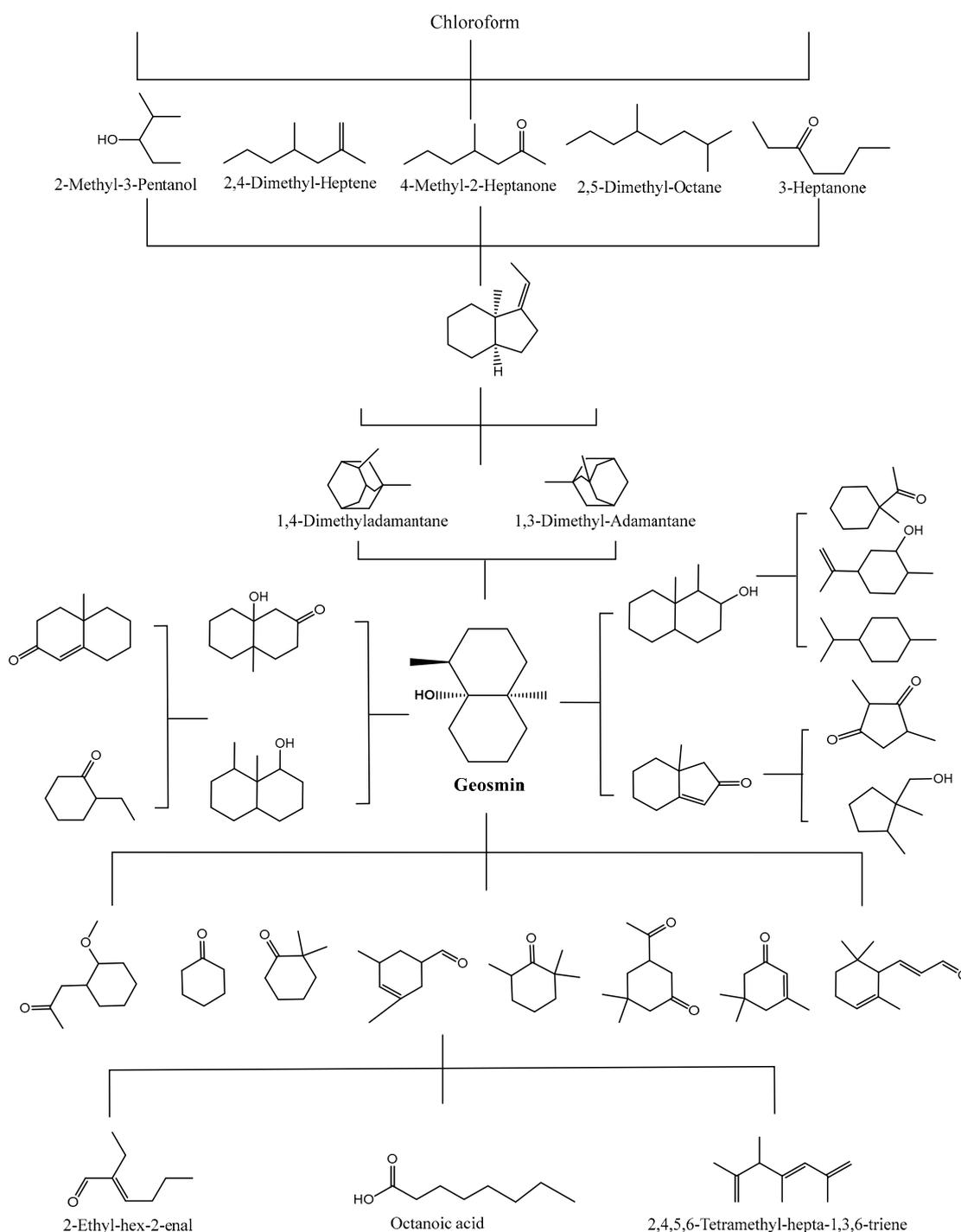


Figure 2. Possible degradation pathway of GSM [4,52,72].

3. Degradation of T&O Compounds by Biological Methods

3.1. Degradation Efficiency of Microorganisms

In recent years, microbial degradation of T&O compounds has become a research hotspot and is widely used in drinking water or wastewater treatment [24]. Compared to physical and chemical methods, a prominent advantage of microbiological methods is that the biological treatment process can be carried out at normal temperature and pressure [20]. The biological treatment process does not require the use of any chemical substances, which is more environmentally friendly [20]. In addition, the degradation process of microorganisms is essentially a general oxidation process, and it seldom produces

complex metabolites [20]. It usually causes mineralization to produce carbon dioxide, water, sulfate and nitrate compounds during the degradation process [20,25]. However, the treatment cycle of the microbiological method is long and it is difficult to control the pH and temperature throughout the treatment process [20,25]. When treated with high concentrations of contaminants, the degradation efficiency of the microorganisms is low [20]. Therefore, it is very important to screen the appropriate strains and optimize the degradation conditions for the efficient degradation of microbial methods.

The microorganism (mainly bacteria and fungi) culture for T&O compound degradation was isolated from nature (e.g., water, soil) through an enrichment technique [82]. Some identified microorganisms have been proven to be effective in degrading T&O compounds (mainly 2-MIB and GSM). Different microorganisms degrading T&O compounds in aqueous solution are shown in Table 3. Taking bacteria for example, odor compounds can be used as the only carbon and energy sources for enrichment and separation of bacteria. The most extensively studied bacteria belong to *Pseudomonas* and *Bacillus* [83]. As shown in Table 3, it takes 25 days for *Pseudomonas* spp. to degrade more than 85% of 2-MIB [84]. In contrast, *Bacillus* has better degradation efficiency. Research has shown that *Bacillus idriensis*, *Bacillus fusiformis* and *Bacillus sphaericus* can almost completely degrade 2-MIB [82,85]. In addition, *Bacillus subtilis* can degrade more than 90% of 2-MIB and GSM within 7 days [86]. Besides the above two genera, Bacteroidetes and α -Proteobacteria strains with the degradation ability of MIB and GSM have also been reported [13]. Although the removal rate of T&O compounds using these bacteria is high, the reaction time is very long.

Table 3. Summary of the literature on biodegradation taste and odor compounds.

Strain	Degradation Substrate	Initial Concentration ($\mu\text{g/L}$)	Period	Degradation Rate	Possible Intermediate	Reference
<i>Rhodococcus ruber</i>	2-MIB	27.8	16 h	--	3-hydroxy-2-MIB	[22]
<i>Pseudomonas putida</i>	2-MIB	3.6	20 h	--	6-hydroxy-2-MIB	[22]
<i>Rhodococcus wratislaviensis</i>	2-MIB	2.5	20 h	--	5-keto-2-MIB	[22]
<i>Bacillus idriensis</i>	2-MIB	2×10^6	20 d	99.98%	--	[82]
Chitinophagaceae bacterium	2-MIB	2×10^6	20 d	99.99%	--	[82]
<i>Bacillus</i> sp.	2-MIB	5×10^6	72 h	60%	---	[87]
<i>Pseudomonas</i> sp.	2-MIB	---	---	---	2-methylcampbene and 2-methylenebornane	[88]
<i>Enterobacter</i> sp.	2-MIB	---	---	---	Camphor 4,7,7-trimethyl-2-oxabicyclo [1,2,2]-heptan-3-one	[88]
<i>Acinetobacter</i>	3-methylindole	2×10^8	6 d	>85%	---	[89]
<i>Bacillus subtilis</i>	2-MIB	0.7	7 d	98%	--	[86]
<i>Bacillus subtilis</i>	GSM	1	7 d	94%	--	[86]
<i>Shinella zoologeoidea</i>	2-MIB	2	3 d	23.3%	--	[82]
<i>Bacillus idriensis</i>	2-MIB	2	3 d	32.9%	--	[82]
Chitinophagaceae bacterium	2-MIB	2	3 d	17%	--	[82]
<i>Micrococcus</i> spp.	2-MIB	4.2×10^6	25 d	86.1%	2-methylborane and 2-methyl-2-borane	[84]
<i>Flavobacterium</i> spp.	2-MIB	4.2×10^6	25 d	84.4%	2-methylborane and 2-methyl-2-borane	[84]
<i>Brevibacterium</i> spp.	2-MIB	4.2×10^6	25 d	86.7%	2-methylborane and 2-methyl-2-borane	[84]
<i>Pseudomonas</i> spp.	2-MIB	4.2×10^6	25 d	86.0%	2-methylborane and 2-methyl-2-borane	[84]
<i>Bacillus fusiformis</i>	2-MIB	5×10^3	72 h	100%	--	[85]
<i>Bacillus sphaericus</i>	2-MIB	5×10^3	72 h	100%	--	[85]
<i>Rhodococcus</i>	2-MIB	6	7 d	--	--	[90]
Comamonadaceae	2-MIB	6	7 d	--	--	[90]
<i>Chryseobacterium</i> sp.	2-MIB	2×10^3	18 d	84.0%	--	[90]
<i>Sinorhizobium</i> sp.	2-MIB	2×10^3	18 d	80.2%	--	[90]
<i>Stenotrophomonas</i> sp.	2-MIB	2×10^3	18 d	74.4%	--	[90]
<i>Methylobacterium</i> sp.	2-MIB	2.5	6 d	90%	--	[87]
<i>Trametes hirsuta</i>	2,6-dibromophenol	---	---	52%	---	[91]
<i>Novosphingobium hassiacum</i>	GSM	--	--	--	--	[13]
<i>Sphingomonas oligophenolica</i>	GSM	--	--	--	--	[13]

Compared to bacteria, there are few studies on the degradation of T&O compounds using fungi. Fungi can effectively remove hydrophobic volatile organic compounds (VOCs) in a biological filter [92]. Therefore, it can be putative that fungi have the potential to degrade T&O compounds. Fungi contain filamentous structures with aerial hyphae and a large surface area, which makes it easy to absorb many VOCs from the gas phase [93]. Meanwhile, their resistance to low humidity favors the mass transfer of hydrophobic VOCs from the gas phase to their surface [93]. In comparison to bacteria, other advantages of fungi include tolerance to low pH and starvation [94]. Various studies indicate that fungi can not only improve the removal ability of biological filters but also enhance the resistance to the environment [92]. However, compared to aerobic bacteria, the fungal metabolic rate is lower and the start-up periods are much longer [95,96]. In addition, their filamentous structures often lead to clogging in biofilters [83].

Besides the screening for new strains of bacteria and fungi, biofiltration, membrane bioreactor (MBR) and moving-bed biofilm reactor (MBBR) have been studied for the removal of T&O compounds. The removal efficiency of 2-MIB and GSM remained more than 90% throughout the 7-month treatment with the filtration with GAC filter [97]. Biofiltration could also be combined with ozonation, where biofiltration removed the by-products and the remaining T&O compounds after ozonation treatment [98]. In the O₃/GAC-biofiltration pilot test, the concentrations of GSM and 2-MIB in water were reduced from 200 ng/L to 0.1 ng/L and 3.85 ng/L, respectively [99]. The performance of biofiltration was improved by inoculating GSM-degrading bacteria to sand filters, resulting in 75% of GSM removal efficiency [100]. By adding biopowdered activated carbon to an immersed ultrafiltration membrane bioreactor (UF-BPAC), the application of MBR intensified the conventional treatment in the removal of T&O compounds, where the average post-treatment concentrations for both 2-MIB and GSM were less than 10 ng/L [101]. A steady-state T&O removal was achieved in the MBBR after 3.5 months of operation, providing 84% and 87% removal of GSM and 2-MIB, respectively [102]. Genetic engineering can also be a potential method to improve the degradation ability of microorganisms. The gene related to camphor degradation from camphor-degrading bacteria was recombinant expressed in *Escherichia coli*, and thus the resulting *E. coli* strain exhibited the ability to degrade 2-MIB [88]. In addition, the development of biologics and targeted modifications to alter the catalytic properties of enzymes may also be promising approaches for the removal of T&O compounds. The solution of hexahistidine-tagged organophosphorus hydrolase (His₆-OPH) was mixed with polyanion to obtain enzyme-polyelectrolyte complexes (EPC) for the detoxification of organophosphorus pesticides, and it provided good detoxification efficiency [103]. Lyagin and Efremenko modeled the structure of EPCs based on His₆-OPH with different biopolymers using molecular docking techniques and the obtained EPCs exhibited 20–40% higher catalytic efficiency in the hydrolysis of organophosphate esters than that of natural His₆-OPH [104].

3.2. Degradation Pathway Using Biological Methods

The possible degradation pathways of 2-MIB under bacterial conditions are shown in Figure 3, during which oxidation and dehydrogenation reactions mainly occurred. Studies have shown that the reason for microbial degradation of 2-MIB and GSM can be attributed to their structure being similar to degradable alicyclic alcohols and ketones [88]. Among them, the structure of 2-MIB is similar to camphor. Therefore, some researchers use bacteria that can degrade camphor to degrade 2-MIB. Researchers have proved that these bacteria can hydroxylate 2-MIB on the three secondary carbons of the six-membered ring and further oxidize them [105,106]. In addition, 2-methylcamphene and 2-methylenebornane were also identified as possible degradation intermediates in the process of bacterial degradation of 2-MIB [105,107]. Compared to the biodegradation of 2-MIB, GSM has been found to be extremely difficult to degrade using microorganisms [108]. The biodegradation of GSM may be similar to cyclohexanol but its degradation pathway has not been clearly

proposed. Saito et al. found that GSM can be degraded into 1, 4a-dimethyl-2, 3, 4, 4a, 5, 6, 7, 8-octahydronaphthalene and a kind of enone [108].

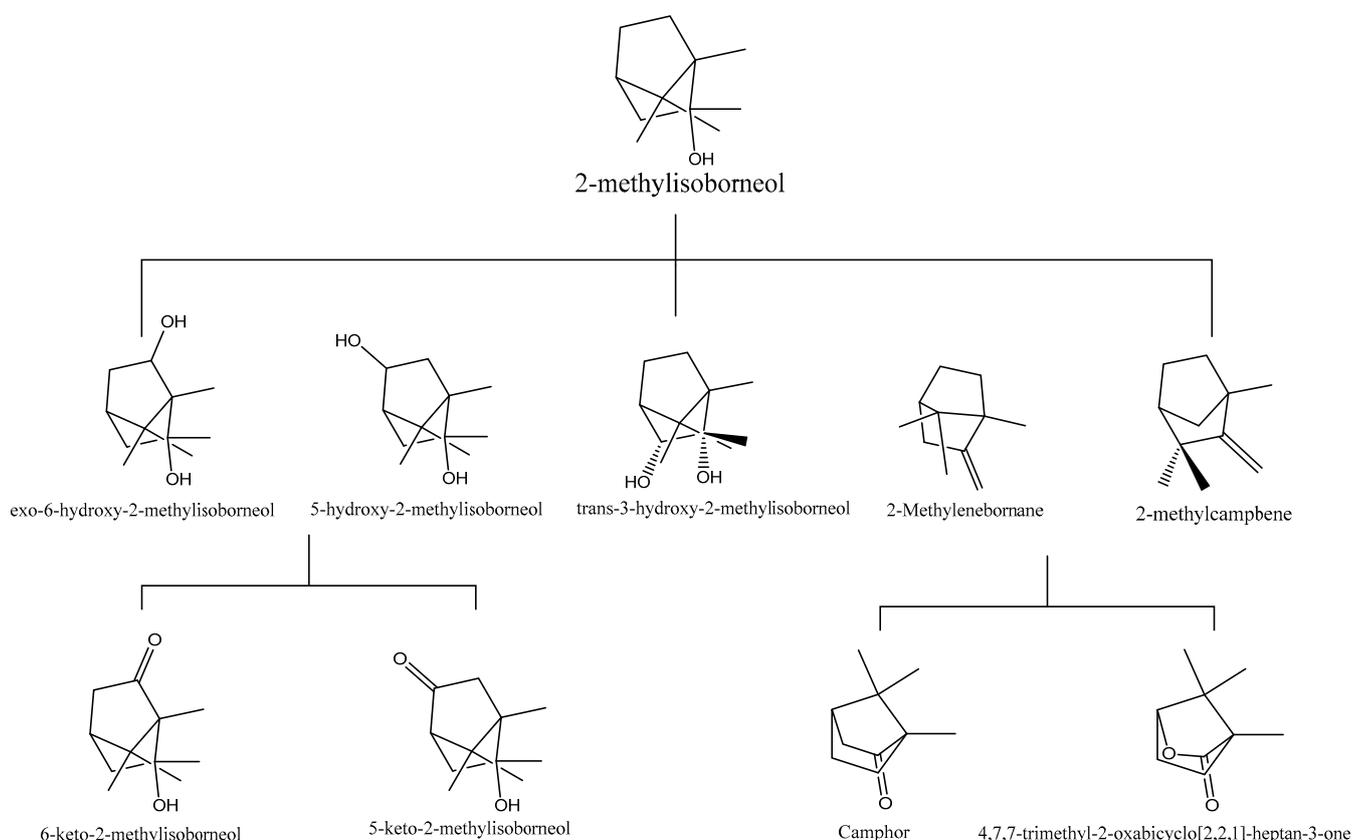


Figure 3. Proposed degradation pathway of 2-MIB using biological methods [105,107].

4. Conclusions and Prospects

Physical methods, mainly referring to adsorption, have the advantages of low investment cost, high removal efficiency and flexibility. However, the adsorption capacity of the adsorbent was limited and could be easily affected by the other organic substances in water. In fact, adsorption was a process for the enrichment of T&O compounds without any transformation. Therefore, how to deal with the T&O compounds in the adsorbent is still a problem. The screen of low-cost and biodegradable adsorbent can be an alternative way to solve this problem. For example, the agricultural lignocellulosic materials possessed good potential for the removal of T&O compounds due to their high porosity and abundant functional groups on the surface. Following adsorption using these materials, microbial degradation or thermal incineration of the adsorbents enriched with T&O compounds could be applied to transform the T&O compounds into nontoxic compounds or energy. Biofiltration with adsorbent possessed good potential in the removal of T&O compounds, where adsorption and biodegradation occurred simultaneously. In addition, the development of novel materials with high adsorption capacity and easy regeneration is also another direction for the treatment of T&O compounds.

Chemical methods can also provide high degradation efficiency. The advanced oxidation process has been proven to be the most promising way. However, the oxidant residues and the toxicity and accumulation of degradation products are the main problems. To solve these problems, photocatalytic-biodegradation (e.g., UV) is an attractive treatment technology for the complete mineralization of T&O compounds. However, the application of UV on a large scale is still difficult due to the energy cost of UV supply and the lack of suitable equipment. Recently, polymer semiconductors are regarded as a new kind of nonmetallic photocatalytic material, which has a wider absorption spectrum and can also

play a photocatalytic role under visible light. Therefore, photocatalytic degradation under visible light using semiconductors can be a potential chemical method in T&O degradation with good prospects.

Biological degradation of pollutants has been a hot research topic in recent years due to the biodegradation being environmentally friendly, capable of completely degrading T&O compounds and being able to be carried out at room temperature and normal pressure. Thus, screening of bacteria and fungi capable of efficiently degrading T&O compounds can be a promising research direction in T&O biodegradation. Moreover, the application of a membrane bioreactor can improve the efficiency of T&O degradation through the combination of microorganisms. In fact, the information on degradation pathways using microbes was limited and the enzymes involved in the degradation could be isolated and characterized. After obtaining this information, genetic engineering and synthetic biology can be applied to construct a new strain with high degradation efficiency. Enzyme degradation of T&O compounds is also a potential method. However, exploring a specific enzyme with high catalytic efficiency is essential for this method. For this purpose, biologics and targeted modifications of enzyme can be an efficient strategy. In addition, the combination of enzymes and other chemical catalysts can be an alternative way to completely degrade T&O compounds into nontoxic compounds.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviation	Term
T&O	Taste and odor
GSM	Geosmin
2-MIB	2-methylisoborneol
IBMP	2-isobutyl-3-methoxypyrazine
IPMP	2-isopropyl-3-methoxypyrazine
TCA	2,4,6-trichloroanisole
OTC	Odor threshold concentration
NOM	Natural organic matter
GAC	Granular activated carbon
PAC	Powdered activated carbon
S-PAC	Super-powdered activated carbon
GO	Graphene oxide
[R.T.]	React time
AOPs	Advanced oxidation methods
PMC	Plant-mineral composite
DOC	Dissolved organic carbon
E-peroxone	Electro-peroxone
TOC	Total organic carbon
POM	Polyoxometalates
rGOF	Reduced graphene oxide supported magnetite
GC-MS	Gas chromatography-mass spectrometry
PBS	Phosphate-buffered saline
VOCs	Volatile organic compounds

UF-BPAC	Ultrafiltration membrane bioreactor
MBR	Membrane bioreactor
MBBR	Moving-bed biofilm reactor
EPCs	Enzyme–polyelectrolyte complexes
His ₆ -OPH	Hexahistidine-tagged organophosphorus hydrolase

References

- Zhang, R.; Qi, F.; Liu, C.; Zhang, Y.; Wang, Y.; Song, Z.; Kumirska, J.; Sun, D. Cyanobacteria derived taste and odor characteristics in various lakes in China: Songhua Lake, Chaohu Lake and Taihu Lake. *Ecotoxicol. Environ. Saf.* **2019**, *181*, 499–507. [\[CrossRef\]](#)
- Yu, C.; Shi, C.; Tang, J.; Ji, Q.; Wang, X.; Xu, X.; Wang, G. Release of taste and odour compounds during *Zizania latifolia* decay: A microcosm system study. *Environ. Pollut.* **2019**, *254*, 112954. [\[CrossRef\]](#)
- Antonopoulou, M.; Konstantinou, I. TiO₂ photocatalysis of 2-isopropyl-3-methoxy pyrazine taste and odor compound in aqueous phase: Kinetics, degradation pathways and toxicity evaluation. *Catal. Today* **2015**, *240*, 22–29. [\[CrossRef\]](#)
- Kim, T.K.; Moon, B.R.; Kim, T.; Kim, M.K.; Zoh, K.D. Degradation mechanisms of geosmin and 2-MIB during UV photolysis and UV/chlorine reactions. *Chemosphere* **2016**, *162*, 157–164. [\[CrossRef\]](#)
- Zhang, T.; Zheng, L.; Li, L.; Song, L. 2-Methylisoborneol production characteristics of *Pseudanabaena* sp. FACHB 1277 isolated from Xionghu Reservoir, China. *J. Appl. Phycol.* **2016**, *28*, 3353–3362. [\[CrossRef\]](#)
- Bang, H.; Slokar, Y.M.; Ferrero, G.; Kruithof, J.C.; Kennedy, M.D. Removal of taste and odor causing compounds by UV/H₂O₂ treatment: Effect of the organic and inorganic water matrix. *Desalin. Water Treat.* **2016**, *57*, 27485–27494. [\[CrossRef\]](#)
- Li, L.; Yang, S.; Yu, S.; Zhang, Y. Variation and removal of 2-MIB in full-scale treatment plants with source water from Lake Tai, China. *Water Res.* **2019**, *162*, 180–189. [\[CrossRef\]](#)
- Adams, H.; Southard, M.; Reeder, S.; Buerkens, F.; Hallford, R.L.; Ikehata, K.; Nix, D.K. Successfully Detecting and Mitigating Algal Blooms and Taste and Odor Compounds. *J. Am. Water Work. Assoc.* **2021**, *113*, 10–19. [\[CrossRef\]](#)
- Zhu, J.; Stuetz, R.M.; Hamilton, L.; Power, K.; Crosbie, N.D.; Tamburic, B. Management of biogenic taste and odour: From source water, through treatment processes and distribution systems, to consumers. *J. Environ. Manag.* **2022**, *323*, 116225. [\[CrossRef\]](#)
- Li, L.; Li, J.Y.; Zhu, C.W.; Yu, S.L. Study of the binding regularity and corresponding mechanism of drinking water odorous compound 2-MIB with coexisting dissolved organic matter. *Chem. Eng. J.* **2020**, *395*, 125015. [\[CrossRef\]](#)
- Antonopoulou, M.; Evgenidou, E.; Lambropoulou, D.; Konstantinou, I. A review on advanced oxidation processes for the removal of taste and odor compounds from aqueous media. *Water Res.* **2014**, *53*, 215–234. [\[CrossRef\]](#)
- Juttner, F.; Watson, S.B. Biochemical and ecological control of geosmin and 2-methylisoborneol in source waters. *Appl. Environ. Microbiol.* **2007**, *73*, 4395–4406. [\[CrossRef\]](#)
- Clerc, N.A.; Druschel, G.K.; Gray, M. Occurrences of 2-methylisoborneol and geosmin-degrading bacteria in a eutrophic reservoir and the role of cell-bound versus dissolved fractions. *J. Environ. Manag.* **2021**, *297*, 113304. [\[CrossRef\]](#)
- Jo, J.O.; Kim, S.D.; Lee, H.J.; Mok, Y.S. Decomposition of taste-and-odor compounds produced by cyanobacteria algae using atmospheric pressure plasma created inside a porous hydrophobic ceramic tube. *Chem. Eng. J.* **2014**, *247*, 291–301. [\[CrossRef\]](#)
- Watson, S.B.; Monis, P.; Baker, P.; Giglio, S. Biochemistry and genetics of taste- and odor-producing cyanobacteria. *Harmful Algae* **2016**, *54*, 112–127. [\[CrossRef\]](#)
- Fang, J.Y.; Liu, J.J.; Shang, C.; Fan, C.H. Degradation Investigation of Selected Taste and Odor Compounds by a UV/Chlorine Advanced Oxidation Process. *Int. J. Environ. Res. Public Health* **2018**, *15*, 284. [\[CrossRef\]](#)
- Guttman, L.; van Rijn, J. 2-Methylisoborneol and geosmin uptake by organic sludge derived from a recirculating aquaculture system. *Water Res.* **2009**, *43*, 474–480. [\[CrossRef\]](#)
- Pirbazari, M.; Borow, H.; Craig, S.; Ravindran, V.; McGuire, M. Physical chemical characterization of five earthy-musty-smelling compounds. *Water Sci. Technol.* **1992**, *25*, 81–88. [\[CrossRef\]](#)
- Mustapha, S.; Tijani, J.O.; Ndamitso, M.M.; Abdulkareem, A.S.; Shuaib, D.T.; Mohammed, A.K. A critical review on geosmin and 2-methylisoborneol in water: Sources, effects, detection, and removal techniques. *Environ. Monit. Assess.* **2021**, *193*, 204. [\[CrossRef\]](#)
- Barbusinski, K.; Kalembe, K.; Kasperczyk, D.; Urbaniec, K.; Kozik, V. Biological methods for odor treatment—A review. *J. Clean. Prod.* **2017**, *152*, 223–241. [\[CrossRef\]](#)
- Kim, Y.; Lee, Y.; Gee, C.S.; Choi, E. Treatment of taste and odor causing substances in drinking water. *Water Sci. Technol.* **1997**, *35*, 29–36. [\[CrossRef\]](#)
- Asghar, A.; Khan, Z.; Maqbool, N.; Qazi, I.A.; Awan, M.A. Comparison of adsorption capability of activated carbon and metal doped TiO₂ for geosmin and 2-MIB removal from water. *J. Nanomater.* **2015**, *2015*, 479103. [\[CrossRef\]](#)
- Paulino, R.; Tamburic, B.; Stuetz, R.M.; Zamyadi, A.; Crosbie, N.; Henderson, R.K. Critical review of adsorption and biodegradation mechanisms for removal of biogenic taste and odour compounds in granular and biological activated carbon contactors. *J. Water Process Eng.* **2023**, *52*, 103518. [\[CrossRef\]](#)
- Srinivasan, R.; Sorial, G.A. Treatment of taste and odor causing compounds 2-methyl isoborneol and geosmin in drinking water: A critical review. *J. Environ. Sci.* **2011**, *23*, 1–13. [\[CrossRef\]](#)
- Ntougias, S.; Melidis, P.; Navrozidou, E.; Tzegkas, F. Diversity and efficiency of anthracene-degrading bacteria isolated from a denitrifying activated sludge system treating municipal wastewater. *Int. Biodeterior. Biodegrad.* **2015**, *97*, 151–158. [\[CrossRef\]](#)

26. Khajouei, G.; Finklea, H.O.O.; Lin, L.S. UV/chlorine advanced oxidation processes for degradation of contaminants in water and wastewater: A comprehensive review. *J. Environ. Chem. Eng.* **2022**, *10*, 107508. [[CrossRef](#)]
27. Feng, G.X.; Jia, R.B.; Sun, S.H.; Wang, M.Q.; Zhao, Q.H.; Xin, X.D.; Liu, L. Occurrence and removal of 10 odorous compounds in drinking water by different treatment processes. *Environ. Sci. Pollut. Res.* **2020**, *27*, 18924–18933. [[CrossRef](#)]
28. Fan, X.J.; Tao, Y.; Wang, L.Y.; Zhang, X.H.; Lei, Y.; Wang, Z.; Noguchi, H. Performance of an integrated process combining ozonation with ceramic membrane ultra-filtration for advanced treatment of drinking water. *Desalination* **2014**, *335*, 47–54. [[CrossRef](#)]
29. Ren, X.Y.; Wu, Q.D.; Shu, J.Y.; Chen, C.; Tiraferri, A.; Liu, B.C. Efficient removal of organic matters and typical odor substances in rural drinking water using Ozone-BAC-UF combined system to meet new water quality standards in China. *Sep. Purif. Technol.* **2023**, *327*, 124899. [[CrossRef](#)]
30. Liu, L.; Li, L.; Zuo, Y.; Huang, Y.; Song, L. Adsorption of 2-methylisoborneol and geosmin by a low-cost hybrid adsorbent synthesized from fly ash and bentonite. *J. Water Supply Res. Technol. Aqua* **2011**, *60*, 478–485. [[CrossRef](#)]
31. Park, S.M.; Heo, T.Y.; Park, N.B.; Na, K.J.; Jun, H.B.; Jung, J.Y. Application of air stripping to powdered activated carbon adsorption of geosmin and 2-methylisoborneol. *J. Water Supply Res. Technol. Aqua* **2010**, *59*, 492–500. [[CrossRef](#)]
32. An, N.; Xie, H.h.; Gao, N.y.; Deng, Y.; Chu, W.h.; Jiang, J. Adsorption of two taste and odor compounds IPMP and IBMP by granular activated carbon in water. *CLEAN—Soil Air Water* **2012**, *40*, 1349–1356. [[CrossRef](#)]
33. Matsui, Y.; Nakano, Y.; Hiroshi, H.; Ando, N.; Matsushita, T.; Ohno, K. Geosmin and 2-methylisoborneol adsorption on super-powdered activated carbon in the presence of natural organic matter. *Water Sci. Technol.* **2010**, *62*, 2664–2668. [[CrossRef](#)]
34. Cho, K.; An, B.M.; So, S.; Chae, A.; Song, K.G. Simultaneous control of algal micropollutants based on ball-milled powdered activated carbon in combination with permanganate oxidation and coagulation. *Water Res.* **2020**, *185*, 116263. [[CrossRef](#)]
35. Bong, T.; Kang, J.K.; Yargeau, V.; Nam, H.L.; Lee, S.H.; Choi, J.W.; Kim, S.B.; Park, J.A. Geosmin and 2-methylisoborneol adsorption using different carbon materials: Isotherm, kinetic, multiple linear regression, and deep neural network modeling using a real drinking water source. *J. Clean. Prod.* **2021**, *314*, 127967. [[CrossRef](#)]
36. Kim, C.; Lee, S.I.; Hwang, S.; Cho, M.; Kim, H.S.; Noh, S.H. Removal of geosmin and 2-methylisoborneol (2-MIB) by membrane system combined with powdered activated carbon (PAC) for drinking water treatment. *J. Water Process Eng.* **2014**, *4*, 91–98. [[CrossRef](#)]
37. Hafuka, A.; Nagasato, T.; Yamamura, H. Application of graphene oxide for adsorption removal of geosmin and 2-Methylisoborneol in the presence of natural organic matter. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1907. [[CrossRef](#)]
38. Westerhoff, P.; Rodriguez-Hernandez, M.; Baker, L.; Sommerfeld, M. Seasonal occurrence and degradation of 2-methylisoborneol in water supply reservoirs. *Water Res.* **2005**, *39*, 4899–4912. [[CrossRef](#)]
39. Wang, J.; Zhou, L.; Gao, J.; Zhu, J.; Zhou, J. Process optimization and mechanism revealing of KMnO_4 pre-oxidation coupled powdered activated carbon adsorption for 2-MIB removal. *J. Water Process Eng.* **2023**, *53*, 103705. [[CrossRef](#)]
40. Lompe, K.M.; Sollicec, M.; Rivas, M.; Peldszus, S.; Barbeau, B. Selecting a single powdered activated carbon against multiple threats: Taste & odour and benzene. *Environ. Sci. Water Res. Technol.* **2022**, *8*, 3091–3100. [[CrossRef](#)]
41. Cerón-Vivas, A.; Villamizar León, M.P.; Cajigas, Á.A. Geosmin and 2-methylisoborneol removal in drinking water treatment. *Water Pract. Technol.* **2023**, *18*, 159–167. [[CrossRef](#)]
42. Azaria, S.; Nussinovitch, A.; Nir, S.; Mordechai, S.; van Rijn, J. Removal of geosmin and 2-methylisoborneol from aquaculture water by novel, alginate-based carriers: Performance and metagenomic analysis. *J. Water Process Eng.* **2021**, *42*, 102125. [[CrossRef](#)]
43. Awad, A.M.; Jalab, R.; Benamor, A.; Nasser, M.S.; Ba-Abbad, M.M.; El-Naas, M.; Mohammad, A.W. Adsorption of organic pollutants by nanomaterial-based adsorbents: An overview. *J. Mol. Liq.* **2020**, *301*, 112335. [[CrossRef](#)]
44. Pivokonsky, M.; Kopecka, I.; Cermakova, L.; Fialova, K.; Novotna, K.; Cajthaml, T.; Henderson, R.K.; Pivokonska, L. Current knowledge in the field of algal organic matter adsorption onto activated carbon in drinking water treatment. *Sci. Total Environ.* **2021**, *799*, 149455. [[CrossRef](#)]
45. Moztahida, M.; Nawaz, M.; Kim, J.; Shahzad, A.; Kim, S.; Jang, J.; Lee, D.S. Reduced graphene oxide-loaded-magnetite: A Fenton-like heterogeneous catalyst for photocatalytic degradation of 2-methylisoborneol. *Chem. Eng. J.* **2019**, *370*, 855–865. [[CrossRef](#)]
46. Xu, H.; Zhang, J.; Wang, W.; Li, Y.; Pei, H. Moderate pre-ozonation coupled with a post-peroxone process remove filamentous cyanobacteria and 2-MIB efficiently: From bench to pilot-scale study. *J. Hazard. Mater.* **2022**, *424*, 127530. [[CrossRef](#)] [[PubMed](#)]
47. Abrha, Y.W.; Kye, H.; Kwon, M.; Lee, D.; Kim, K.; Jung, Y.; Ahn, Y.; Kang, J.W. Removal of Algae, and Taste and Odor Compounds by a Combination of Plant-Mineral Composite (PMC) Coagulant with UV-AOPs: Laboratory and Pilot Scale Studies. *Appl. Sci.* **2018**, *8*, 1502. [[CrossRef](#)]
48. Yao, W.; Qu, Q.; Von Gunten, U.; Chen, C.; Yu, G.; Wang, Y. Comparison of methylisoborneol and geosmin abatement in surface water by conventional ozonation and an electro-peroxone process. *Water Res.* **2017**, *108*, 373–382. [[CrossRef](#)]
49. Meunier, L.; Canonica, S.; Von Gunten, U. Implications of sequential use of UV and ozone for drinking water quality. *Water Res.* **2006**, *40*, 1864–1876. [[CrossRef](#)]
50. Mizuno, T.; Ohara, S.; Nishimura, F.; Tsuno, H. $\text{O}_3/\text{H}_2\text{O}_2$ process for both removal of odorous algal-derived compounds and control of bromate ion formation. *Ozone Sci. Eng.* **2011**, *33*, 121–135. [[CrossRef](#)]
51. Qi, F.; Xu, B.; Feng, L.; Chen, Z.; Zhang, L.; Sun, D. Formation of aldehyde during ozonation of taste and odour compounds in water. *J. Water Supply Res. Technol. Aqua* **2013**, *62*, 120–128. [[CrossRef](#)]

52. Yuan, B.; Xu, D.; Li, F.; Fu, M.L. Removal efficiency and possible pathway of odor compounds (2-methylisoborneol and geosmin) by ozonation. *Sep. Purif. Technol.* **2013**, *117*, 53–58. [[CrossRef](#)]
53. Kutschera, K.; Börnick, H.; Worch, E. Photoinitiated oxidation of geosmin and 2-methylisoborneol by irradiation with 254 nm and 185 nm UV light. *Water Res.* **2009**, *43*, 2224–2232. [[CrossRef](#)] [[PubMed](#)]
54. Song, W.; O’Shea, K.E. Ultrasonically induced degradation of 2-methylisoborneol and geosmin. *Water Res.* **2007**, *41*, 2672–2678. [[CrossRef](#)] [[PubMed](#)]
55. Kurokawa, Y.; Maekawa, A.; Takahashi, M.; Hayashi, Y. Toxicity and carcinogenicity of potassium bromate—A new renal carcinogen. *Environ. Health Perspect.* **1990**, *87*, 309–335. [[CrossRef](#)] [[PubMed](#)]
56. Butler, R.; Godley, A.; Lytton, L.; Cartmell, E. Bromate environmental contamination: Review of impact and possible treatment. *Crit. Rev. Environ. Sci. Technol.* **2005**, *35*, 193–217. [[CrossRef](#)]
57. Berl, M.M.G.; Schneider, R.D.D.; Machado, E.L.; Kist, L.T. Comparative assessment of the degradation of 2-methylisoborneol and geosmin in freshwater using advanced oxidation processes. *Environ. Technol.* **2021**, *42*, 3832–3839. [[CrossRef](#)]
58. Zhao, Y.; Deng, N.; Fan, Z.; Hu, Z.T.; Fan, L.; Zhou, J.; Huang, X. On-site H₂O₂ electro-generation process combined with ultraviolet: A promising approach for odorous compounds purification in drinking water system. *Chem. Eng. J.* **2022**, *430*, 132829. [[CrossRef](#)]
59. Bakheet, B.; Yuan, S.; Li, Z.; Wang, H.; Zuo, J.; Komarneni, S.; Wang, Y. Electro-peroxone treatment of Orange II dye wastewater. *Water Res.* **2013**, *47*, 6234–6243. [[CrossRef](#)]
60. Wang, H.; Mustafa, M.; Yu, G.; Östman, M.; Cheng, Y.; Wang, Y.; Tysklind, M. Oxidation of emerging biocides and antibiotics in wastewater by ozonation and the electro-peroxone process. *Chemosphere* **2019**, *235*, 575–585. [[CrossRef](#)]
61. Li, Y.; Shen, W.; Fu, S.; Yang, H.; Yu, G.; Wang, Y. Inhibition of bromate formation during drinking water treatment by adapting ozonation to electro-peroxone process. *Chem. Eng. J.* **2015**, *264*, 322–328. [[CrossRef](#)]
62. Qi, F.; Xu, B.B.; Chen, Z.L.; Zhang, L.Q.; Zhang, P.Y.; Sun, D.Z. Mechanism investigation of catalyzed ozonation of 2-methylisoborneol in drinking water over aluminum (hydroxyl) oxides: Role of surface hydroxyl group. *Chem. Eng. J.* **2010**, *165*, 490–499. [[CrossRef](#)]
63. Xu, B.B.; Qi, F. Reaction Mechanism of 2-Methylisoborneol and 2,4,6-Trichloroanisole in Catalytic Ozonation by γ -AlOOH: Role of Adsorption. *Clean Soil Air Water* **2016**, *44*, 1099–1105. [[CrossRef](#)]
64. Kazankov, G.M.; Sergeeva, V.S.; Efremenko, E.N.; Alexandrova, L.; Varfolomeev, S.D.; Ryabov, A.D. Highly efficient degradation of thiophosphate pesticides catalyzed by platinum and palladium aryl oxime metallacycles. *Angew. Chem. Int. Ed.* **2000**, *39*, 3117–3119. [[CrossRef](#)]
65. Park, J.A.; Nam, H.L.; Choi, J.W.; Ha, J.; Lee, S.H. Oxidation of geosmin and 2-methylisoborneol by the photo-Fenton process: Kinetics, degradation intermediates, and the removal of microcystin-LR and trihalomethane from Nak-Dong River water, South Korea. *Chem. Eng. J.* **2017**, *313*, 345–354. [[CrossRef](#)]
66. Jo, C.H.; Dietrich, A.M.; Tanko, J.M. Simultaneous degradation of disinfection byproducts and earthy-musty odorants by the UV/H₂O₂ advanced oxidation process. *Water Res.* **2011**, *45*, 2507–2516. [[CrossRef](#)]
67. Springer, J.C.; Kashinkunti, R.; Hong, Y. Medium-Pressure UV/Chlorine Advanced Oxidation of Taste and Odor Compounds. *J. Am. Water Work. Assoc.* **2018**, *110*, E16–E27. [[CrossRef](#)]
68. Antonopoulou, M.; Ioannidis, N.; Kaloudis, T.; Triantis, T.M.; Hiskia, A. Kinetic and mechanistic investigation of water taste and odor compound 2-isopropyl-3-methoxy pyrazine degradation using UV-A/Chlorine process. *Sci. Total Environ.* **2020**, *732*, 138404. [[CrossRef](#)]
69. Zhang, Y.L.; Lin, Y.L.; Zhang, T.Y.; Lu, Y.S.; Zhou, X.Y.; Liu, Z.; Zheng, Z.X.; Xu, M.Y.; Xu, B. Degradation of odorous 2, 4, 6-trichloroanisole in chlorinated water by UV-LED/chlorination: Kinetics and influence factors. *Environ. Sci. Pollut. Res.* **2023**, *30*, 44325–44336. [[CrossRef](#)]
70. Tan, F.; Chen, H.; Wu, D.; Lu, N.; Gao, Z. Optimization of Removal of 2-methylisoborneol from Drinking Water using UV/H₂O₂. *J. Adv. Oxid. Technol.* **2016**, *19*, 98–104. [[CrossRef](#)]
71. Xie, P.; Ma, J.; Liu, W.; Zou, J.; Yue, S.; Li, X.; Wiesner, M.R.; Fang, J. Removal of 2-MIB and geosmin using UV/persulfate: Contributions of hydroxyl and sulfate radicals. *Water Res.* **2015**, *69*, 223–233. [[CrossRef](#)] [[PubMed](#)]
72. Fotiou, T.; Triantis, T.M.; Kaloudis, T.; Papaconstantinou, E.; Hiskia, A. Photocatalytic degradation of water taste and odour compounds in the presence of polyoxometalates and TiO₂: Intermediates and degradation pathways. *J. Photochem. Photobiol. A Chem.* **2014**, *286*, 1–9. [[CrossRef](#)]
73. Guo, Y.; Hu, W.; Lu, H.; Zhu, Z. Efficient Photocatalytic Degradation of 2-Methylisoborneol by Zn-Al-La Multi-Metal Oxide Composites Derived from LDH. *Water Air Soil Pollut.* **2023**, *234*, 24. [[CrossRef](#)]
74. Guo, X.P.; Zang, P.; Li, Y.M.; Bi, D.S. TiO₂-powdered activated carbon (TiO₂/PAC) for removal and photocatalytic properties of 2-Methylisoborneol (2-MIB) in water. *Water* **2021**, *13*, 1622. [[CrossRef](#)]
75. Huang, X.; Wang, S.; Wang, G.; Zhu, S.; Ye, Z. Kinetic and mechanistic investigation of geosmin and 2-methylisoborneol degradation using UV-assisted photoelectrochemical. *Chemosphere* **2022**, *290*, 133325. [[CrossRef](#)]
76. Qi, F.; Xu, B.; Chen, Z.; Feng, L.; Zhang, L.; Sun, D. Catalytic ozonation of 2-isopropyl-3-methoxypyrazine in water by γ -AlOOH and γ -Al₂O₃: Comparison of removal efficiency and mechanism. *Chem. Eng. J.* **2013**, *219*, 527–536. [[CrossRef](#)]
77. Liu, S.; Tang, L.; Wu, M.; Fu, H.; Xu, J.; Chen, W.; Ma, F. Parameters influencing elimination of geosmin and 2-methylisoborneol by K₂FeO₄. *Sep. Purif. Technol.* **2017**, *182*, 128–133. [[CrossRef](#)]

78. Liu, X.; Ding, S.; Wang, P.; Hong, Y.; Zhao, H.; Chu, W. Simultaneous mitigation of disinfection by-product formation and odor compounds by peroxide/Fe (II)-based process: Combination of oxidation and coagulation. *Water Res.* **2021**, *201*, 117327. [[CrossRef](#)]
79. Lee, J.; Nam, S.H.; Koo, J.W.; Kim, E.; Hwang, T.M. Comparative evaluation of 2-isopropyl-3-methoxypyrazine, 2-isobutyl-3-methoxypyrazine, and 2, 4, 6-trichloroanisole degradation by ultraviolet/chlorine and ultraviolet/hydrogen peroxide processes. *Chemosphere* **2021**, *279*, 130513. [[CrossRef](#)]
80. Jiang, Q.; Wang, Y.; Tian, L.; Liu, Y.; Liu, J.; He, G.; Li, J. Pilot-scale and mechanistic study of the degradation of typical odors and organic compounds in drinking water by a combined UV/H₂O₂-BAC process. *Chemosphere* **2022**, *292*, 133419. [[CrossRef](#)]
81. Meng, T.; Su, X.; Sun, P. Degradation of geosmin and 2-methylisoborneol in UV-based AOPs for photoreactors with reflective inner surfaces: Kinetics and transformation products. *Chemosphere* **2022**, *306*, 135611. [[CrossRef](#)] [[PubMed](#)]
82. Du, K.; Zhou, B.; Yuan, R. Biodegradation of 2-methylisoborneol by single bacterium in culture media and river water environment. *Int. J. Environ. Stud.* **2017**, *74*, 399–411. [[CrossRef](#)]
83. Arriaga, S.; Revah, S. Improving hexane removal by enhancing fungal development in a microbial consortium biofilter. *Biotechnol. Bioeng.* **2005**, *90*, 107–115. [[CrossRef](#)] [[PubMed](#)]
84. Yuan, R.; Zhou, B.; Shi, C.; Yu, L.; Zhang, C.; Gu, J. Biodegradation of 2-methylisoborneol by bacteria enriched from biological activated carbon. *Front. Environ. Sci. Eng.* **2012**, *6*, 701–710. [[CrossRef](#)]
85. Lauderdale, C.V.; Aldrich, H.C.; Lindner, A.S. Isolation and characterization of a bacterium capable of removing taste-and odor-causing 2-methylisoborneol from water. *Water Res.* **2004**, *38*, 4135–4142. [[CrossRef](#)]
86. Luo, G.; Wang, J.; Ma, N.; Liu, Z.; Tan, H. Effects of inoculated bacillus subtilis on geosmin and 2-methylisoborneol removal in suspended growth reactors using aquacultural waste for biofloc production. *J. Microbiol. Biotechnol.* **2016**, *26*, 1420–1427. [[CrossRef](#)]
87. Xue, Q.; Shimizu, K.; Sakharkar, M.K.; Utsumi, M.; Cao, G.; Li, M.; Zhang, Z.; Sugiura, N. Geosmin degradation by seasonal biofilm from a biological treatment facility. *Environ. Sci. Pollut. Res.* **2012**, *19*, 700–707. [[CrossRef](#)]
88. Ho, L.; Hoefel, D.; Bock, F.; Saint, C.P.; Newcombe, G. Biodegradation rates of 2-methylisoborneol (MIB) and geosmin through sand filters and in bioreactors. *Chemosphere* **2007**, *66*, 2210–2218. [[CrossRef](#)]
89. Tesso, T.A.; Zheng, A.; Cai, H.; Liu, G. Isolation and characterization of two Acinetobacter species able to degrade 3-methylindole. *PLoS ONE* **2019**, *14*, e0211275. [[CrossRef](#)]
90. Guttman, L.; van Rijn, J. Isolation of bacteria capable of growth with 2-methylisoborneol and geosmin as the sole carbon and energy sources. *Appl. Environ. Microbiol.* **2012**, *78*, 363–370. [[CrossRef](#)]
91. Schroeder, M.; Pöllinger-Zierler, B.; Aichernig, N.; Siegmund, B.; Guebitz, G. Enzymatic removal of off-flavors from apple juice. *J. Agric. Food Chem.* **2008**, *56*, 2485–2489. [[CrossRef](#)] [[PubMed](#)]
92. Cheng, Z.; Lu, L.; Kennes, C.; Yu, J.; Chen, J. Treatment of gaseous toluene in three biofilters inoculated with fungi/bacteria: Microbial analysis, performance and starvation response. *J. Hazard. Mater.* **2016**, *303*, 83–93. [[CrossRef](#)] [[PubMed](#)]
93. Hernández-Meléndez, O.; Bárzana, E.; Arriaga, S.; Hernández-Luna, M.; Revah, S. Fungal removal of gaseous hexane in biofilters packed with poly(ethylene carbonate) pine sawdust or peat composites. *Biotechnol. Bioeng.* **2008**, *100*, 864–871. [[CrossRef](#)]
94. Lebrero, R.; Rodríguez, E.; Martín, M.; García-Encina, P.A.; Muñoz, R. H₂S and VOCs abatement robustness in biofilters and air diffusion bioreactors: A comparative study. *Water Res.* **2010**, *44*, 3905–3914. [[CrossRef](#)] [[PubMed](#)]
95. Kennes, C.; Veiga, M.C. Fungal biocatalysts in the biofiltration of VOC-polluted air. *J. Biotechnol.* **2004**, *113*, 305–319. [[CrossRef](#)]
96. Prenafeta-Boldú, F.X.; Illa, J.; van Groenestijn, J.W.; Flotats, X. Influence of synthetic packing materials on the gas dispersion and biodegradation kinetics in fungal air biofilters. *Appl. Microbiol. Biotechnol.* **2008**, *79*, 319–327. [[CrossRef](#)]
97. Doederer, K.; De Vera, G.A.; Espino, M.P.; Pype, M.L.; Gale, D.; Keller, J. MIB and geosmin removal during adsorption and biodegradation phases of GAC filtration. *Water Sci. Technol. Water Supply* **2018**, *18*, 1449–1455. [[CrossRef](#)]
98. Elhadi, S.L.N.; Huck, P.M.; Slawson, R.M. Removal of geosmin and 2-methylisoborneol by biological filtration. *Water Sci. Technol.* **2004**, *49*, 273–280. [[CrossRef](#)]
99. Chen, S.Y.; Dong, B.Z.; Gao, K.; Li, T. Pilot study on advanced treatment of geosmin and 2-MIB with O₃/GAC. *Water Supply* **2019**, *19*, 1253–1263. [[CrossRef](#)]
100. McDowall, B.; Hoefel, D.; Newcombe, G.; Saint, C.P.; Ho, L. Enhancing the biofiltration of geosmin by seeding sand filter columns with a consortium of geosmin-degrading bacteria. *Water Res.* **2009**, *43*, 433–440. [[CrossRef](#)]
101. Liang, S.; Li, X.; Yang, Y.L.; Liu, L.; Liu, Y.W.; Cheng, Z.J.; Li, B.; Li, G.B. PAC addition on immersed ultrafiltration membrane for the treatment of raw water containing taste and odor compounds. In Proceedings of the 2nd International Conference on Structures and Building Materials (ICSBM), Hangzhou, China, 9–11 March 2012; pp. 2855–2859.
102. Doederer, K.; Gale, D.; Keller, J. Effective removal of MIB and geosmin using MBBR for drinking water treatment. *Water Res.* **2019**, *149*, 440–447. [[CrossRef](#)] [[PubMed](#)]
103. Maslova, O.; Senko, O.; Efremenko, E. The influence of enzymatic removal of chlorpyrifos from feed grain mixes on biochemical parameters of rat blood. *Biochem. Mosc. Suppl. Ser. B* **2018**, *12*, 181–185. [[CrossRef](#)]
104. Lyagin, I.V.; Efremenko, E.N. Biomolecular engineering of biocatalysts hydrolyzing neurotoxic organophosphates. *Biochimie* **2018**, *144*, 115–121. [[CrossRef](#)] [[PubMed](#)]
105. Eaton, R.W.; Sandusky, P. Biotransformations of 2-Methylisoborneol by Camphor-Degrading Bacteria. *Appl. Environ. Microbiol.* **2009**, *75*, 583–588. [[CrossRef](#)] [[PubMed](#)]

106. Yuan, J.; Mortazavian, S.; Crowe, G.; Flick, R.; Passeport, E.; Hofmann, R. Evaluating the relative adsorption and biodegradation of 2-methylisoborneol and geosmin across granular activated carbon filter-adsorbers. *Water Res.* **2022**, *215*, 118239. [[CrossRef](#)] [[PubMed](#)]
107. Tanaka, A.; Oritani, T.; Uehara, F.; Saito, A.; Kishita, H.; Niizeki, Y.; Yokota, H.; Fuchigami, K. Biodegradation of a musty odour component, 2-methylisoborneol. *Water Res.* **1996**, *30*, 759–761. [[CrossRef](#)]
108. Saito, A.; Tokuyama, T.; Tanaka, A.; Oritani, T.; Fuchigami, K. Microbiological degradation of (-)-geosmin. *Water Res.* **1999**, *33*, 3033–3036. [[CrossRef](#)]

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