



A critical review on geosmin and 2-methylisoborneol in water: sources, effects, detection, and removal techniques

S. Mustapha · J. O. Tijani · MM Ndamitso ·
A. S. Abdulkareem · D. T. Shuaib ·
A. K. Mohammed

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Abstract The exposure to geosmin (GSM) and 2-methylisoborneol (2-MIB) in water has caused a negative impact on product reputation and customer distrust. The occurrence of these compounds and their metabolites during drinking water treatment processes has caused different health challenges. Conventional treatment techniques such as coagulation, sedimentation, filtration, and chlorination employed in removing these two commonest

taste and odor compounds (GSM and 2-MIB) were found to be ineffective and inherent shortcomings. The removal of GSM and MIB were found to be effective using combination of activated carbon and ozonation; however, high treatment cost associated with ozonation technique and poor regeneration efficiency of activated carbon constitute serious setback to the combined system. Other shortcomings of the activated carbon adsorption and ozonation include low adsorption efficiency due to the presence of natural organic matter and humic acid. In light of this background, the review is focused on the sources, effects, environmental pathways, detection, and removal techniques of 2-MIB and GSM from aqueous media. Although advanced oxidation processes (AOPs) were found to be promising to remove the two compounds from water but accompanied with different challenges. Herein, to fill the knowledge gap analysis on these algal metabolites (GSM and 2-MIB), the integration of treatment processes vis-a-viz combination of one or more AOPs with other conventional methods are considered logical to remove these odorous compounds and hence could improve overall water quality.

S. Mustapha (✉) · J. O. Tijani · M. Ndamitso
Department of Chemistry, Federal University
of Technology, Bosso Campus, PMB 65, Minna, Nigeria
e-mail: saheedmustapha09@gmail.com

S. Mustapha · J. O. Tijani · M. Ndamitso ·
A. S. Abdulkareem
Nanotechnology Research Group, Africa Center
of Excellence for Mycotoxin and Food Safety, Federal
University of Technology, PMB 65, Minna, Niger State,
Nigeria

A. S. Abdulkareem
Department of Chemical Engineering, Federal University
of Technology, Gidan Kwano Campus, PMB 65, Minna,
Niger State, Nigeria

D. T. Shuaib
Department of Chemistry, Illinois Institute of Technology,
3101 S Dearborn Street, Chicago, IL 60616, USA

A. K. Mohammed
Department of Chemistry and Biochemistry, North
Carolina Central University, 1801 Fayetteville Street,
NC 27707 Durham, USA

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Introduction

Water remains an integral component of the environment required for human socioeconomic development and therefore should be preserved for posterity. At the moment, according to the World Health Organization (2015), the demand for clean water in terms of quantity and quality already exceeds supply, especially in water-stressed countries due to the increasing human population. It has been projected that the global human population will increase to 9 billion people by 2050. The implication of this is that more regions of the world, especially the rural areas of developing countries, will not have access to sustainable clean water supplies and sanitary facilities (WHO, 2014). Currently, the little available clean water is being polluted via different natural and anthropogenic activities such as flooding, earthquakes, industrial development, agricultural practices, urbanization, and of course, the widely debated climate change. Anthropogenic activities lead to the generation of wastewater that encompasses different constituents ranging from organic contaminants to inorganic substances and microbes. Of particular interest in this study are the pollutants which are currently detected at nanogram per liter to microgram per liter concentrations in various water sources. These substances generally impact negatively on the acceptability of water quality.

Marcoux et al. (2013), Ahmed et al. (2015), and Jiang et al. (2015) defined emerging contaminants as substances that are not necessarily new to the market but are currently not regulated and may cause environmental hazard, potentially affect aquatic and human health. Different definitions for emerging contaminants have been proposed by several authors. These contaminants include pesticides, pharmaceuticals and personal care products, fragrances, plasticizers, hormones, flame retardants, nanoparticles, perfluoroalkyl compounds, chlorinated paraffin, siloxanes, algal toxins produced by cyanobacteria, rare earth, and radionuclides (Sauvé & Desrosiers, 2014).

Cyanobacteria otherwise known as blue-green in algal are biological organisms caused by nutrient loads of water bodies and global warming resulting in algae bloom (Sauvé & Desrosiers, 2014). These algal blooms are either always visible or sometimes blue or brownish-red species that cause unpleasant smells in water

(NOAA, 2016). These stale odors in water have become a source of considerable concern among researchers due to heavy pollution of the water bodies and serious health effects (Yu et al., 2014). The compounds from blue-green algae growth are primarily geosmin (GSM), 2-methylisoborneol (2-MIB), 2-isobutyl-3-methoxy pyrazine (2-IBMP), 2,3,6-trichloroanisole (2,3,6-TCA), and 2,4,6-trichloroanisole (2,4,6-TCA) (Zuo et al., 2016). Geosmin (GSM) and 2-methylisoborneol (2-MIB) are the main compounds responsible for the poor taste and odor in water (Kakimoto et al., 2014). These compounds are volatile in nature, cause musty and earthy off-flavors, and their presence of in drinking water will cause more harm (Greenwald et al., 2015). The removal of these taste and odor (T&O) compounds from drinking water has been challenging due to the fact that their odor threshold concentrations are usually in nanogram per liter or part per trillion (Antonopoulou et al., 2014).

The identification, quantification, and removal of GSM and 2-MIB from water are necessary in order to satisfy the final consumers. The problem of taste and odor in water is a global phenomenon and not peculiar to a particular region but becomes more obvious during the summer (Kakimoto et al., 2014). The continuous presence of these compounds in water has caused loss of customer confidence in different water distribution companies as regards their capacity to provide safe water (Zamyadi et al., 2015). Different removal techniques such as the use of superfine powdered activated carbon (SPAC), coagulation, sedimentation, membrane filtration, flocculation, ozonation, powdered activated carbon (PAC), electro dialysis, precipitation, co-precipitation, and heterogeneous photocatalysis have been applied to remove color, taste, or odor from water (Fotiou et al., 2016; Guo et al., 2016; Zamyadi et al., 2015). Each of these methods has inherent shortcomings. For instance, it was found that the hydrophilicity of PAC was opposed to the maximum adsorption capacity due to the loss of utilization of the interior regions of the carbon particle while the use of visible light process do not degrade GSM and 2-MIB due to their lack of double bonds and functional groups that can interact with O_2 .

In recent times, advanced oxidation technologies have been identified as logical options to effectively decompose contaminants and microorganisms of emerging concerns (Garrido-Cardenas et al., 2020).

These technologies involving heterogeneous photocatalysts such as TiO_2 have demonstrated promising results for the removal and degradation of different taste and odor compounds. Photocatalyst semiconductors such as ZnO , WO_3 , Fe_2O_3 , CdS , and TiO_2 have been explored due to their extensive range of technologically useful characteristics such as good stability, easy applications, but may cause environmental issues among others (Banerjee et al., 2014). The photocatalytic activity of TiO_2 for the degradation and mineralization of microcystin-LR, GSM, and 2-MIB under solar and visible light irradiation was investigated by Fotiou et al. (2015a). The authors found that the photocatalytic technique was rather a complicated method to apply based on some experimental conditions such as light intensity, the presence of oxygen, catalyst loading, and concentration of the compound to be treated. The advance oxidation technique especially photocatalysis is expensive and besides, generates toxic sludge. Other disadvantages include the transfer of the pollutants from one phase to another without effective removal from aqueous media. Ma et al. (2018) reported that more than 95% of 2-MIB and GSM depended on UV intensity and free chlorine dosage where hydroxyl and chlorine radicals are important active species for the degradation of 2-MIB and GSM. The study promoted the formations of ketone and aldehyde on the degradation of these compounds. These products can be classified as sources of carcinogenic substances. Contrarily, Bu et al. (2017) proposed pathways for 2-MIB and GSM degradation and noticed a total mineralization of aldehyde and ketone to carbon (IV) oxide and water (conversion of organics to inorganics) by chemical oxidation process using boron doped diamond electrode. During this process, 2-MIB and GSM removal were current density dependent. Persulfate and reactive species increased with current density and gave rise to an increase in oxygen evolution potential for 2-MIB (53–88%) and GSM (56–99%) degradation.

Park et al. (2015) suggested that O_3 /granular activated carbon (GAC) and $\text{O}_3/\text{H}_2\text{O}_2/\text{GAC}$ should be considered to remove GSM and 2-MIB. Notably, the use of O_3/GAC was found to remove 94 to 100% of GSM at 50–1000 ng/L and 87 to 100% of 2-MIB at 50–300 ng/L. They also observed that $\text{O}_3/\text{H}_2\text{O}_2/\text{GAC}$ accounted for 94 to 100% GSM while 2-MIB removals were from 93 to 100%. Despite reduced

GSM and 2-MIB for the biologically active carbon (BAC), it was important to add $\text{H}_2\text{O}_2/\text{O}_3$ for effective removal of GSM and 2-MIB (Beniwal et al., 2018). Thus, removal efficiency of these two compounds via AOPs is dependent on oxidants. Li et al. (2018) reported that low ozone dosage is not enough for 2-MIB removal. Similar finding was made by Xia et al. (2020) who observed that increasing the dosage of ozone demonstrated high 2-MIB removal. Unstable 2-MIB removal was resistance to conventional water treatment processes such as coagulation, sedimentation, and sand filtration but 2-MIB removal by O_3/GAC was 98–100% (Li et al., 2019). It was, however, noted that natural organic matter reacts fast with ozone, consuming high ozone dosage for effective 2-MIB removal. Interestingly, direct oxidation and hydroxyl radical generated during ozonation attacked these compounds and negatively affect water quality through inactivation of microorganisms in water that are resistance to disinfectants thereby increasing the microbial growth. In another study of Visentin et al. (2019), vacuum UV was used for MIB and GSM removal and incomplete elimination of these compounds was observed due to the generation of oxidation by-products instead; Sun et al. (2018) reported that UV/chlorine removed 95% of 2-MIB and 96% of GSM in 10 min at pH 5. Berlt et al. (2020) examined the degradation of 2-MIB and GSM using UV radiation, ozone (O_3/UV). According to the authors, the use of either the UV radiation or ozone alone was found to be inefficient. Thus, the degradation of these two compounds was achieved using O_3/UV combination.

In view of these facts, it is obvious that no single technique is capable of completely removing 2-MIB and GSM in the water and instead process integration of both conventional and advanced oxidation techniques is considered the feasible option to effectively eliminate 2-MIB and GSM from water prior to its supply to the final consumer. Considering the previous literature, Srinivasan and Sorial (2011) did a critical review on 2-MIB and GSM in drinking water but failed to provide the reaction mechanisms involved in the degradation of these compounds. Antonopoulou et al. (2014) focused on the degradation of 2-MIB and GSM under various AOPs. However, their presentation left out conventional approaches. Best to authors' knowledge, this is the first critical review article

on conventional, integrated, and AOP methods for 2-MIB and GSM removal. The review aims to focus and provide wide information on sources and removal of 2-MIB and GSM in aqueous media. The review also attempted to provide a mechanistic pathway of these T&O compounds and their statutory rate based on application of advanced oxidation and integrated methods. Finally, the industrial removal of 2-MIB and GSM during treatment of water was also covered.

Sources of 2-methylisoborneol and geosmin

Determination of physico-chemical parameters of drinking water is a standard approach for assessing the quality of a water supply. Water with distinct tastes, unpleasant odors, and appearances can be easily detected. The discrepancy in the taste, odor, and appearance of drinking water are associated in some cases to seasonal variations (Doria, 2010). A high water temperature due to global warming intensifies eutrophication of water from rivers and lakes and promotes the growth of algae blooms and consequently affects the quality of water. These blue-green algae have become serious environmental problems resulting in the reduction of dissolved oxygen, chemical oxygen demand, production of cyanotoxins and musty-earthy compounds (Jo et al., 2014). These odorous compounds in water bodies are due to human activities such as the disposal of agricultural, municipal, and industrial wastes (Antonopoulou et al., 2014). These compounds generally influence the quality of drinking water by physiological and external factors. It is a well-known fact that the palatability of drinking water depends on the treatment processes employed for water purification which include the addition or removal of chemicals during treatment and reaction inputs during storage and distribution (Dietrich et al., 2014). The senses of taste and odor are called the chemical senses, and the concentrations of detection range from mg/dm³ to pg/dm³ and sometimes g to ng/dm³ (Piriou et al., 2009).

Tastes and odors in drinking water have become a global source of concern. Countries such as the USA, Australia, UK, among others, have come up with a valuable control process called consumers' complaint surveillance in order to enhance microbiological and chemical water quality monitoring (Dietrich et al., 2014). According to Gallagher and

Dietrich (2014), the implementation of CCS will not only help to control harmful pollutants but equally accelerate the detection of aesthetic problems in any water distribution system. Similarly, a class of earthy-musty compounds refer to 2,4,6-trichloroanisole produced during water treatment usually in extremely low concentration could cause obnoxious tastes and odors in drinking water and agricultural facilities (Antonopoulou & Konstantinou, 2015). The microbial activities responsible for these tastes and odors, of odor threshold concentration in ng/dm³, are used for sensory analysis of musty odor compounds in water (Callejóna et al., 2016), and accurate measurement is always done with at least five individuals. If they are detected, distilled water is used to dilute the odorous water (Talaiekhosani et al., 2016).

2-Methylisoborneol and geosmin in water






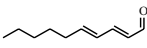
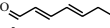
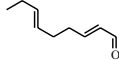









2-Methylisoborneol (IR-exo)-1,2,7,7-tetramethyl-exobicyclo-[2.2.2]-heptan-2-ol; 2-exo-hydroxy-2-methyl bornane, 2-MIB, and geosmin (trans-1,10-dimethyl-trans-9-decalol, GSM, are tertiary alcohols also classified as monoterpene and sesquiterpene, respectively. These two main semi-volatile compounds in drinking water are caused by actinomycetes or filamentous bacteria and blue-green algae or cyanobacteria (Auffret et al., 2011). Some of the physical properties of 2-MIB and GSM are shown in Table 1.

















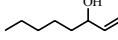
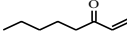
Some of the cyanobacterial species responsible for these chemical substances are *Anabaena circinalis* (Wang et al., 2015c), *Phormidium tenue*, *Oscillatoria f. granulata* (Joh & Lee, 2012), *Planktothrix* sp. (Su et al., 2013), *Oscillatoria simplicissima*, *Anabaena*

Table 1 Properties of 2-MIB and GSM

Property	MIB	GSM
Empirical formula	C ₁₁ H ₁₂ O	C ₁₂ H ₂₂ O
Molecular weight (g/mol)	168.28	182.31
Boiling point (°C)	196.70–208.70	270.00
Density (kg/m ³)	929.00	949.00
Aqueous solubility (mg/dm ³)	150.00	194.50
Vapor pressure (atm)	6.68 × 10 ⁻⁵	5.49 × 10 ⁻⁵
Refractive index	1.47	1.47
Henry's law constant (PGm ³ mol ⁻¹)	5.84	6.75

Table 2 Physico-chemical properties of odour and musty-odour compounds

Compound	Chemical formula	Chemical structure	Odour	Odour threshold concentration (ng/dm ³)	pK _a	Water solubility (mg/cm ³)	Molecular weight (g/mol)
Geosmin (GSM)	C ₁₂ H ₂₂ O		Earthy, musty	4	-0.0047	0.0512	182.303
2-methylisoborneol (MIB)	C ₁₁ H ₂₀ O		Earthy, musty	15	-0.42	0.45	168.276
2-isobutyl-3-methoxypyrazine (IBMP)	C ₉ H ₁₄ N ₂ O		Woody, musty, coal particles	1	0.98	20.9	166.22
2-isopropyl-3-methoxypyrazine (IPMP)	C ₈ H ₁₂ N ₂ O		Muddy	0.2	0.88	61.4	152.194
3-methyl-1-butanal	C ₅ H ₁₀ O		Oily	150	16.33	17	86.23
Trans-2, trans-4-decadienal	C ₁₀ H ₁₆ O		Cucumber, oily,	300	-4.1	0.0376	152.233
Trans-2, trans-4-heptadienal	C ₇ H ₁₀ O		Fishy, oily	25,000		Insoluble	110.073
Trans, cis-2,6-nonadienal	C ₉ H ₁₄ O		Cucumber	20			138.207
Beta-Ionone	C ₁₃ H ₂₀ O		Violets	7	19.71	0.104	192.297
Beta-Cyclocitral	C ₁₀ H ₁₆ O		Fruity	19,000		Insoluble	152.233
Cis-3-hexen-1-ol	C ₆ H ₁₂ O		Grassy	70,000	16.79	16.2	100.159
1-penten-3-one (Ethylvinylketone)	C ₅ H ₈ O		Rotten fish	1250			84.116
Dimethyl trisulphide	C ₂ H ₆ S ₃		Rotten vegetable	10		2.2	126.264
Hydrogen sulphide	H ₂ S	H-S-H	Rotten eggs	0.47		3.74	34.081
Sulphur oxide	SO ₂	O=S=O	Pungent	9000		107	64.064
Dimethyl sulphide	C ₂ H ₆ S		Cabbage	100	-9.9	18.5-22	62.134
2-propene-1-thiol (Allyl mercaptan)	C ₃ H ₆ S		Garlic	50			74.145
1-thiol-pentane	C ₅ H ₁₂ S		Stench	300			104.22
Benzyl mercaptan (Benzylthiol)	C ₇ H ₈ S		Leek, garlic-like	190			124.21

2-bentene-1-thiol (But-2-ene-1-thiol)	C ₄ H ₈ S		Skunk-like	29			88.171
Ethyl mercaptan (Ethanethiol)	C ₂ H ₆ S		Rotten cabbage, flatulence	190			62.134
Methyl mercaptan (Methanethiol)	CH ₄ S	—SH	Rotten cabbage, flatulence	1100			48.104
Propyl mercaptan	C ₃ H ₈ S		Cabbage-like	15			76.161
Tert-butylthiol	C ₄ H ₁₀ S		Skunk-like	80			90.1
Thiocresol (Methyl benzenethiol)	C ₇ H ₈ S		Rancid	62			124.21
Ammonia	NH ₃		Choking	1000000	8.06	4.82	17.031
2,4,6-Trichloroanisole (2,4,6-TCA)	C ₇ H ₅ Cl ₃ O		Musty	30	-4.9	0.0236	211.473
2,3,6-Trichloroanisole (2,3,6-TCA)	C ₇ H ₅ Cl ₃ O		Musty	0.1-2	-4.9		211.473
2,3,4-Trichloroanisole (2,3,4-TCA)	C ₇ H ₅ Cl ₃ O		Musty	0.2-2	-4.9		211.473
2,4,6-Tribromoanisole (TBA)	C ₇ H ₅ Br ₃ O		Earthy, musty	0.03	-	0.00494	344.826
Tetrachloroanisole	C ₇ H ₄ Cl ₄ O		Mould	4	-4.9	0.00341	245.918
Pentachloroanisole	C ₇ H ₃ Cl ₅ O		Musty, earthy	nil			280.363
2,4-Dichloroanisole	C ₇ H ₆ Cl ₂ O		Musty	nil			177.028
2,6-Dichloroanisole	C ₇ H ₆ Cl ₂ O		Musty	0.5			177.028
Benzothiazole	C ₇ H ₅ NS		Chemical	80	2.28	0.765-4.3	135.186
2-Chlorophenol	C ₆ H ₅ ClO		Medicinal	360		28.5	128.556
2,6-Dibromophenol	C ₆ H ₄ Br ₂ O		Medicinal	0.5			521.9
1-Octen-3-ol	C ₈ H ₁₆ O		Fungus	0.5	-1.7	1.31	128.212
1-Octen-3-one	C ₈ H ₁₄ O		Fungus	3	-4.7	0.241	126.196
Iodoform	CHI ₃			30		Insoluble	393.732
Low molecular weight aldehydes			Fruity	>30			

Source: (Antonopoulou et al. 2014; Callejón et al. 2016; Talaiekhosani et al. 2016)

scheremetievi, *Oscillatoria f. curviceps*, and *Oscillatoria tenuis* (Catherine et al., 2013). Apart from these bacteria, several other odorous compounds which produce odor and taste in water whose concentration have been reported to be in the range of ng/dm³ are listed in Table 2. Several of these have been identified and quantified with different analytical tools. However, compared to other musty odorants in water, 2-MIB and GSM have attracted more attention because they are the most frequently occurring musty odorant worldwide.

The growth of secondary metabolites of 2-MIB and GSM are based on some environmental factors specifically phosphorus, nitrogen, and temperature. An increase in eutrophication can be due to fertilizer application from agricultural activities and may enhance the level of the metabolites (Wang et al., 2015c). Freeman (2010) linked the occurrence of harmful algal bloom to high bacterial densities and increased water temperature. It is, therefore, necessary to mitigate eutrophication and cyanobacterial blooms by controlling the levels of nitrogen, phosphorus and phytoplankton growth. This is necessary in order to reduce the production of taste and odor compounds, such as 2-MIB and GSM in water bodies.

Wang and Li (2015) evaluated the effects of light and temperature on the MIB-producing *Pseudanabaena* sp. *Lauterborn* and GSM-producing *Anabaena ucrainica* (Schorb.) Watanabe. The authors detected maximum odor production and lowest growth rate at 35 °C, the light intensity of 60 $\mu\text{mol photon m}^{-2} \text{s}^{-1}$. They linked high proportion of GSM and 2-MIB to decrease cellular metabolic activity in cyanobacteria. In their report, the temperature was considered an important parameter for the release of 2-MIB and GSM. Similarly, Greenwald et al. (2015) observed that the presence of natural organic matter (NOM) enhanced the levels of these compounds in surface water.

Geosmin and 2-methylisoborneol from wastewater

Anthropogenic sources such as wastewater discharges and chemical spills serve as the primary sources of many contaminants. Industrial wastes together with municipal wastewater discharge contaminated water bodies through the addition of volatile organic compounds and algal volatile organic compounds. These organic compounds originated from pulp and paper

industries effluents, petrochemical factories, and farmlands activities (eutrophication) percolate via the soil into the rivers and groundwater. Some of these effluents contain GSM and 2-MIB, which, if left unresolved, could hinder the recycling of water in agricultural systems (Sarker et al., 2014). These problems of odor usually lead to loss of customers' interest in eating fish and shellfish (Burr et al., 2012). This is because GSM and 2-MIB easily get absorbed through the gills, skin and gastrointestinal tracts of fishes, thus reducing their commercial values (Hathurusingha & Davey, 2014).

GSM, 2-MIB, and other volatile odorants such as 2,4,6-trichloroanisole (TCA), 2-pyrrolidone and hydroxyvanillin were detected in effluents from wastewater plants before and after treatment (Agus et al., 2011; Urase & Sasaki et al., 2013). Agus et al. (2011) and Urase and Sasaki (2013) independently observed that TCA was more effectively removed than GSM and 2-MIB on the application of ozonation. The effective removal of TCA was ascribed to interference of similar structural compounds, such as camphor (Eaton & Sandusky, 2010). Carbonyl compounds such as decanal was reported to be present in organic wastewater and this enhanced the rapid growth of cyanobacteria in water due to complex organic disinfectants applied during water treatment operations (Wu & Duirk, 2013).

Organic chemicals released from industrial activities, emission of substances from water purification processes, pesticides, insecticides, and fertilizers from agricultural farmlands and domestic effluents also lead to the production of odor in the environment. Thus, plans on how to remove or minimize the occurrence of odor in water bodies because of these activities vis-a-viz search for alternative techniques that could remove these contaminants below threshold limits should be given adequate priority.

Effects of 2-methylisoborneol and geosmin

Researchers have recognized tastes and odor compounds in drinking water supplies as water quality problems and various toxicological studies have attested to this issue. These compounds have not actually been reported to have any known adverse effects on humans (Newcombe et al., 2010). Taste and odor posed a risk to the final consumers, and many consumers' complaints have been reported (Olsen et al.,

2016). Since the provision of safe drinking water to the consumer is always the major priority of water suppliers, continuous widespread public alarm and distrust in potable water suppliers could be linked to T&O problems which could impact negatively on product reputation (Dietrich & Burlingame, 2015; Dunlap et al., 2015).

Septic odor in aquatic life has been investigated in bighead carp (*Hypophthalmichthys nobilis*) (Zhang et al., 2016a), barramundi (*Lates calcarifer*) (Hathurusingha & Davey, 2014), rainbow trout (*Oncorhynchus mykiss*) (Hathurusingha & Davey, 2014; Schrader et al., 2014) atlantic salmon, *salmo salar* (Davidson et al., 2014a), and arctic charr (*Salvelinus alpinus*) (Houle et al., 2011). The authors attributed the odor in these different kinds of seafoods to GSM and 2-MIB. In fact, the presence of these compounds in some of the seafood has affected their yields and prices (Zhang et al., 2016b). As suggested by Schrader et al. (2014) odor-causing bacteria in seafoods could be depurated from the aquatic flesh by moving them to odor-free water. However, the question is “will there still be no cyanobacteria growth in the freshwater as a result of certain concentrations trapped in the gills or the flesh of the aquatic species that are being transferred”? The ultimate answer is that concrete measures have to be taken in order to control the bloom of these compounds in the aquatic environment.

Investigation on effects of 2-MIB and GSM is urgently needed to fully address the safety of drinking water and toxicological effects on humans and other animals. This is because blue-green algae produce various toxins such as hepatotoxins, cylindrospermopsins, microcystins, neurotoxins, anatoxins, homoanatoxins, saxitoxins, dermatoxins, lyngbya toxins, and aplysia toxins that cause several diseases like liver, neural system, and skin damages (Graham et al., 2010). It was reported by US EPA (2013) that the exposed parts of the body to water containing cyanobacteria cell and their toxins could cause dermal damage while their ingestion could lead to abdominal pain, vomiting and nausea, dry cough, diarrhea, blistering around the mouth, sore throat, and pneumonia. It was also confirmed by Davidson et al. (2014b) that these algal toxins cause skin, cancer, and liver damage. Based on these health implications, effective measures are required by drinking water supply industries to rid

the aquatic environment of these emerging contaminants. This could be done by developing rapid, sensitive, and robust techniques to identify, monitor, and remove these compounds thereby restoring consumers' confidence.

Detection of 2-methylisoborneol and geosmin

2-MIB and GSM have odor detection concentrations below 10 ng/dm³ (Kim et al., 2014). These contaminants affect aquatic species even at low concentrations; thus, it is important that efficient method for their accurate determination is developed. Reliable extraction analytical techniques have been developed to analyze trace amounts of these compounds. Some of the analytical methodologies mostly employed include closed-loop stripping and open-loop stripping (Wang et al., 2015b), liquid–liquid extraction (Wen-Hsing et al., 2012), liquid-phase microextraction (Cortada et al., 2011; Marquez-Sillero et al., 2011), purge and trap (Deng et al., 2012; Yuan et al., 2013), solid-phase extraction (Kim et al., 2015), solid-phase microextraction (Burr et al., 2012; Ding et al., 2014a, b; Machado et al., 2011), and stir bar sorptive extraction (Ruan et al., 2013; Wu & Duirk, 2013). Gas chromatography coupled with highly sensitive mass spectrometry (GC/MS) has also been used for a very long time, for the identification and quantification of these compounds (Ma et al., 2011; Peng et al., 2014; Ruan et al., 2014). Based on each method, different forms of two chemical substances have been identified and determined as summarized in Table 3. The accurate determination of these compounds even at very low concentrations requires selective, sensitive, and simple techniques. To date, various techniques for the extraction of GSM and 2-MIB in water samples including GC/MS have been employed and the most commonly used technique has been found to be the solid phase microextraction as depicted in Table 3. The extraction methods depend mostly on solvent extraction, solvent volume, temperature, configuration time, speed, and stirring rate.

The conventional analytical method, closed-loop stripping and open-loop stripping is simple and cost-effective but requires a large volume of sample, time, labor, and high-resolution mass spectrometer. Other techniques such as liquid–liquid extraction and solid-phase extraction have certain shortcomings

Table 3 Summary of analytical techniques used for the determination of GSM and MIB in aqueous matrix

Compounds	Media/country	Reaction parameters	Technique	Findings	Reference
2-MIB and GSM		Solvent volume and type, sample volume centrifugation speed and time, extraction time and temperature	LLME	Detection limit of 2.00 ng/dm ³ and 9.00 ng/dm ³ for geosmin and MIB respectively	Cortada et al. (2011)
2-MIB and GSM		Optimization of extraction and detection condition, extraction solvent, head space and microdrop volume, stirring rate, equilibrium and extraction time and ionic strength	HS-LPME	Detection limit of GSM and MIB were 1.10 and 1.00 ng/dm ³ respectively	Ma et al. (2011)
2-MIB and GSM		High purity nitrogen purge gas	PT	Detection limit was < 0.08 ng/L for GSM and < 1.5 ng/dm ³ for MIB. No solvent was used for the extraction and concentration technique	Deng et al. (2012)
2-MIB and GSM	Jinan	SPE column and eluting solvent	SPE	Methanol used as solvent. Detection limit of 0.5–1.5 ng/dm ³	Sun et al. (2012)
2-MIB and GSM		Temperature	SBSE	Detection limit and limits of quantification of GSM and 2-MIB were 0.3 ng/dm ³ and 1 ng/dm ³	Raun et al. (2013)
2-MIB and GSM		Extraction temperature and time, desorption time, sonication time and temperature and GC/MS configuration	HS-SPME	Low detection limit	Wu and Duijk (2013)
2-MIB and GSM		Temperature and time	HS-SPME	Detection limit of 1.3 ng/dm ³ , %relative standard deviation (% RSD) in the range of 4.4 to 9.9 %	Ding et al. (2014a)
2-MIB and GSM	Jiangsu province of China	Concentration	HS-SPME	Detection limit < 10 ng/dm ³	Ding et al. (2014b)
2-MIB and GSM	Nova Scotia, Canada	Optimization of methods linearity, precision and accuracy	SPE	Detection limit of 0.9 ng/dm ³ and 5.5 ng/dm ³ for GSM and 2-MIB respectively	Wright et al. (2014)
2-MIB and GSM			SPE	Detection limit of 0.87 ng/dm ³ and 0.62 ng/dm ³ for 2-MIB and GSM, respectively	Kim et al. (2015)
2-MIB and GSM	Liaoning	Time, salt, and temperature	HS-SPME	Absence of organic solvent. Detection limit of 3–3.36 ng/dm ³	Cheng et al. (2015)

SPE solid-phase extraction, PT purge and trap, HS-SPME headspace solid-phase microextraction, LLME liquid–liquid microextraction, OLS open loop stripping, SBSE stir bar sorptive extraction

which include multiple operational procedures, time consumption, uncertainty in the detection limits and unsuitability for low boiling points earthy compounds (Capriotti et al., 2010).

The adsorption of 2-MIB and GSM using SPME extraction procedure has been reported to be unique and analytically effective. This procedure has advantages over the earlier LLE, SPE, and PT which include simplicity, robustness, cheap, and solvent-free with rapid extraction times, required small sample volumes and allowing fast automation (Kristiana et al., 2010). Despite several advantages, SPME still has certain drawbacks such as the choice of fiber, equilibration time, temperature conditions, extraction times, and use of salts to alter the solvent's ionic strength. Yuan et al. (2013a) found PT coupled with GC/MS method to be more suitable for the analysis of GSM and 2-MIB in clearer water samples and head-space solid-phase microextraction is more advantageous in the determination of these compounds in eutrophic water samples. Since 2010 till date, several studies have reported the use of SPME as an analytical technique which has great advantage over other methods due to the low detection limits obtained under the optimized parameters such as extraction time, temperature, ionic strength, and type of fiber. Among the newly developed techniques, hollow-fiber liquid-phase microextraction was more appropriate for the extraction of earthy-musty odorous compounds. In this technique, Yu et al. (2014) reported that hollow fibers with different pore sizes, wall thicknesses, internal diameters, and membrane porosities were compared for the extraction of earthy-musty odorous compounds in water. It was found that the MIF-1b polyvinylidene fluoride (PVDF) fibers hollow fiber, which had relatively high porosity and enhanced solvent compatibility, gave a good extraction performance. It was established that the method is robust and reliable. It was also reported that PVDF HF-LPME technique coupled with GC-MS provides a rapid and sensitive approach for routine determination of trace levels of these compounds in water samples.

Although the conventional analytical methods used so far for these compounds demonstrated some quantitative advantages, there are limitations on speedy assessments of water quality due to their complex pretreatment procedures and lack of experienced operators of the equipment involved (Son et al., 2015). For

instance, the GC-MS analysis of these compounds requires sufficient pre-concentration or extraction methods for the targeted compounds. Thus, highly automated methods requiring less sample preparation with simultaneous determination ability in a single analysis and identification of odorants in complex water sources at low sensory threshold levels are needed. Therefore, in a study, the combination of data from gas chromatography-olfactometry with mass spectrometry and comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry for the identification of potential odorants in highly complex water matrices has been considered (Guo et al., 2016). Results from the study showed that combined analysis could be used for the identification of earthy and musty odorous compounds in source waters with complex matrices.

Furthermore, olfactory nanovesicles (human olfactory receptor-based bioelectronic nose) functionalized with the single-walled carbon nanotubes field-effect transistor was designed to detect GSM and 2-MIB at the same time for accurate monitoring of water quality and water contamination (Son et al., 2015). The bioelectronics nose measured GSM and 2-MIB at concentrations below (10 ng/dm^3) from the tap, bottled, and river waters without pretreatment methods. This method has shown some remarkable qualities due to absence of pretreatment technique when compared to other conventional methods.

Treatment techniques for 2-methylisoborneol and geosmin

Different treatment techniques such as physical, chemical, and biological methods have been utilized to remove 2-MIB and GSM in water. Some of the different techniques developed for the removal of 2-MIB and GSM in water include coagulation, flocculation, adsorption, precipitation, reverse osmosis, membrane bioreactor, nanofiltration, and ozonation electro dialysis. However, the taste and odor compound removal using activated carbon could be reduced due to the strong competition between the natural organic matter in water, and the compounds of interest for activated carbon adsorption sites (Wang et al., 2020). The performance of activated carbon could be affected by its surface properties and pore size distribution. The adsorption processes based on the removal of organic compounds using coagulation, powdered activated

carbon, granular activated carbon, super fine activated carbon, and biologically activated carbon are examined as follows:

Coagulation and chemical oxidation processes

Over the years, standard conventional water treatment processes (coagulation, flocculation, sedimentation, and filtration) were primarily used to remove cyanobacteria (blue-green algae) that produce toxins in finished water (Zamyadi et al., 2015). Seckler et al. (2013) demonstrated the removal of 2-MIB by PAC adsorption combined with salt as a coagulant. The effectiveness of the treatment before and after adsorption was evaluated using coagulant dosages in the range of 10 to 30 mg/dm³ and PAC dosage of 10 to 40 mg/dm³. The optimization results revealed that the highest 2-MIB removal was at 70% without an addition of a coagulant. However, the lower 2-MIB removal rate was attributed to the addition of the coagulant which caused serious competition between the iron precipitate and coagulant for adsorption sites. The level of interference in the system occurred because the surface of the PAC was coated by the coagulant and this interfered with the adsorbed odorous compound. Thus, the powdered activated carbon was less effective upon the addition of the coagulant (iron precipitate) although it was noted that the authors used high PAC dosage in order to obtain high 2-MIB removal efficiency. Furthermore, the combination of these methods could incur considerable expense to water utilities. In another study, the effect of pH on the released metabolites by cyanobacteria in water treatment plant by Qian et al. (2014) demonstrated that the pH of water contributed to the reduction of cyanobacteria metabolites which include GSM and 2-MIB in water. It was observed that below pH 5, the application of coagulants resulted in the release of these compounds while above the pH 5, and the rate of contamination of water by these cyanobacteria was considerably reduced. Although, the authors opined that keeping the pH above 5 could be dangerous for human consumption.

Adsorption using different types of activated carbon

Activated carbon is a material used to absorb natural organic compounds, and other synthetic organic chemicals in drinking water samples. The

carbon materials of different forms are widely used to remove micropollutants and hydrophobic compounds in water treatment plants due to their porosity which provides a large surface area for the uptake of pollutants (Matsui et al., 2015). These adsorbents are classified into GAC, PAC, and super fine activated carbon (SFAC) depending upon their particle sizes. The deterioration of surface water quality and improvement of consumer demand has brought about the application of these classes of activated carbon to remove GSM and MIB from the water. However, the performance of the activated carbon for the removal of these contaminants in drinking water is often limited due to factors such as surface area, dissolved organic carbon (DOC), contact time, and dosage (Kim et al., 2014). The effectiveness of adsorption using activated carbon for municipal drinking water supplies and other water treatment processes is based on its wider application and simplicity. However, adsorbent dosage at milligram levels is usually required for most activated carbon applications which are much higher than the part per trillion or nanogram per cubic decimeter concentration usually required for treating water samples containing emerging contaminants. Also, the adsorption rate of 2-MIB and GSM from water samples is usually low due to the presence of NOM which compete for the available adsorption sites on the surface of activated carbon during the adsorption process (Matsui et al., 2013).

Several studies on the removal of GSM and 2-MIB via activated carbon adsorption process have been reported. Ho et al. (2010) demonstrated the use of a granular activated carbon filter for the removal of cyanobacteria in water and found that adsorption column experiment using GAC validated the effective removal of some physicochemical parameters, cyanobacterial metabolites and dissolved organic carbon. Filtration processes using activated carbon, slow sand filtration, and ultrafiltration was also used for the removal of GSM and 2-MIB in drinking water. Removal rates were found to depend on filter media, temperature, biomass, and contact time. It has also been reported that PAC is mostly influenced by its particle sizes, simply because adsorption occurs in the internal pore structure (Summers et al., 2013). The overall performance of PAC or GAC is a function of contact time, and this has remarkable flexibility in application. Summers et al. (2013) utilized laboratories GAC column to remove 2-MIB from the water.

They found that dissolved organic matter concentration reduced the adsorption rate of 2-MIB by granular activated carbon.

Adsorption kinetics was carried out to evaluate 2-MIB and GSM removal efficiency of a PAC-membrane hybrid system coarse powder activated carbon contactor and a submerged membrane tank (Kim et al., 2014). Optimum PAC dosages were determined to be 15 and 5 mg/dm³ for 2-MIB and GSM, respectively. Kim et al. (2014) found that coarse powdered activated carbon contactor was able to remove above 7% of 2-MIB and GSM each. The removal efficiency of 2-MIB and GSM in the coarse powdered activated carbon contactor was directly proportional to the temperature of water and the biological efficiency was almost doubled as the raw water temperature increased from 5 to 20 °C.

The application of the homogeneous surface diffusion model (HSDM) as a tool for predicting the PAC dosages for the removal of 2-MIB and GSM in drinking water has also been investigated. Yu et al. (2016) suggested a simplified approach for the application of the homogeneous surface diffusion model. Their model was used to predict the PAC doses in three water samples for the removal of 2-MIB. They compared this model with the experimental data obtained for equilibrium and kinetic experiments. The differences between the predicted and observed results of different treatment steps were within 10%. It was noted that only the removal of the 2-MIB by HSDM was monitored in the source water, although the model was tested for the destruction of GSM. They postulated that the combination of the kinetic experimental results and the simplified HSDM approach would aid possible prediction of PAC doses and contact times, thus providing more flexibility in the related applications.

Different modelling approaches such as the tracer, the equivalent background compound, and the simplified equivalent background compound models were applied to describe the competitive adsorption of 2-MIB and GSM and NOM (Zoschke et al., 2011). The adsorption of GSM and 2-MIB onto powdered activated carbon was done to reduce the compounds below their threshold concentrations. It was found that flocculation removed only NOM that was unconnected to the adsorption sites on the carbon surface. In addition, a simplified equivalent background compound model served as an excellent

tool for the use of powdered activated carbon in the reduction of these contaminants below their odor threshold concentrations. The significance of industrial, landfill, and agricultural level as sources of 2-MIB and GSM and cyanobacteria metabolites in drinking water systems including the empirical data remain crucial to this model. Hence, it was proposed that more research is required for the implementation of the simplified equivalent background compound model.

The use of superfine powdered activated carbon has also been found to improve the uptake of adsorbates from water samples. According to Ando et al. (2010) and Matsui et al. (2011), fine activated carbon particles have a higher adsorption capacity than PAC or GAC. In addition, Matsui et al. (2012) who studied the competitive adsorption of 2-MIB and natural organic matter by super fine and powdered activated carbons showed that there was an increased adsorption of NOM compared to 2-MIB. This observation was consistent with an earlier report that GSM and 2-MIB removal efficiencies by activated carbon are influenced by natural organic matter present in the water. It was also established that the removal of the 2-MIB in the sample was attributed to carbon particle size, which enhanced NOM uptake since smaller adsorbent particles have faster adsorption kinetics than bigger ones.

Integrated processes

A combination of ozonation and PAC has been employed to treat water containing MIB and GSM. It was established that the PAC confined in a fixed filter in conjunction with ozone mineralized 2-MIB and GSM into lower molecular weight compounds. Andreadakis et al. (2010) used both PAC and ozonation for the removal of both 2-MIB and GSM from surface water. They observed that the adsorption of the former was far greater than that of the latter and further utilization of ozone dosage in the range of 1–3 mg/dm³ at a contact time of 5–10 min reduced the concentration of both these cyanobacteria metabolites to level below the odor threshold concentrations. Despite the fact that 2-MIB and GSM were typically removed in water treatment plants through the addition of PAC, the cost performance variables which depend on the water chemistry should be the major priority.

Potassium permanganate and PAC were introduced into a sludge thickener that contained 2-MIB of 1500 ng/dm³ (Zamyadi et al., 2016). It was observed that more than 99% of MIB in the sludge thickener was removed in the finished water. The results showed that the combination of oxidant and activated carbon helped to reduce the concentration of cyanobacteria during the water treatment process. However, the authors failed to examine the removal of DOC from the water sample. The effect of activated carbon for the adsorption of the metabolites and the interaction of DOC with 2-MIB and GSM was not investigated. Li et al. (2015) combined PAC and oxidants such as chlorine and potassium permanganate to destroy algal metabolites such as GSM and 2-MIB in water. The authors reported that the oxidants were ineffective while PAC exhibited excellent performance in the removal of the earthy/musty odorants. They came to a conclusion that the adsorption mechanism was as a result of hydrophobic and π-electron interaction which was involved in the adsorption performance of the 2-MIB and GSM.

Advanced oxidation processes

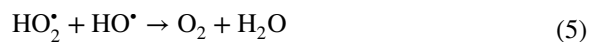
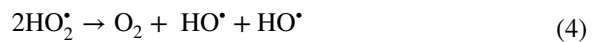
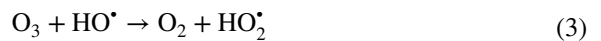
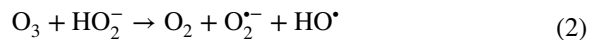
Over the past few years, several publications have focused on the degradation of taste and odor compounds in water using AOPs. Advanced oxidation processes include ozonation, ozone/hydrogen peroxide, ozone/UV, hydrogen peroxide/UV, UV/TiO₂, ozone/biological activated carbon, UV/VUV (vacuum UV), irradiation ultrasonic irradiation or sonolysis, photocatalytic and electrochemical. These are treatment processes for the degradation of both organic and inorganic compounds in water through oxidation with hydroxyl radicals.

Generally, AOPs are divided into homogeneous and heterogeneous involving the initial attacks on target compounds by hydroxyl radicals and fragmentation of the organic pollutants into carbon(IV) oxide and water. The advantages of the AOPs include fast reaction rates and non-selective oxidation and effective elimination of organic compounds in aqueous media (Antonopoulou et al., 2014). Although the use of AOPs has been introduced as alternative pre or post-treatment techniques for the removal of musty compounds in water, they could be potentially costly and technically demanding.

In the last couple of years, due to the systematic failure of the conventional techniques, advanced treatment options based on oxidation involving the use of free reactive oxygen species to decompose organic pollutants into harmless compounds such as carbon (IV) oxide and water have been developed. These technologies are categorized into photochemical and non-photochemical processes which include photolysis, radiolysis, sonolysis, Fenton cavitation, electro-Fenton, photo-Fenton, heterogeneous photocatalysis, hydrodynamic cavitation, and electrohydraulic discharge and reviewed as follows:

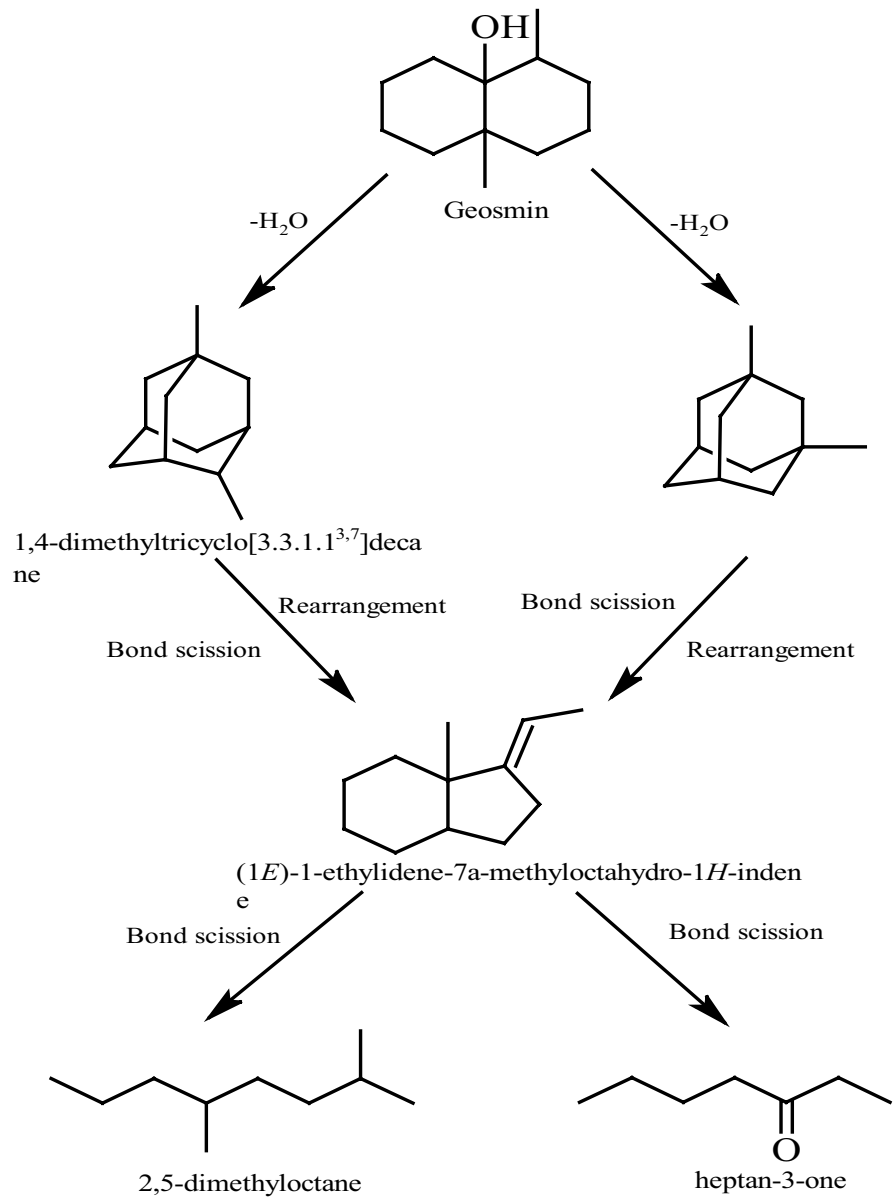
Ozonation

Ozonation involves the reactions of ozone with organic compounds. In this process, the hydroxyl radical which is the dominant species in the solution is formed by ozone decomposition as shown in the Eqs. 2–6.



Ozone is one of the short-lived, unstable but strongest oxidants useful for the degradation of 2-MIB and GSM in water. The degradation of organic pollutants via ozonation technique is dependent on pH, temperature, and ozone dosage. The degradation process of ozonation is the first step of the radical mechanism which leads to the formation of the hydroxyl radicals. Yuan et al. (2013b) found that the degradation of 2-MIB and GSM produced secondary metabolites as described in Figs. 1 and 2. Results of their findings revealed that the removal efficiency of 2-MIB and GSM was higher than 90% at pH 3 while no 2-MIB and GSM was detected at pH 9.1. The removal rate declines with the initial concentration of 2-MIB and GSM. The removal rate of GSM decreased from 97.9 to 72.6% at 100–500 ng/L and the removal rate of MIB reduced from 93.6 to

Fig. 1 Proposed pathway of GSM degradation during ozonation (Yuan et al., 2013b)



66.4% at 100–500 ng/L. The ozonation process led to 99.9% GSM removal at 30 min and ozone dosage of 4.19 mg/L. Though, the degradation mechanism followed dehydration process through formation of cyclodecane compounds. However, bond scission and rearrangement occurred to form bicyclic diene as one of the intermediates. The 2,5-dimethyloctane and heptan-3-one formed through the ring-opening reaction (scission) during the last stages.

The mechanistic degradation steps described in Fig. 2 involved a dehydration process, bond Destruction

of 2-MIB by cleavage, and demethylation to produce decanal (C₁₀H₂₀O). It has been reported that the yield of decanal in a chemical reaction may have adverse respiratory health effects on humans upon exposure. Thus, it is necessary to minimize the quantity produced during the removal of these pollutants in water.

Contrary to the findings of Qi et al. (2009), the removal efficiency, products, and degradation pathways of 2-MIB in drinking water are not dependent on the initial concentrations as reported by Yuan et al. (2013b). Qi et al. (2009) found that hydroxyl

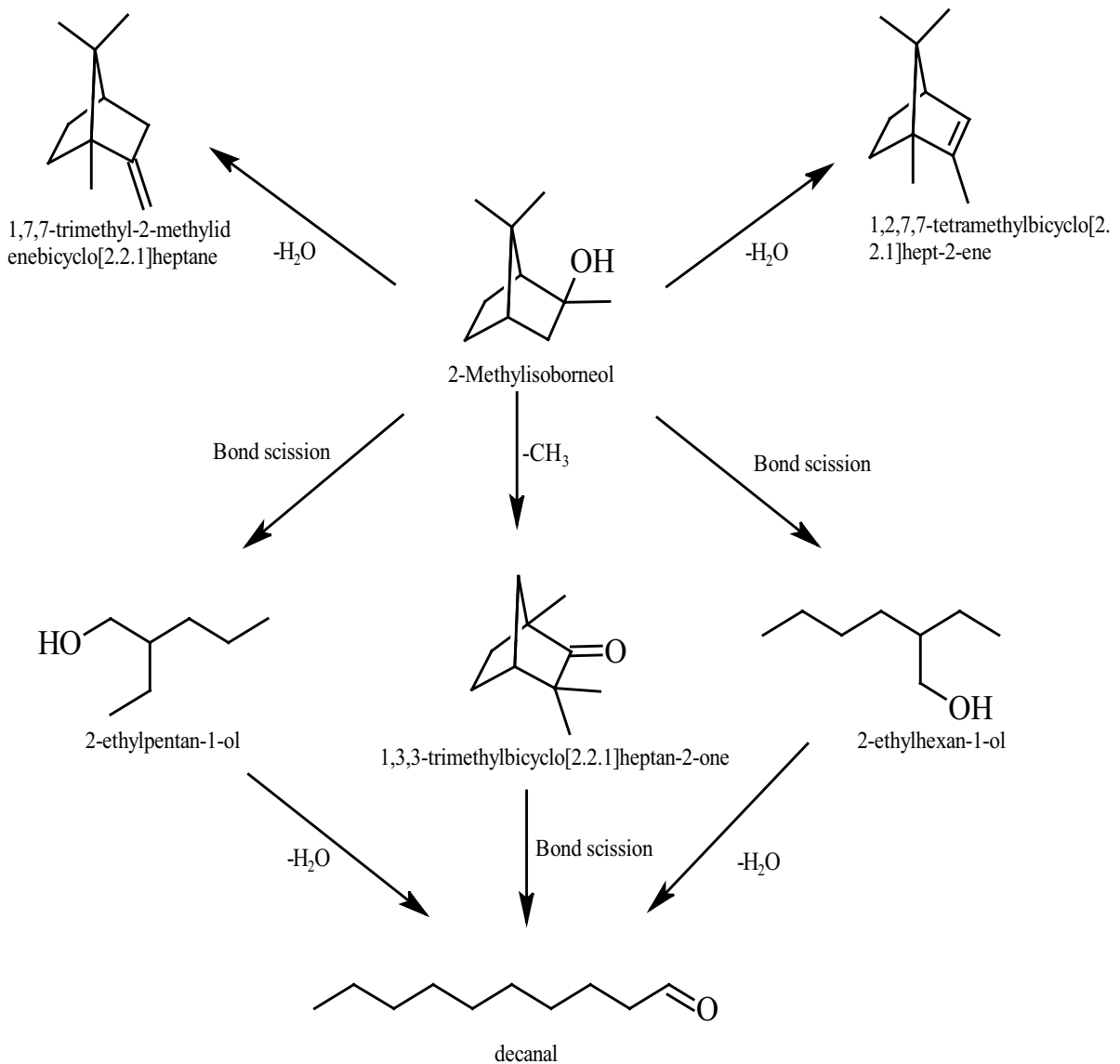


Fig. 2 Proposed pathway of 2-MIB degradation during ozonation (Yuan et al., 2013b)

radicals are the major species responsible for 2-MIB destruction. Effective removal of 95% of 2-MIB was achieved at ozone concentration of 62.5 $\mu\text{mol/L}$ for MIB concentration in the range of 0.0744 to 0.2976 $\mu\text{mol/L}$ after 30 min. The proposed mechanisms for the destruction of 2-MIB at different reaction time detected by GC-MS analysis revealed 1,7,7-trimethylbicyclo [2.2.1] heptan-2-one, also known as camphor, as the major product. This compound further decomposes by oxidation to form aldehydes, ketones, and carboxylic acids as intermediates. The isolated

surface water was found to require low ozone dosage compared to the surface water that contained dissolved organic carbon, humic acid, and hydrophobic organic matter. The study by Qi et al. (2009), however, failed to establish the degradation mechanisms that led to the detection of extracellular organic products and their by-products in treating water. Figure 3 indicates the two key intermediate compounds, namely alkanonic acid and alkanone produced as a result of a high dose of ozone and oxygen for an extended period of time as detected by GC-MS analysis under neutral pH

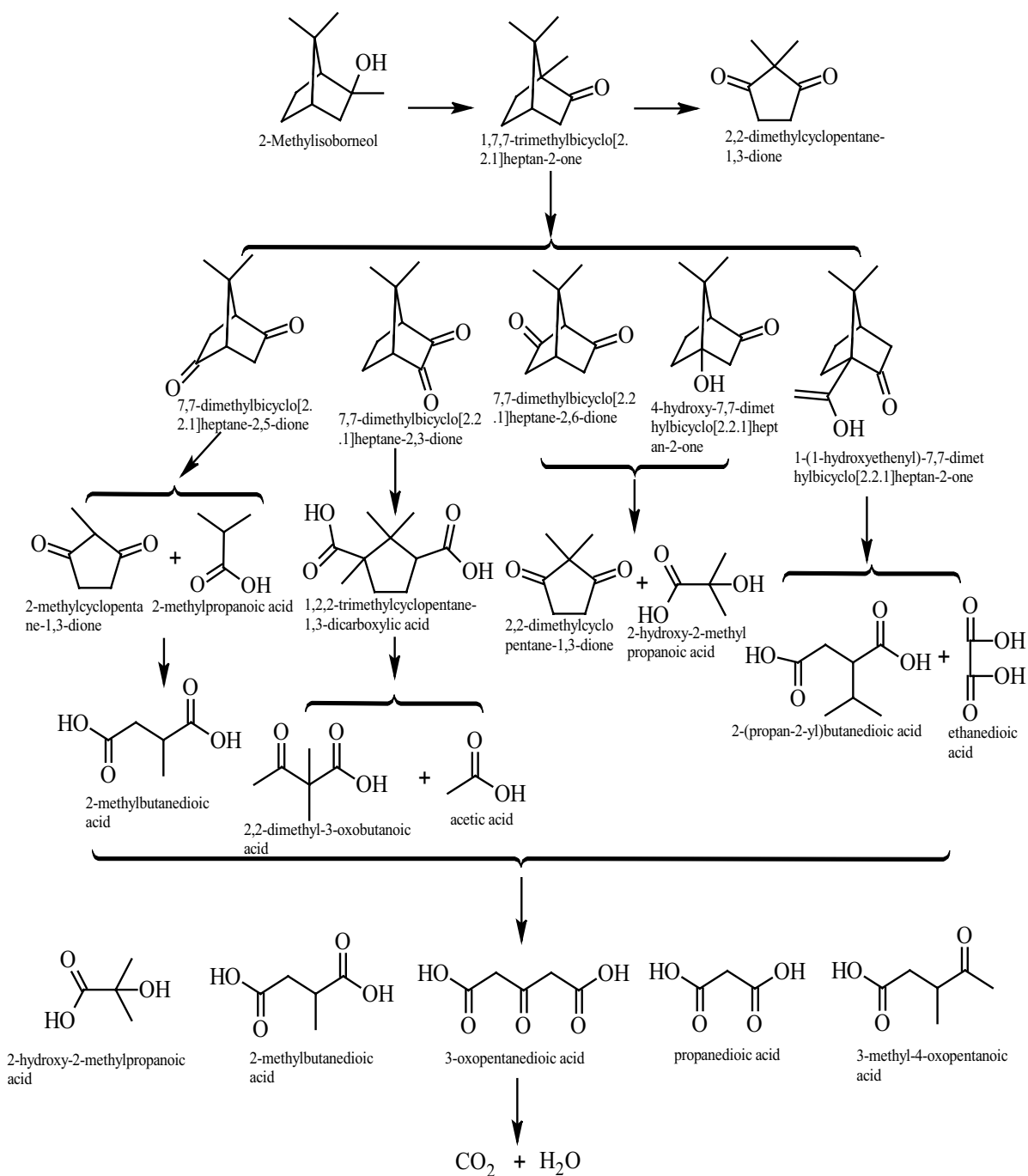


Fig. 3 Proposed degradation pathway of 2-MIB in drinking water by ozonation (Qi et al., 2009)

condition. These products further degraded into carbon dioxide and water.

The degradation pathway of 2-MIB by ozonation was studied by Qi et al. (2009) at a pH of 7. It was

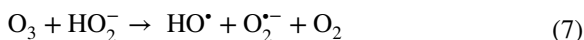
established that the tertiary alcohol group of 2-MIB was oxidized to form a ketone with the loss of the methyl group attached to the carbon bearing the alcohol substituent. The carbons further reacted with

ozone to form carbonyl (–CHO) groups and with the hydroxyl radical to form carboxyl (–COOH) and hydroxyl groups. It was also shown that the removal of these emerging contaminants was influenced by high ozone dosage, high temperature and light intensities (Wang & Li, 2015).

In general, although ozonation has proven to be an effective way of decomposing odor causing compounds in water, it is very expensive and produces transformation by-products such as bromate, aldehydes, ketones, and carboxylic acids whose full toxicities are yet to be known. Taking into cognizance the highlighted shortcomings, the application of the ozonation technique may have to be in combination with other techniques that will help in the complete removal of 2-MIB and GSM and other toxic by-products.

Ozone/hydrogen peroxide

The reaction of hydrogen peroxide with ozone, often called the peroxone process, produce the hydroxyl radicals, and the process has been used for the removal of certain by-products in water purification. The overall reaction involves the splitting of hydrogen peroxide in water and the subsequent reaction of reactive species (HO₂⁻) with ozone as indicated in the Eqs. 6 and 7.



The peroxone process has been found to effectively control bromate formation and natural organic matter during the purification of water (Li et al., 2015; Pisarenko et al., 2012; Qi et al., 2016). Similar results have been found for the degradation of GSM and 2-MIB using this process. Lately, complete removal of septic odor from Huangpu river water in China was demonstrated by the addition of peroxide prior to ozone-biological activated carbon treatment (Wang et al., 2014). These authors found that with the addition of different ratios of H₂O₂ and O₃ to obtain the optimum suitable ozone dose (2 mg/dm³), complete removal of odor was achieved. It was established that experimental design enhanced the removal of odor, and that of carcinogenic bromate formed.

Destruction of 2-MIB by O₃/H₂O₂ in water was investigated by Li et al. (2010a), using GC-MS, and they identified ketones and aldehydes as transformation by-products of the 2-MIB and GSM. The degradation of 2-MIB reached 89.2% under the following conditions: reaction time (20 min) and H₂O₂ concentration 6 mg/L. It was also established that the degradation efficiency of the 2-MIB by ozonation was inhibited by the presence of natural organic matter in the water.

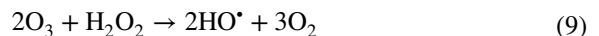
Although bicyclic and monocyclic compounds are often formed in the ozonation of 2-MIB in water, some of them are intermediates of bicycloheptanone (higher molecular weight to cyclopentanedione) and a cyclopentanone (lower molecular weight) that can further be degraded to CO₂ and H₂O. However, Li et al. (2010a, b) did not achieve the complete conversion of 2-MIB into harmless compounds such as CO₂ and H₂O as presented in Fig. 4. Therefore, the appropriate combinations of methods that will ensure full mineralization are needed.

Ozone/ultraviolet radiation

This is the combination of ozone with ultraviolet (UV) radiation in the presence of water to produce peroxide (Eq. 8).

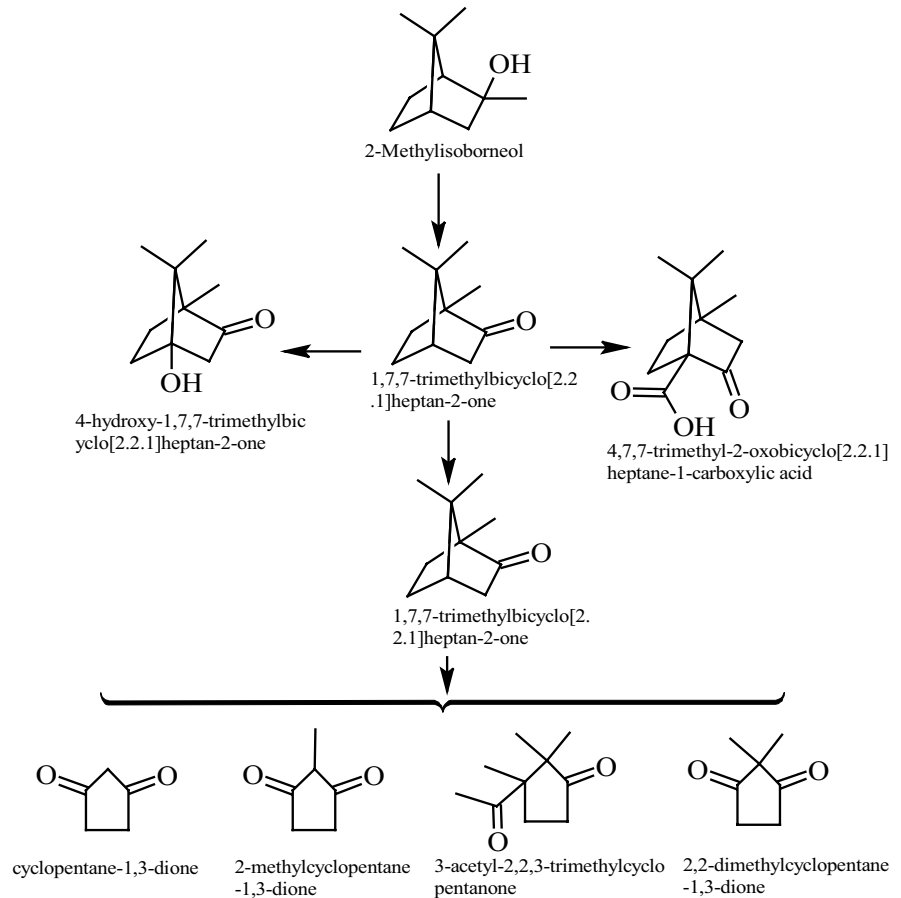


The reaction between ozone and peroxide in the presence of ultraviolet light yields the hydroxyl radicals (Eqs. 9 and 10) which is a strong oxidizing agent.



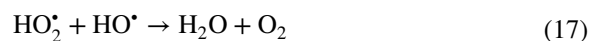
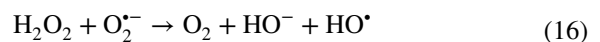
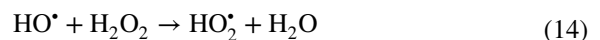
Zoschke et al. (2012) found that the concentrations of GSM and 2-MIB in water were reduced by ozone/UV radiation. They also further used combination of vacuum UV (VUV) and ozone, which resulted in the formation of non-toxic by-products such as nitrate and bromate. Although previous studies have shown that ozone/UV radiation process often produces bromate (BrO₃⁻) as a result of ozone reacting with bromide ions in water as indicated in Eq. 11, the reverse was the case in the study reported by Zoschke et al. (2012).

Fig. 4 Degradation pathway of 2-MIB under ozonation Li et al. (2010a, b)



Ultraviolet radiation/hydrogen peroxide

The degradation of organic compounds or micropollutants using UV/H₂O₂ may occur either as a photolysis or an oxidation reaction. The reaction mechanisms involve three steps (initiation, propagation, and termination). The effectiveness of this process depends on the oxidation mechanism for the destruction of organic compounds. The unreacted hydroxyl radicals are consumed by hydrogen peroxide for further production of radicals since the hydroxyl radical is the predominant active species as shown in the following equations.



The UV/H₂O₂ process has the advantage of the high solubility of H₂O₂ in water and can be added to the source water at high concentrations with no formation of bromate. These systems have been widely studied by various authors (Rosa et al., 2015; Shan et al., 2015; Zuo et al., 2016). The destruction of GSM and 2-MIB by UV photolysis, UV/chlorine, and UV/H₂O₂ processes was investigated by Wang et al. (2015a).

It was observed that degradation rate increased with an increase in hydroxyl radicals as the solution pH increased from 6.5 to 8.5. However, there were slight decreases in the rates of destruction of the two compounds due to the presence of the hydroxyl radicals and carbonate ion which are present in water at high pH. Thus, carbonate species interfered with the rate of removal of both compounds in water by competing with the available hydroxyl radicals at alkaline pH values.

Ultraviolet and UV/chlorine radiation remediation

UV irradiation photolysis provides an effective means for the degradation of large molar absorption coefficient organic pollutants (Sarathy & Mohseni, 2016). The variation in degradation by UV photolysis depends on the conditions and the nature of the target contaminants in water. The use of UV and UV/chlorine irradiation has not been extensively used in the removal of GSM and 2-MIB. Only a few studies have been conducted to examine and identify the intermediates of these compounds using the two methods. For instance, Fotiou et al. (2015b) studied the degradation of cyanotoxin under visible light and found that microcystins and cylindrospermopsin degraded slowly while GSM and 2-MIB were completely recalcitrant to degradation under visible light.

Furthermore, Wang et al. (2015a) investigated both pilot and full-scale performance of the considered UV/chlorine process for the destruction of GSM, 2-MIB and caffeine as a surrogate in two different surface waters. The efficiency of the UV/chlorine process at pH 7.5 and 8.5 was comparable to that of the UV/hydrogen peroxide process under parallel conditions and was superior at pH 6.5. Caffeine was found to be a suitable surrogate for GSM and 2-MIB and could be used as a more economical alternative to either GSM or 2-MIB spiking for site-specific full-scale testing. The formation of disinfection by-products is an important concern in the UV/chlorine system even though 90% of 2-MIB and GSM were decomposed (Wang et al., 2015a).

The degradation of GSM and 2-MIB by conventional UV and UV/chlorine radiation as shown in Figs. 5 and 6 was conducted by Kim et al. (2016). The authors found that GSM oxidized faster than 2-MIB under UV/chlorine and UV photolysis at 254 nm within 40 to 60 min than 2-MIB. The possible reason

was due to greater steric hindrance in 2-MIB which slowed down the reaction with hydroxyl radicals. On the other hand, Wang et al. (2015a) examined the degradation of these compounds in water using UV/chlorine reaction but failed to identify the intermediates formed. Kim et al. (2016) identified and proposed the possible degradation pathways for some of the identified intermediates. In either of the mechanisms, the first step in the degradation sequence was the removal of water molecules via dehydration under UV photolysis and UV/chlorine for both 2-MIB and GSM. Further attacks on the intermediates by hydroxyl radicals produced 2-methylhexan-3-ol, 2,4-dimethylhept-1-ene, and 4-methylheptan-2-one for 2-MIB and GSM, respectively. The authors also observed that UV treatment of chlorinated water enhanced the concentration of disinfection by-products such as haloalkanes.

The proposed pathways were found to be pH, time and hydroxyl radical dependent and fast degradations were observed in the pH region of 5–7 (Kim et al., 2016). 1 M of GSM and 2-MIB yielded 0.75 M and 0.87 M chloroform, respectively, on reaction with UV/chlorine. The formation of chloroform at pH 9 was the highest followed by pH 5 and 7 and lowest at pH 11. At pH 5 and 7 chloroform was degraded by hydroxyl radicals. The formation of chloroform started to increase from 20–90 min and later declined. GSM and 2-MIB were highly degraded at pH 5 to 7 due to the production of hydroxyl radicals by HOCl but slow degradation was observed at higher pH due to hydroxyl radicals which is attributed to the scavenging effect of OCI^- ions. It was posited that the fast bond cleavage at the acidic pH values could be due to a low concentration of hydroxyl radical scavengers such as carbonate ion. However, the UV photolysis method is considered to be more energy intensive, which is one of the shortcomings militating against its wide applicability. For instance, a high amount of energy is required to achieve complete mineralization of the major pollutants, whereas the formation of DBPs such as inorganic chloramines, organohalogenated by-products and trichloramines is problematic. It has been shown that exposure to these DBPs could damage the lungs and may cause asthma in children. Thus, the use of this method could be highly expensive to be adopted for water purification, especially in developing nations (Nam et al., 2015).

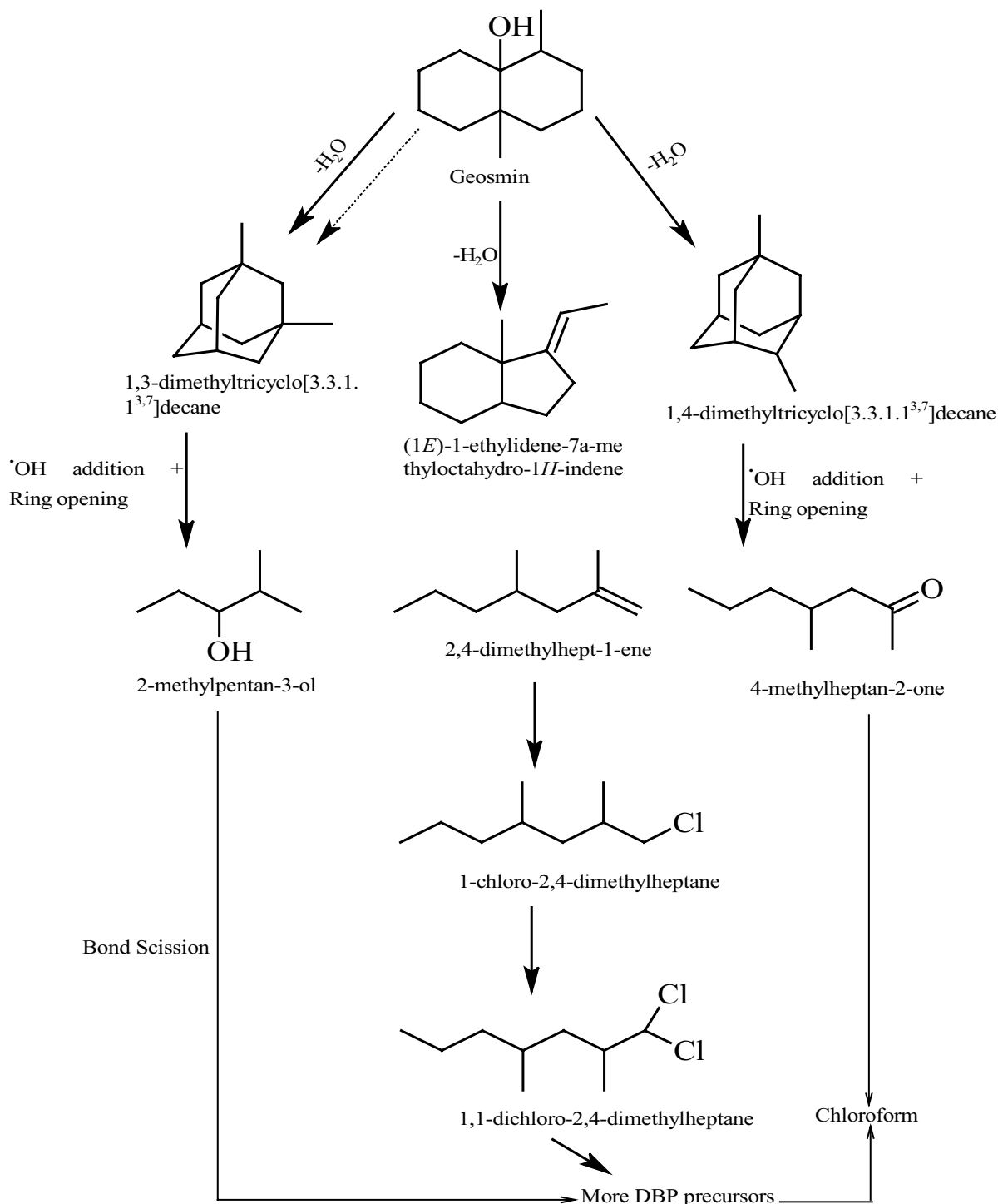


Fig. 5 Proposed degradation pathway of GSM by UV photolysis (dotted line) and UV/chlorine (bold line) (Kim et al., 2016)

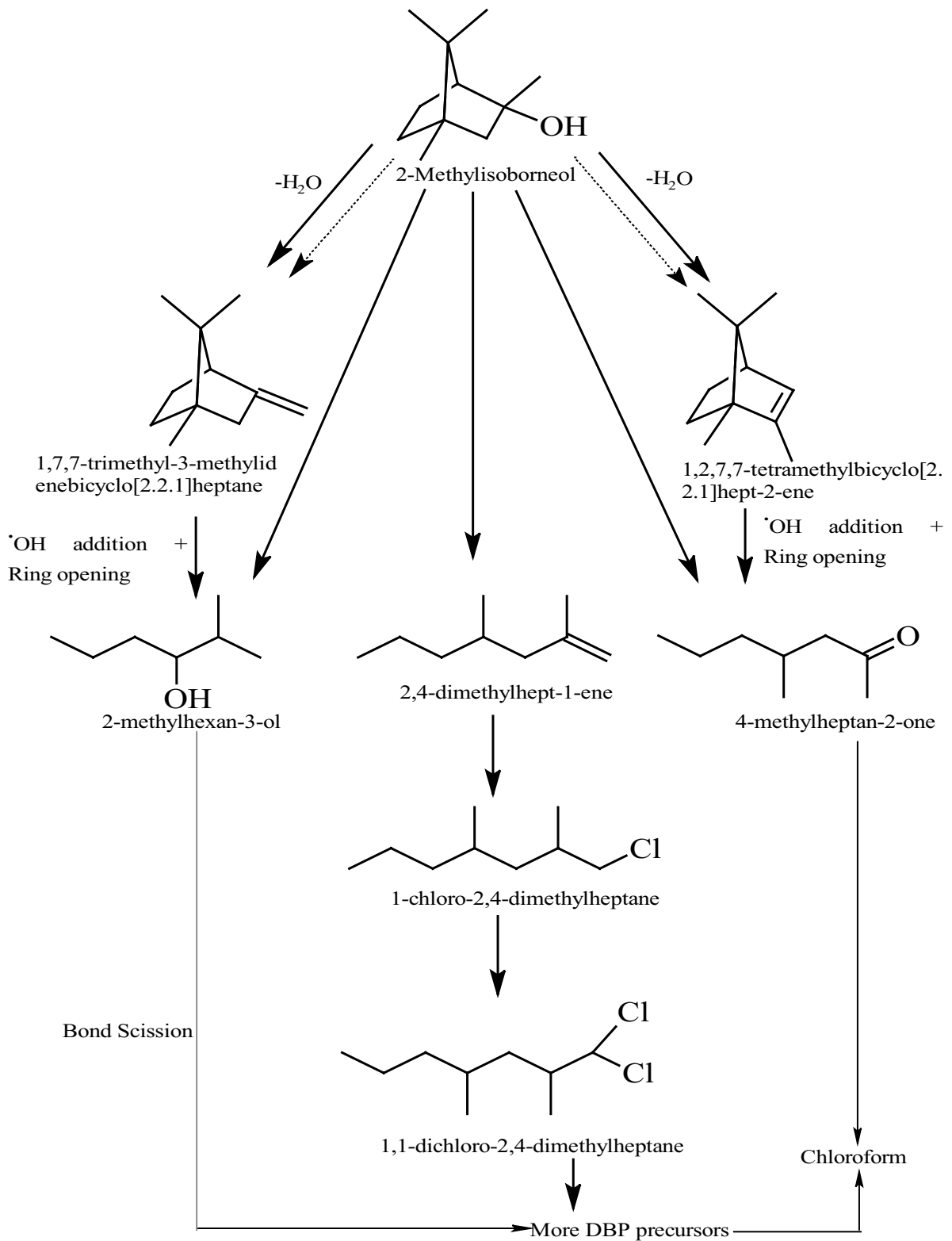
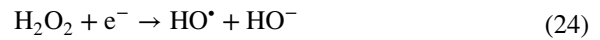
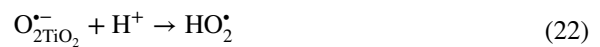
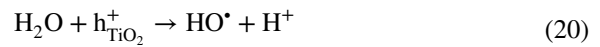
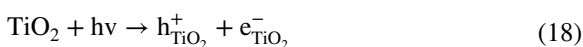


Fig. 6 Proposed degradation pathway of 2-MIB by UV photolysis (dotted line) and UV/chlorine (bold line) (Kim et al., 2016)

Ultraviolet radiation/nanoparticle utilization

Heterogeneous photocatalysis is a photocatalytic process based on the irradiation of semiconductor photocatalysts such as TiO_2 , CdS, WO_3 , and ZnO with a photon of UV or visible light. In the last few years, heterogeneous photocatalysis especially TiO_2 has been widely studied and is considered to be very promising due to its photo-activity, low toxicity, chemical and biological inertness, and resistance to corrosion (Antoniou et al., 2016). UV/ TiO_2 has been used to destroy organic contaminants, including toxic cyanobacterial metabolites. The efficacy of photodegradation of 2-MIB and GSM with TiO_2 resulted in the formation of the highly ROS (electron pairs and oxidizing HO^\bullet) which lead to the oxidation and mineralization of the targeted compounds into harmless substances (Fotiou et al., 2015a, 2016).

This catalytic TiO_2 process require a band gap energy of $\sim 3.2\text{--}3.0$ eV and UV of wavelength less than 400 nm for excitation of electrons and holes (Fotiou et al., 2015b; Sarathy & Mohseni, 2016), while co-doped TiO_2 with non-metals such as nitrogen, sulfur, and carbon showed better degradation of GSM and 2-MIB than undoped TiO_2 (Pillai et al., 2015). It was posited that the production of hydroxyl during visible light photocatalysis is an indication of a combination of UV constituents with TiO_2 . The formation of hydroxyl radicals from electron vacancies called holes (h^+) was found not to be thermodynamically possible due to the position of the valence band. Thus, limitations on a rapid charge of recombination of e^-/h^+ pairs and the wide band gap involved in this process were pointed out by Fotiou et al. (2015b). These defects can be corrected by introducing either metal or non-metal impurities which could act as dopants on the surface of TiO_2 . Eventually, the TiO_2 excited by UV radiation produces hydroxyl radicals and dissolved oxygen serves as the electron acceptor which transforms into superoxide radical anions ($\text{O}_2^{\bullet-}$) leading to the formation of reactive oxygen species (HO^\bullet). The mechanisms of formation of electron-hole pairs in TiO_2 nanoparticles leading to the formation of the hydroxyl radical as shown in Eqs. 18–25.



Among the researchers who had worked on the removal of toxic cyanobacteria metabolites using TiO_2 and doped- TiO_2 with UV irradiation were Bamuzape and Chirwan (2010, 2011, 2012), Pestana et al. (2014), Fotiou et al. (2014), and Fotiou et al. (2015a, b). They found that the effective photodegradation of GSM and 2-MIB was due to the availability of hydroxyl radicals. An investigation by Fotiou et al. (2014) provided degradation pathways as well as details of mineralization but failed to mention the overall performance of TiO_2 photocatalyst on GSM and MIB degradation. Illumination of aqueous solution performed at ambient temperature using photolysis apparatus, oxygen saturated solution of GSM, and 2-MIB under UV irradiation ($\lambda_{\text{max}} = 365$ nm) in the presence of photocatalysts silica tungstate and commercially available TiO_2 Degussa P25 resulted to the degradation of GSM and 2-MIB. A complete degradation of GSM and 2-MIB was observed at 30 and 25 min, respectively, after 5 h of irradiation in the presence of TiO_2 . During the destruction of these compounds, the intermediate products formed from photodegradation of GSM (as shown in Fig. 7) were due to α -hydrogen abstraction and hydroxylation. This resulted to cyclic ketones while alcohols, ketones, diketone derivatives, cyclic compounds, and open chain aliphatic compounds were the intermediates identified for 2-MIB degradation (Fig. 8).

On the other hand, GSM which is a bicyclic compound was converted to a cyclic compound through the removal of molecules of water and the methyl group leading to the formation of ketones. The formation of such intermediates as aldehydes, carboxylic acids and alkenes during the photocatalytic degradation of GSM was investigated and mechanism elucidated.

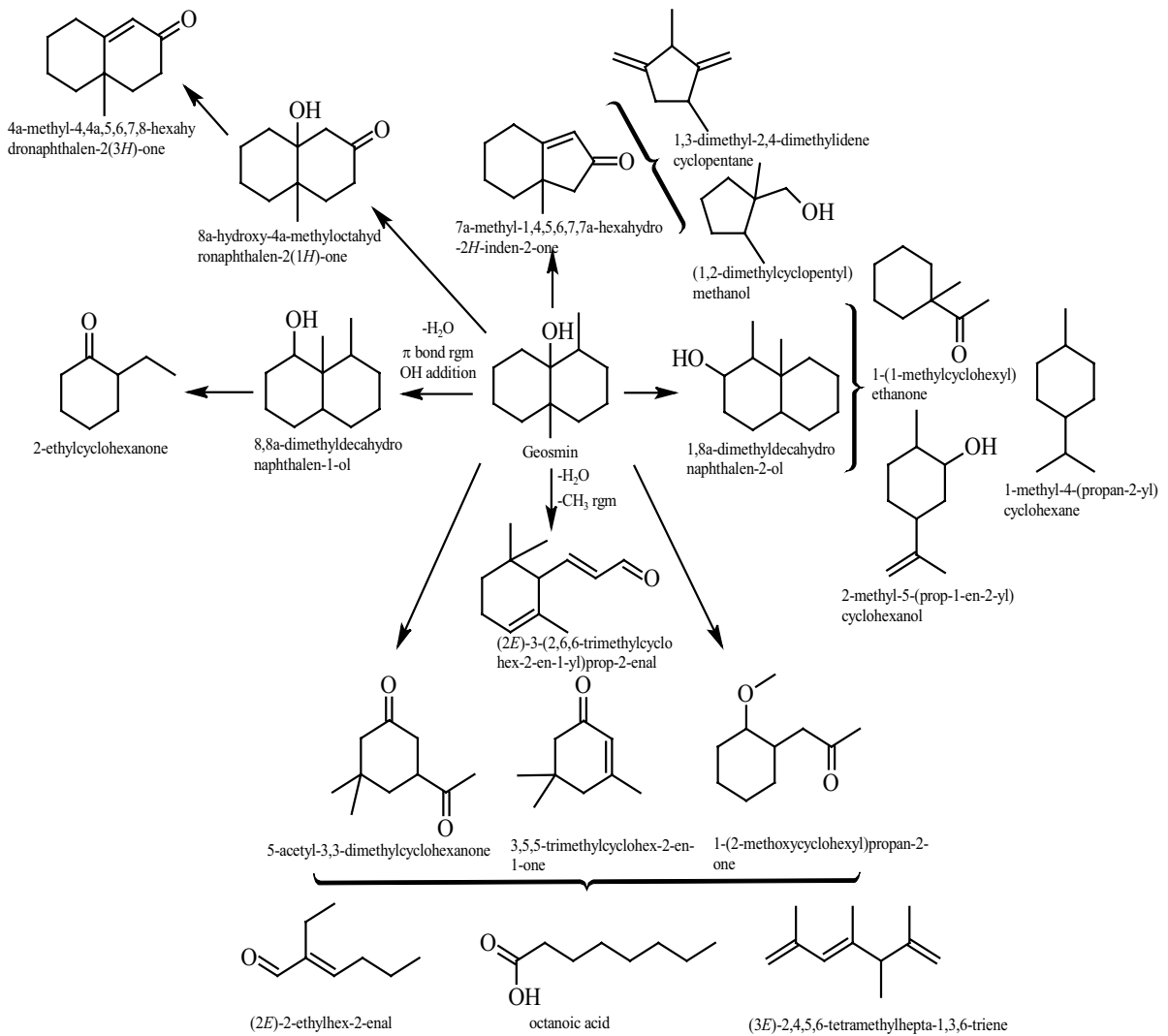
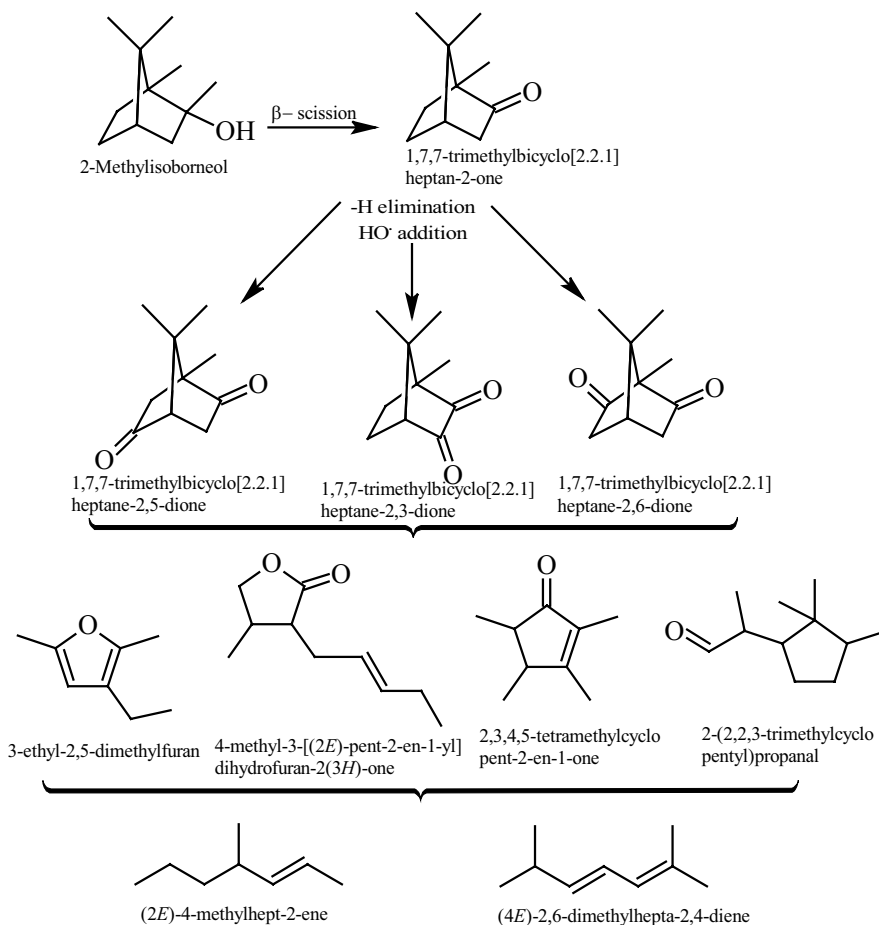


Fig. 7 Proposed intermediate formed during photocatalytic degradation pathways of GSM in the presence of UV/TiO₂ (Fotiou et al., 2014)

Figure 7 explicitly described the formation of D-camphor based on hydrogen abstraction with the further addition of hydroxyl radicals. This led to the formation of three diketone compounds as intermediates. Further degradation of these intermediate compounds yielded saturated and unsaturated cyclic compounds. Finally, conjugated and non-conjugated (isolated) dienes were formed. This implies that further degradation could cause the isolated dienes to disintegrate into smaller compounds due to delocalization of charge by resonance and hybridization energy.

A shorter degradation time was attributed to the formation of organic intermediates produced which further reacted with the photocatalyst. Since the ROS reacts with the targeted compounds (2-MIB and GSM), it is necessary to optimize the TiO₂ photocatalytic performance under different conditions such as pH, irradiation wavelength, mineralization, intermediate products, toxicity, light intensity, catalyst loading, and presence of oxygen so as to establish the optimum conditions that will be responsible for high percentage degradation.

Fig. 8 Proposed intermediate formed during photocatalytic degradation pathways of 2-MIB in the presence of UV/TiO₂ (Fotiou et al., 2014)



Ultrasonic irradiation

Organic pollutants in wastewater can be readily decomposed using ultrasonic irradiation, sonolysis, or cavitation. These methods generate free radicals by cavitation when ultrasound is irradiated at low frequencies or high pressure. Cavitation is the occurrence and implosion of small bubbles formed under the collision that eventually produce free radicals that damage the cell walls of blue-green algae (Kohno et al., 2011). This method is rapid and suitable for algal bloom control and it involves three (3) degradation pathways which have been identified as follows: (i) oxidation by hydroxyl radicals, (ii) pyrolytic decomposition by high temperature and pressure, and (iii) supercritical oxidation. A significant advantage of this method over other advanced oxidation processes earlier discussed is that it does not

require the addition of any chemical. For instance, Jiang et al. (2012) investigated the influence of ultrasonic irradiation on blue-green algae and found that frequency and input power were the major factors responsible for the destruction of the algal growth in water bodies. The energy produced during this treatment is said to have caused the degradation of the blue-green algae, thus altering the constituent structure of the water and allowing the water to be more easily separated since the ultrasound attacked the bacterial cell walls (Kumar et al., 2014). The identification of degradation products and proposed specific degradation pathways for 2-MIB and GSM was investigated by Song and O'Shea (2007) as reviewed by Antonopoulou et al. (2014). The ultrasonic induced decomposition of GSM and 2-MIB was examined at 640 kHz immersed in ice bath at 4 °C. Upon ultra-sonication, 10 µg/L 2-MIB and

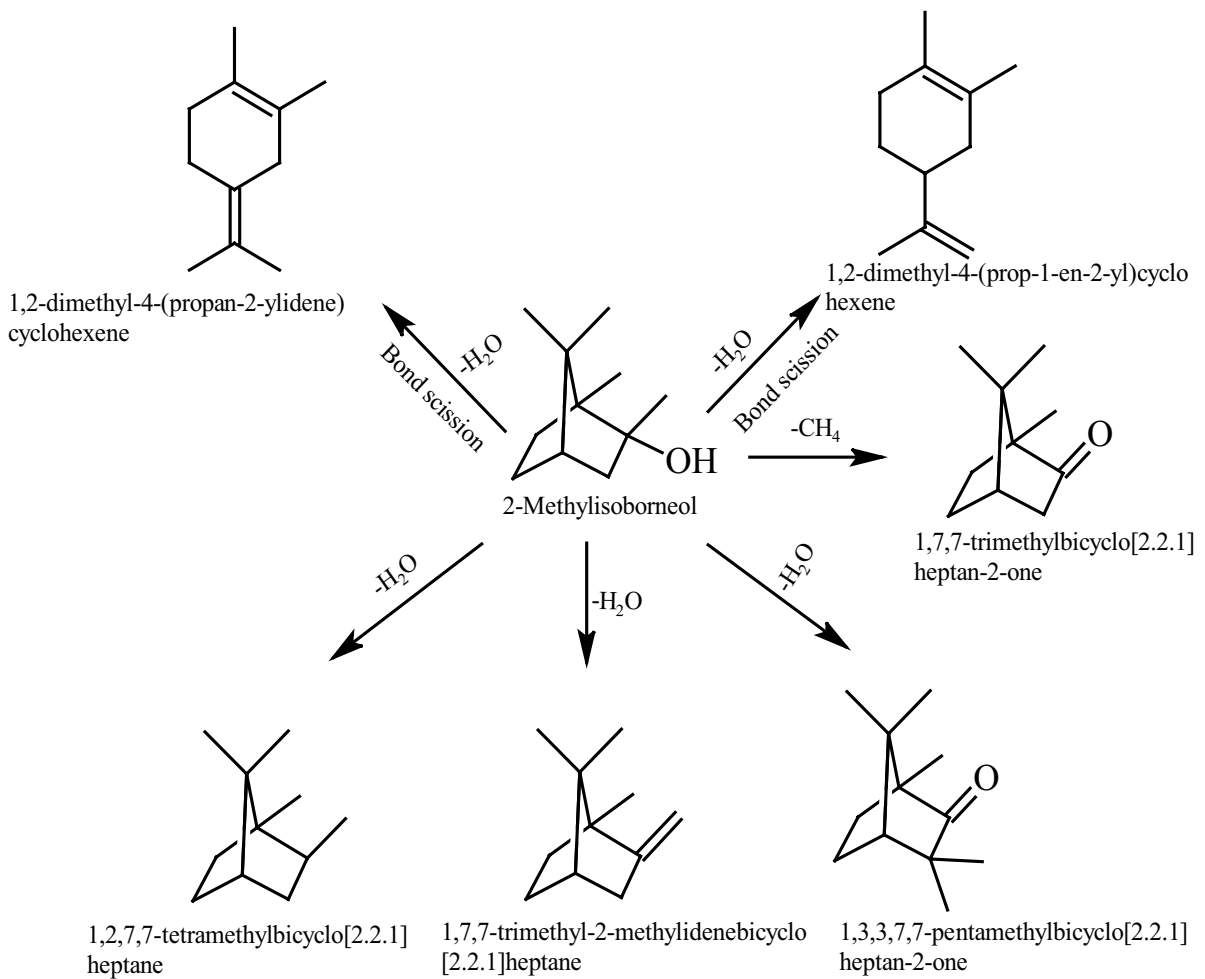


Fig. 9 Proposed products of ultrasonic-induced degradation of GSM in aqueous media (Song & O’Shea, 2007) as reviewed by Antonopoulou et al. (2014)

GSM completely decomposed at 10 min and over 90% of the degraded compounds were observed after 40 min irradiation. The rapid decomposition of 2-MIB and GSM under argon-saturation condition obeyed first-order kinetic, increasing the yield of hydroxyl radical and direct pyrolysis. The authors found that the compounds degraded faster via ultrasonic irradiation, and the first-order reaction rate coefficient was 0.12 min^{-1} for GSM and 0.07 min^{-1} for 2-MIB. The result from the rate coefficient constant was not affected by radical scavengers such as bicarbonate, carbonate, and humic acid during the degradation process. It was established that the

hydroxyl radicals and the cavitation temperature played a significant role during the degradation as presented in Fig. 9.

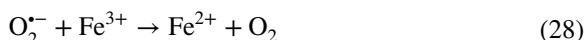
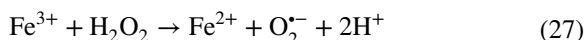
Application of ultrasound for water treatment is considered expensive due to the high maintenance cost of the ultrasound probe, and the process cannot be scaled up easily. Thus, careful evaluation of its economic feasibility is required, and research on the effect of water turbidity, temperature, and energy consumption needs to be conducted in order to effectively arrive at a suitable and cost-effective treatment system that would have the potential for the removal of 2-MIB and GSM in water.

Other advanced oxidation processes

Previously mentioned processes have shown some removal efficiencies toward GSM and 2-MIB in water. Information also exists on the application of electrochemical, Fenton, photo-Fenton, radiolysis, and dielectric barrier systems for the treatment of wastewater containing 2-MIB and GSM. The Fenton reagent is known to be an unstable iron oxide complex that occurs when iron(II) reacts with hydrogen peroxide to generate hydroxyl radicals as shown in Eq. 27.



Photo-Fenton is based on the photoreduction of the Fenton process with radiation. The by-product, Fe(II) ion, then reacts with the peroxide to regenerate ferrous ions. During this method, the destruction of organic contaminants is mainly due to the oxidation reaction by hydroxyl radicals (see Eqs. 27 and 28).



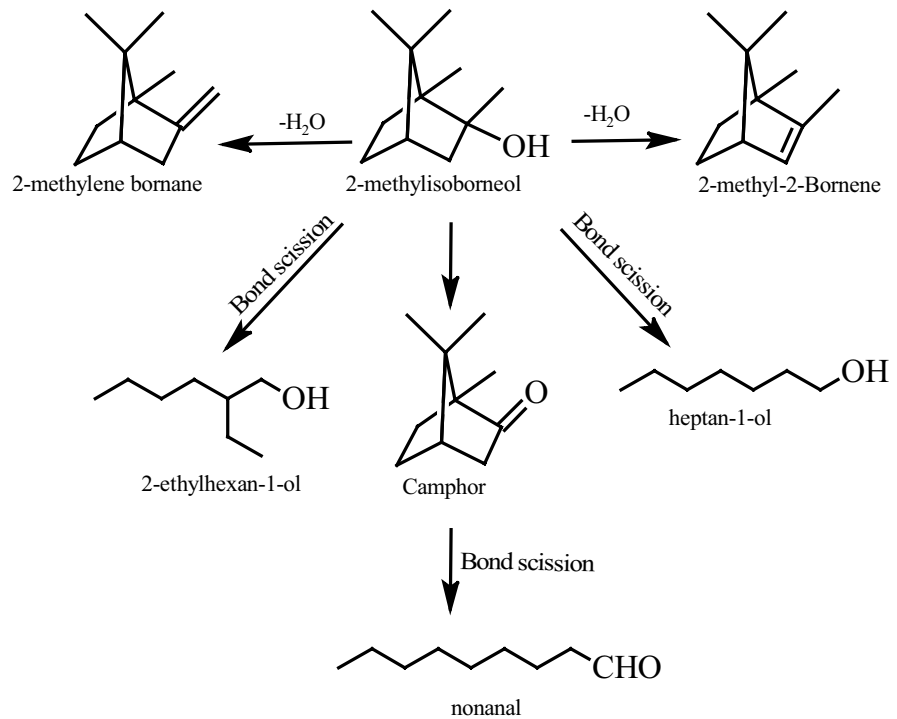
Different researchers have employed Fenton and photo-Fenton processes to decompose organic pollutants in water. For instance, Park et al. (2017) showed that GSM and 2-MIB can be degraded using the photo-Fenton process. Water samples from Nak-Dong River water located in South Korea were collected and analyzed. The study investigated their kinetics, and the degradation intermediates under optimum operational conditions such as reaction time, pH, Fe(II)/H₂O₂ concentration, organic matter, and initial concentration. The removal of these compounds was pH dependent. At a pH of 3, 78.86% of GSM and 100% of 2-MIB were removed. On the other hand, 100 and 54.73% of 2-MIB and GSM were, respectively, removed at a pH value of 5. At a higher pH value of 7, 53.26 and 58.87% of GSM and 2-MIB were, respectively, removed using this technique under the UV fluence rate of 5022 mJ/cm² which decreases with an increase in pH. The concentration of Fe(II) and H₂O₂ were also important during the degradation of GSM and 2-MIB using the photo-Fenton process. The degradation increased as the generation of hydroxyl radical increased using

high concentration of H₂O₂. Contrarily, increasing the Fe(II) concentration reduced the removal efficiency of GSM and 2-MIB which was attributed to the competing effect of hydroxyl radical with less concentration of GSM and 2-MIB. The highest degradation efficiencies were found to be 43.38% for GSM and 84.25% for 2-MIB at experimental conditions (Fe(II)=2 mg/L; H₂O₂=20 mg/L; UV fluence=3,348 mJ/cm²). The presence of organic matter affects the removal of GSM and 2-MIB, and this was attributed to sufficient UV during the photo-Fenton process. This method was also found to be efficient not only in the degradation of these compounds but other cyanobacterial blooms containing trihalomethanes (THMs) and microcystins-LR (MC-LR) without the release of toxic by-products in the water. However, the carbonyl compounds released as by-products usually have adverse effects on man and other living organisms. For instance, the release of carbonyl and carboxylic products during the degradation of MC-LR using ozonation has been reported to be toxic (Chang et al., 2014).

Figures 10 and 11 describe the formation of intermediates during the degradation of GSM and 2-MIB via dehydration and ring-opening pathways by hydroxyl radicals during the photo-Fenton process at UV fluence=0–5022 mJ/cm² and pH range of 4.8–5, concentration of 100 µg, 2 mg and 20 mg/dm³ of GSM or MIB, Fe(II) ion and H₂O₂, respectively.

Li et al. (2010b) investigated GSM removal from aqueous solutions using an electrical method at the Ti/RuO₂-Pt anode in the presence of sodium chloride. The authors established that the electrochemical method is a promising and rapid way of removing GSM from water under the influence of current density, pH, and concentration. The research work indicated that GSM removal efficiencies decreased with respect to time and it was indicated that hypochlorite (HOCl) consumed by the oxidation of GSM played a significant role during the degradation steps. The decrease in pH was reported as a result of the dissociation reaction of HOCl and OCl⁻ which oxidized the GSM. In addition, Zhang et al. (2016b) revealed that bacteria and natural organic matter in water were controlled by dielectric barrier discharge devices. They reported that the removal of bacteria was effectively observed within a short period while elongation of treatment time helped in the removal of NOM. However, proper optimization of other parameters in order

Fig. 10 Degradation pathways of 2-MIB using photo-Fenton process (Park et al., 2017)



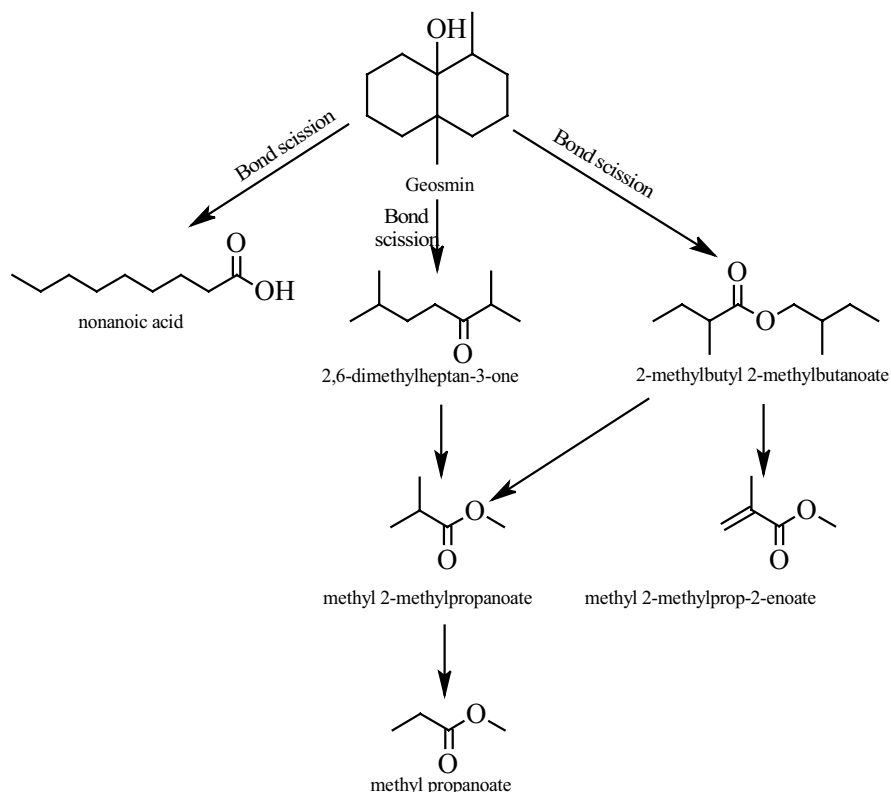
to arrive at the optimal removal condition for both GSM and 2-MIB in water was not carried out by the authors.

Industrial removal of 2-methylisoborneol and geosmin

The impediment of industries on the quality of water and best management practices has improved the access of good water quality and palatability of water. The presence of GSM and 2-MIB in raw water has gingered scientists to develop technologically viable industrial techniques for their removal in countries such as the USA, New Zealand, Canada, Australia, China, Brazil, and South Africa, among others. For instance, the occurrence of 2-2-MIB and GSM in water supply in Jiangsu province in China was investigated by Ding et al. (2014b) and conventional treatment processes such as coagulation and sedimentation, filtration, and chlorination successfully removed the odorous compounds in tap water supplied to the provinces. Wang et al. (2015a) used advanced oxidation methods such as UV/H₂O₂ and UV/chlorine processes to control GSM and 2-MIB

in water purification plant in the city of Cornwall, Ontario, Canada, and almost complete decomposition of 2-MIB and GSM were achieved. In South African, Midvaal Water Company utilized series of conventional methods combined with advanced oxidation techniques to purify Vaal River (van Rensburg et al., 2016). These methods include ozonation, coagulation and flocculation, lime addition, ferric chloride, aluminum sulfate and polyelectrolyte, flotation, adsorption using activated carbon, filtration and chlorination (chemical disinfection). Surprisingly, there was no total removal of these pollutants in the treated water. Thus, the authors recommended proper optimization of treatment techniques taking into cognizance the cost implication. Rescorla (2012) worked on the water supply from Minneapolis water works from Mississippi, USA. According to the US geological survey, the main cause of odor in the Mississippi River basin was as a result of phosphorus from agricultural fertilizer (Naidenko et al., 2012). The multiple treatment processes carried out on the Mississippi raw water to remove 2-MIB and GSM include softening, sedimentation, adsorption, filtration, and disinfection. Sun et al. (2014) investigated the presence of 2-MIB and GSM in one hundred and one (111) drinking water

Fig. 11 Degradation pathways of GSM using photo-Fenton process (Park et al., 2017)



plants in thirty-four cities across China and found that 2-MIB and GSM were not easily removed using conventional processes. It can be seen that the commercially available conventional treatment techniques are not capable of removing these xenobiotics; thus, the incorporation of advanced oxidation processes either as a pre or post treatment is desirable.

Perspectives and prospects

Effective water purification requires highly efficient, cost-effective, and sustainable techniques. The aim of protecting human health should be of utmost priority no matter the cost implications. The existing methods applied by researchers in the removal of these contaminants in municipal water treatment plants did not produce a satisfactory result, and advanced oxidation processes had proved to be promising. Thus, advanced oxidation processes such as ozonation, UV/chlorine, and UV/photocatalyst should be used to mineralize these pollutants after the introduction of conventional methods. The applications of these

methods will also bring fast reaction rates and non-selective oxidation allowing the treatment of these pollutants at equal rate. Furthermore, the combination of AOPs with conventional physicochemical and biological processes applied for the treatment of odorous water can provide an effective technological solution for water treatment. To obtain consistent and desired outcomes in the optimization of GSM and 2-MIB removal, the enlisted future perspectives are recommended.

- Employ full-scale operational water conditions for the sequestration of GSM and 2-MIB through integration of conventional and advanced oxidation processes. A schematic representation of effective treatment techniques for the taste, odor, and other pollutant removal is presented in Fig. 12.
- Implementation of strategies/frequent checkup for accurate estimation of T&O compound release is imperative. This could be achieved through manual and digital monitoring ability.
- Pilot-scale studies should focus on the fate of T&O compounds and aesthetic quality on large-

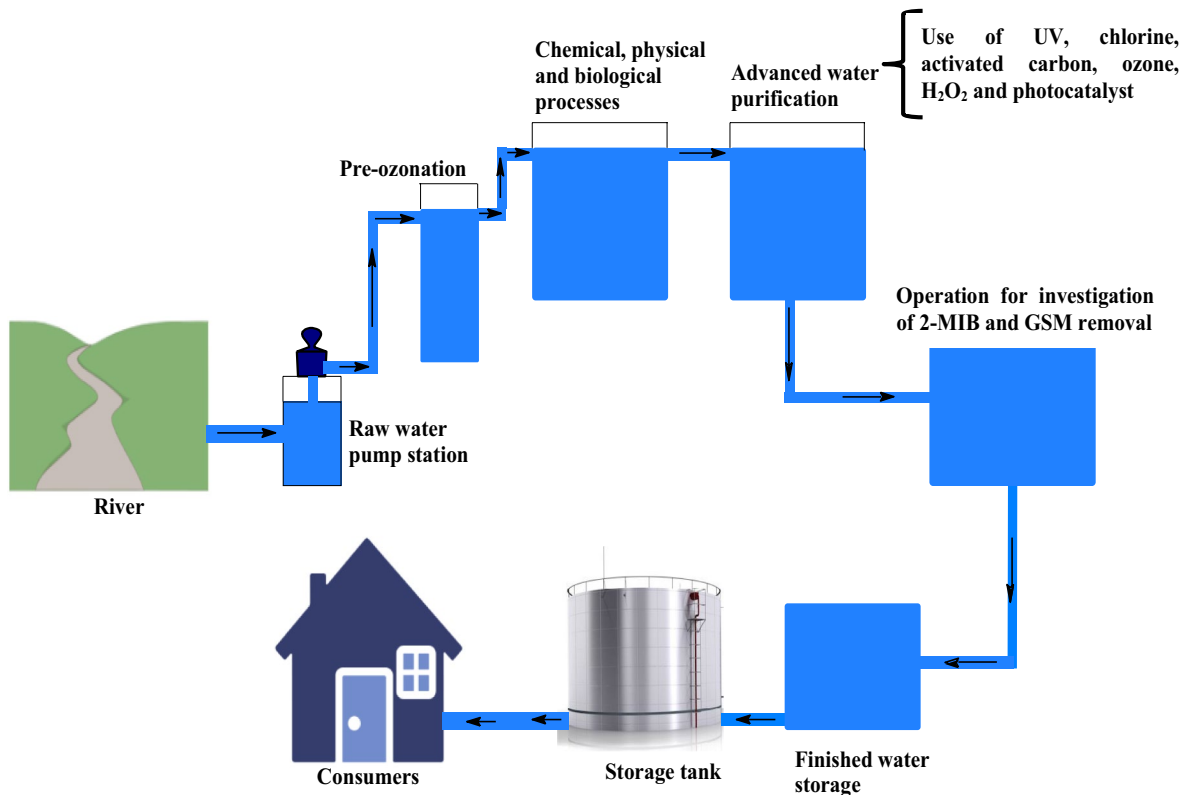


Fig. 12 Drinking water supplies from river to customers via different treatment routes

scale water treatment processes for better understanding, application, and elucidation of degradation pathways of GSM and 2-MIB under various treatment techniques.

Conclusions

In summary, the review provided the sources, effect, and removal techniques for 2-MIB and GSM in aqueous media. The literature demonstrated the mechanistic degradation pathways of these T&O compounds under various AOPs and point out produced by-products during these processes. Most studies have shown that the removal of 2-MIB and GSM is influenced by ozone dosage, humic, natural organic matter, temperature, and pH light intensity, among others. These factors have seriously affected complete removal of these T&O compounds in water. The sorption of 2-MIB and GSM onto granular, powdered,

and superfine powdered activated carbon have been influenced by natural organic matter which compete with the adsorption sites on the surface of activated carbon. This technological approach has high operating costs and additional treatment has to be performed for the regeneration of the activated carbon, there is the need for methods integration to solve the enumerated problems. Integrated methods such as ozonation//H₂O₂/UV/powdered activated carbon and TiO₂/UV/H₂O₂/activated carbon could enable water industries to meet the growing demand for potable and good quality clean water for consumers. However, scanty information is available on some novel methods such as electrochemical, radialysis, and dielectric barrier discharge for the treatment of GSM and 2-MIB in water. More research efforts should focus on the integration of electrochemical, dielectric barrier discharge with other conventional methods such as activated carbon adsorption, electrocoagulation to remove these two compounds from water.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

- Agus, E., Lim, M. H., Zhang, L., & Sedlak, D. L. (2011). Odorous compounds in municipal wastewater effluent and potable water reuse systems. *Environmental Science and Technology*, *45*, 9347–9355.
- Ahmed, M. B., Zhou, J. L., Ngo, H. H., & Guo, W. (2015). Adsorptive removal of antibiotics from water and wastewater: progress and challenges. *Science of the Total Environment*, *532*, 112–126.
- Ando, N., Matsui, Y., Kurotobi, R., Nakano, Y., Matsushita, T., & Ohno, K. (2010). Comparison of natural organic matter adsorption capacities of super-powdered activated carbon and powdered activated carbon. *Water Research*, *44*(14), 4127–4136.
- Andreadakis, A. D., Mamais, D., Gavalakis, E. A., Noutsopoulos, C., Kouris, N., & Nikitopoulos, G. (2010). Removal of taste and odour from potable water by ozone and powdered activated carbon (PAC). *International Journal of Environment and Waste Management*, *5*(3–4), 392–409.
- Antoniou, M. G., Zhao, C., O’Shea, K. E., Zhang, G., Dionysiou, D. D., Zhao, H., Han, C., Nadagouda, M. N., Choi, H., Fotiou, T., Triantis, T. M., & Hiska, A. (2016). Photocatalytic degradation of organic contaminants in water: process optimization and degradation pathways. *Photocatalysis: Applications 1*, 1–34.
- Antonopoulou, M., & Konstantinou, I. (2015). TiO₂ photocatalysis of 2-isopropyl-3-methoxy pyrazine taste and odor compound in aqueous phase: Kinetics, degradation pathways and toxicity evaluation. *Catalyst Today*, *240*, 22–29.
- Antonopoulou, M., Evgenidou, E., Lambropoulou, D., & Konstantinou, I. (2014). A review on advanced oxidation processes for the removal of taste and odor compounds from aqueous media. *Water Research*, *53*, 215–234.
- Auffret, M., Pilote, A., Proulx, E., Proulx, D., Vandenberg, G., & Villemur, R. (2011). Establishment of a real-time PCR method for quantification of geosmin-producing *Streptomyces* spp. in recirculating aquaculture systems. *Water Research*, *45*, 6753–6762.
- Bamuza-Pemu, E. E., & Chirwa, E. M. N. (2010). Photocatalytic degradation of taste and odour causing compounds in natural water sources. *Chemical Engineering Transactions*, *23*, 387–392.
- Bamuza-Pemu, E. E., & Chirwa, E. M. N. (2011). Photocatalytic degradation of geosmin: Intermediates and degradation pathway analysis. *Chemical Engineering Transactions*, *24*, 91–96.
- Bamuza-Pemu, E. E., & Chirwa, E. M. N. (2012). Photocatalytic degradation of geosmin: reaction pathway analysis. *Water SA*, *38*(5), 689–696.
- Banerjee, S., Pillai, S. C., Falaras, P., Shea, K. E. O., Byrne, J. A., & Dionysiou, D. D. (2014). New insights into the mechanism of visible light photocatalysis. *The Journal of Physical Chemistry Letters*, *5*(15), 2543–2554.
- Beniwal, D., Taylor-Edmonds, L., Armour, J., & Andrews, R. C. (2018). Ozone/peroxide advanced oxidation in combination with biofiltration for taste and odour control and organics removal. *Chemosphere*, *212*, 272–281.
- Berlt, M. M. G., Schneider, R. D. C. D. S., Machado, Ê. L., & Kist, L. T. (2020). Comparative assessment of the degradation of 2-methylisoborneol and geosmin in freshwater using advanced oxidation processes. *Environmental Technology*, 1–8.
- Bu, L., Zhou, S., Shi, Z., Deng, L., & Gao, N. (2017). Removal of 2-MIB and geosmin by electrogenerated persulfate: Performance, mechanism and pathways. *Chemosphere*, *168*, 1309–1316.
- Burr, G. S., Wolters, W. R., Schrader, K. K., & Summerfelt, S. T. (2012). Impact of depuration of earthy-musty off-flavors on fillet quality of Atlantic salmon, *Salmo salar*, cultured in a recirculating aquaculture system. *Aquacultural Engineering*, *50*, 28–36.
- Callejóna, R. M., Ubedab, C., Ríos-Reinaa, R., Moralesa, M. L., & Troncosoa, A. M. (2016). Recent developments in the analysis of musty odour compounds in water and wine: A review. *Journal of Chromatography A*, *1428*, 72–85.
- Capriotti, A. L., Cavaliere, C., Giansanti, P., Gubbiotti, R., Samperi, R., & Laganà, A. (2010). Recent developments in matrix solid-phase dispersion extraction. *Journal of Chromatography A*, *1217*(16), 2521–2532.
- Catherine, Q., Susanna, W., Isidora, E. S., Mark, H., Aurelie, V., & Jean-François, H. (2013). A review of current knowledge on toxic benthic freshwater cyanobacteria ecology, toxin production and risk management. *Water Research*, *47*, 5464–5479.
- Chang, J., Chen, Z. L., Wang, Z., Shen, J. M., Chen, Q., Kang, J., Yang, L., Liu, X. W., & Nie, C. X. (2014). Ozonation degradation of microcystin-LR in aqueous solution: Intermediates, byproducts and pathways. *Water Research*, *63*, 52–61.
- Cheng, J., Liu, K., Ba, M., Cheng, C., Yu, Y., & Zhou, X. (2015). Determination of 2-methylisoborneol and geosmin in drinking water using headspace solid phase micro-extraction coupled with gas chromatography-mass-spectrometry. *Chinese Journal of Chromatography*, *33*, 1287–1293.
- Cortada, C., Vidal, L., & Canals, A. (2011). Determination of geosmin and 2-methylisoborneol in water and wine samples by ultrasound-assisted dispersive liquid-liquid microextraction coupled to gas chromatography-mass spectrometry. *Journal of Chromatography A*, *1218*, 17–22.
- Davidson, J., Schrader, K., Ruan, E., Swift, B., Aalhus, J., Juarez, M., Wolters, W., Burr, G., Good, C., & Summerfelt, S. T. (2014a). Evaluation of depuration procedures to mitigate the off-flavor compounds geosmin and 2-methylisoborneol from Atlantic Salmon *Salmo Salar* raised to market-size in recirculating aquaculture systems. *Aquacultural Engineering*, *61*, 27–34.
- Davidson, K., Gowen, R. J., Harrison, P. J., Fleming, L. E., Hoagland, P., & Moschonas, G. (2014b). Anthropogenic nutrients and harmful algae in coastal waters. *Journal of Environmental Management*, *146*, 206–216.

- Deng, X. W., Xie, P., Qi, M., Liang, G. D., Chen, J., Ma, Z. M., & Jiang, Y. (2012). Microwave-assisted purge-and-trap extraction device coupled with gas chromatography and mass spectrometry for the determination of five predominant odors in sediment, fish tissues, and algal cells. *Journal of Chromatography A*, *1219*, 75–82.
- Dietrich, A. M., & Burlingame, G. A. (2015). Critical review and rethinking of USEPA secondary standards for maintaining organoleptic quality of drinking water. *Environmental Science & Technology*, *49*(2), 708–720.
- Dietrich, A. M., Phetxumphou, K., & Gallagher, D. L. (2014). Systematic tracking, visualizing, and interpreting of consumer feedback for drinking water quality. *Water Research*, *66*, 63–74.
- Ding, Z., Peng, S., Jin, Y., Xuan, Z., Chen, X., & Yin, L. (2014a). Geographical and seasonal patterns of geosmin and 2-methylisoborneol in environmental water in Jiangsu Province of China. *Journal of Analytical Methods in Chemistry*, *1*, 1–6.
- Ding, Z., Peng, S., Xia, W., Zheng, H., Chen, X., & Yin, L. (2014b). Analysis of five earthy-musty odourants in environmental water by HS-SPME/GC-MS. *International Journal of Analytical Chemistry*, *1*, 1–11.
- Doria, M. d. F. (2010). Factors influencing public perception of drinking water quality. *Water Policy*, *12*, 1–19.
- Dunlap, C. R., Sklenar, K. S., & Blake, L. J. (2015). A costly endeavor: addressing algae problems in a water supply. *Journal-American Water Works Association*, *107*(5), 255–262.
- Eaton, R. W., & Sandusky, P. (2010). Biotransformations of (+/-)-geosmin by terpene-degrading bacteria. *Biodegradation*, *21*(1), 71–79.
- Fotiou, T., Triantis, T. M., Kaloudis, T., O’Shea, K. E., Dionysiou, D. D., & Hiskia, A. (2016). Assessment of the roles of reactive oxygen species in the UV and visible light photocatalytic degradation of cyanotoxins and water taste and odor compounds using C-TiO₂. *Water Research*, *90*, 52–61.
- Fotiou, T., Triantis, T. M., Ioannidis, N., Kaloudis, T., & Hiskia, A. (2015a). Photocatalytic degradation of cyanotoxins under visible light; Elucidation of the reaction mechanism. Proceedings of the 14th International Conference on Environmental Science and Technology Rhodes, Greece, 3–5 September 2015.
- Fotiou, T., Triantis, T. M., Kaloudis, T., & Hiskia, A. (2015b). Evaluation of the photocatalytic activity of TiO₂ based catalysts for the degradation and mineralization of cyanobacterial toxins and water off-odor compounds under UV-A, solar and visible light. *Chemical Engineering Journal*, *261*, 17–26.
- Fotiou, T., Triantis, T. M., Kaloudis, T., Papaconstantinou, E., & Hiskia, A. (2014). Photocatalytic degradation of water taste and odour compounds in the presence of polyoxometalates and TiO₂: Intermediates and degradation pathways *Journal of Photochemistry and Photobiology A: Chemistry*, *286*, 1–9.
- Freeman, K. S. (2010). Harmful algal blooms: Musty warnings of toxicity. *Environmental Health Perspective*, *118*, A473.
- Gallagher, D. L., & Dietrich, A. M. (2014). Statistical approaches for analyzing customer complaint data to assess aesthetic episodes in drinking water. *Journal of Water Supply: Research and Technology-AQUA*, *63*(5), 358–367.
- Garrido-Cardenas, J. A., Esteban-García, B., Agüera, A., Sánchez-Pérez, J. A., & Manzano-Agugliaro, F. (2020). Wastewater treatment by advanced oxidation process and their worldwide research trends. *International Journal of Environmental Research and Public Health*, *17*(1), 170–188.
- Graham, J., Loftin, K., Meyer, M., & VZiegler, A. (2010). Cyanotoxins mixtures and taste-and-odor compounds in cyanobacterial blooms from the Midwestern United States. *Environmental Science & Technology*, *44*(19), 7361–7368.
- Greenwald, M. J., Redding, A. M., & Cannon, F. S. (2015). A rapid kinetic dye test to predict the adsorption of 2-methylisoborneol onto granular activated carbons and to identify the influence of pore volume distributions. *Water Research*, *68*, 784–792.
- Guo, Q., Yang, K., Yu, J., Wang, C., Wen, X., Zhang, L., Yang, M., Xia, P., & Zhang, D. (2016). Simultaneous removal of multiple odorants from source water suffering from septic and musty odors: Verification in a full-scale water treatment plant with ozonation. *Water Research*, *100*, 1–6.
- Hathurusingha, P. I., & Davey, K. I. (2014). A predictive model for taste taint accumulation in Recirculating Aquaculture Systems (RAS) farmed-fish-demonstrated with geosmin (GSM) and 2-methylisoborneol (MIB). *Ecological Modelling*, *291*, 242–249.
- Ho, L., Craig, K., Bustamante, H., & Newcombe, G. (2010). Removal of cyanobacterial metabolites: Laboratory evaluation of granular activated carbon. *Water (Melbourne, Artarmon)*, *37*(3), 65–70.
- Houle, S., Schrader, K. K., Francois, N. R., Comeau, Y., Kharoune, M., Summerfelt, S. T., Savoie, A., & Vandenberg, G. W. (2011). Geosmin causes off-flavour in Arc-tic charr in recirculating aquaculture systems. *Aquaculture Research*, *42*(3), 360–365.
- Jiang, D. L., Ni, G. W., Zhang, Y. M., & Su, Y. P. (2012). Algal control by low-frequency, low-power ultrasonic in eutrophic water bodies. *Advanced Materials Research*, *433–440*, 811–816.
- Jiang, J. J., Lee, C. L., Fang, M. D., Boyd, K. G., & Gibb, S. W. (2015). Source apportionment and risk assessment of emerging contaminants: An approach of pharmaco-signature in water systems. *PLoS One*, *10*, 1–21.
- Jo, J., Kim, S. D., Lee, H., & Mok, Y. S. (2014). Decomposition of taste and odour compounds produced by cyanobacteria algae using atmosphere pressure plasma created inside a porous hydrophobic ceramic tube. *Chemical Engineering Journal*, *247*, 291–309.
- Joh, G., & Lee, Y. (2012). Cyanobacterial biofilms on sedimentation basins in a water treatment plant in South Korea. *Journal of Applied Phycology*, *24*(2), 285–293.
- Kakimoto, M., Ishikawa, T., Miyagi, A., Saito, K., Miyazaki, M., Asaeda, T., et al. (2014). Culture temperature affects gene expression and metabolic pathways in the 2-methylisoborneol producing cyanobacterium *Pseudanabaena galeata*. *Journal of Plant Physiology*, *171*(3–4), 292–300.
- Kim, C., Lee, S. I., Hwang, S., Choa, M., Kim, H., & Noh, S. H. (2014). Removal of geosmin and 2-methylisoborneol (2-MIB) by membrane system combined with powdered activated carbon (PAC) for drinking water treatment. *Journal of Water Process Engineering*, *4*, 91–98.
- Kim, H., Hong, Y., Sangb, B., & Sharmac, V. K. (2015). Application of SPE followed by large-volume injection GC/MS for the analysis of geosmin and 2-methylisoborneol in water. *Analytical Methods*, *7*(16), 6678–6685.
- Kim, T., Moon, B., Kim, T., Kim, M., & Zoh, K. (2016). Degradation mechanism of geosmin and 2-MIB during UV photolysis and UV/chlorine reactions. *Chemosphere*, *162*, 157–164.

- Kohno, M., Ozawa, T., & Niwano, Y. (2011). Free radical formation from sonolysis of water in the presence of different gases. *Journal of Clinical Biochemistry and Nutrition*, 49(2), 96–101.
- Kristiana, I., Heitz, A., Joll, C., & Sathasivan, A. (2010). Analysis of polysulfides in drinking water distribution systems using headspace solid-phase microextraction and gas chromatography–mass spectrometry. *Journal of Chromatography A*, 1217, 5995–6001.
- Kumar, R., Yadav, N., Rawat, L., & Goyal, M. K. (2014). Effect of two waves of ultrasonic on waste water treatment. *Journal of Chemical Engineering & Process Technology*, 5(3), 1–6.
- Li, L., Yang, S., Yu, S., & Zhang, Y. (2019). Variation and removal of 2-MIB in full-scale treatment plants with source water from Lake Tai, China. *Water Research*, 162, 180–189.
- Li, L., Zhu, C., Xie, C., Shao, C., Yu, S., Zhao, L., & Gao, N. (2018). Kinetics and mechanism of Pseudoanabaena cell inactivation, 2-MIB release and degradation under exposure of ozone, chlorine and permanganate. *Water Research*, 147, 422–428.
- Li, M., Xue, Q., Zhang, Z., Feng, C., Chen, N., Lei, X., et al. (2010a). Removal of geosmin (trans-1,10-dimethyl-trans-9-decalol) from aqueous solution using an indirect electrochemical method. *Electrochimica Acta*, 55(23), 6979–6982.
- Li, X., Huang, Y., & Wang, D. (2010b). Efficiency and mechanism of degradation of 2-methylisoborneol (2-MIB) by O_3/H_2O_2 in water. *4th International Conference on Bioinformatics and Biomedical Engineering (iCBBE)* (pp. 1–4). Chengdu.
- Li, Y., Shen, W., Fu, S., Yang, H., Yu, G., & Wang, Y. (2015). Inhibition of bromate formation during drinking water treatment by adapting ozonation to electro-peroxone process. *Chemical Engineering Journal*, 264, 322–328.
- Ma, J. P., Lu, W. H., Li, J. H., Song, Z. W., Liu, D. Y., & Chen, L. X. (2011). Determination of geosmin and 2-methylisoborneol in water by headspace liquid-phase microextraction coupled with gas chromatography–mass spectrometry. *Analytical Letters*, 44(8), 1544–1557.
- Ma, L., Wang, C., Li, H., Peng, F., & Yang, Z. (2018). Degradation of geosmin and 2-methylisoborneol in water with UV/chlorine: Influencing factors, reactive species, and possible pathways. *Chemosphere*, 211, 1166–1175.
- Machado, S., Goncalves, C., Cunha, E., Guimaraes, A., & Alpendurada, M. F. (2011). New developments in the analysis of fragrances and earthy–musty compounds in water by solid-phase microextraction (metal alloy fibre) coupled with gas chromatography–(tandem) mass spectrometry. *Talanta*, 84, 1133–1140.
- Marcoux, M. A., Matias, M., Olivier, F., & Keck, G. (2013). Review and prospect of emerging contaminants in waste-key issues and challenges linked to their presence in waste treatment schemes: General aspects and focus on nanoparticles. *Waste Management*, 33(11), 2147–2156.
- Marquez-Sillero, I., Aguilera-Herrador, E., Cardenas, S., & Valcarcel, M. (2011). Determination of 2,4,6-trichloroanisole in water and wine samples by ionic liquid-based single-drop microextraction and ion mobility spectrometry. *Analytica Chimica Acta*, 702(2), 199–204.
- Matsui, Y., Ando, N., Yoshida, T., & Kurotobi, R. (2011). Matsushita, K. Ohno, Modeling high adsorption capacity and kinetics of organic macromolecules on super-powdered activated carbon. *Water Research*, 45, 1720–1728.
- Matsui, Y., Nakao, S., Sakamoto, A., Taniguchi, T., Pan, L., Matsushita, T., & Shirasaki, N. (2015). Adsorption capacities of activated carbons for geosmin and 2-methylisoborneol vary with activated carbon particle size: Effects of adsorbent and adsorbate characteristics. *Water Research*, 85, 95–102.
- Matsui, Y., Nakao, S., Taniguchi, T., & Matsushita, T. (2013). Geosmin and 2-methylisoborneol removal using superfine powdered activated carbon: Shell adsorption and branched pore kinetic model analysis and optimal particle size. *Water Research*, 47, 2873–2880.
- Matsui, Y., Yoshida, T., Nakao, S., Knappe, D. R. U., & Matsushita, T. (2012). Characteristics of competitive adsorption between 2-methylisoborneol and natural organic matter on superfine and conventionally sized powdered activated carbons. *Water Research*, 46, 4741–4749.
- Naidenko, O. V., Cox, C., & Bruzelius, N. (2012). Trouble water from pollution threatens drinking water, Environmental working group Washington, DC 20009, 2012.
- Nam, S. W., Yoon, Y., Choi, D. J., & Zoh, K. D. (2015). Degradation characteristics of metoprolol during UV/chlorination reaction and a factorial design optimization. *Journal of Hazardous Materials*, 285, 453–463.
- National Oceanic and Atmospheric Administration (NOAA). (2016). What is a harmful algal bloom? Available from <http://www.noaa.gov/what-isharmful-algal-bloom>. Accessed 1 Nov 2018
- Newcombe, G., House, J., Ho, L., Baker, P., & Burch, M. (2010). Management Strategies for Cyanobacteria (Blue-green Algae): a Guide for Water Utilities. Water Quality Research Australia, Adelaide, Australia, p. 101. Res report 74.
- Olsen, B. K., Chislock, M. F., & Wilson, A. E. (2016). Eutrophication mediates a common off-flavor compound, 2-methylisoborneol, in a drinking water reservoir. *Water Research*, 92, 228–234.
- Park, H., Kim, T. Y., Woo, D., & Cho, Y. S. (2015). Comparison of $O_3 + GAC$, $O_3 + H_2O_2 + GAC$, and GAC unit operation on natural organic matter and taste and odor causing compounds removal using a pilot plant study. *Water Science and Technology: Water Supply*, 15(6), 1383–1395.
- Park, J., Nama, H., Choi, J., Ha, J., & Lee, S. (2017). 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. *Chemical Engineering Journal*, 313, 345–354.
- Peng, S., Ding, Z., Zhao, L., Fei, J., Xuan, Z., Huang, C., & Chen, X. (2014). Determination of seven odorants in purified water among worldwide brands by HS–SPME. *Chromatographia*, 77(9–10), 729–735.
- Pestana, C. J., Robertson, P. K. J., Edwards, C., Wilhelm, W., McKenzie, C., & Lawton, L. A. (2014). A continuous flow packed bed photocatalytic reactor for the destruction of 2-methylisoborneol and geosmin utilising pelletised TiO_2 . *Chemical Engineering Journal*, 235, 293–298.
- Pillai, S. C., Štanger, U. L., Byrne, J. A., Pérez-Larios, A., & Dionysiou, D. D. (2015). Photocatalysis for disinfection and removal of contaminants of emerging concern. *Chemical Engineering Journal*, 261, 1–2.
- Piriou, P., Devesa, R., de Lalande, M., & Glucina, K. (2009). European reassessment of MIB and geosmin perception in drinking water. *Journal of Water Supply: Research and Technology-AQUA*, 58(8), 532–538.

- Pisarenko, A. N., Stanford, B. D., Yan, D., Gerrity, D., & Snyder, S. A. (2012). Effects of ozone and ozone/peroxide on trace organic contaminants and NDMA in drinking. *Water Research*, *46*, 316–326.
- Qi, F., Xu, B., Chen, Z., Ma, J., Sun, D., & Zhang, L. (2009). Efficiency and products investigations on the ozonation of 2-methylisoborneol in drinking water. *Water Environment Research*, *81*(12), 2411–2419.
- Qi, S., Mao, Y., Lv, M., Sun, L., Wang, X., Yang, H., & Xie, Y. F. (2016). Pathway fraction of bromate formation during O₃ and O₃/H₂O₂ processes in drinking water treatment. *Chemosphere*, *144*, 2436–2442.
- Qian, F., Dixon, D. R., Newcombe, G., Ho, L., Dreyfus, J., & Scales, P. J. (2014). The effect of pH on the release of metabolites by cyanobacteria in conventional water treatment processes. *Harmful Algae*, *39*, 253–258.
- Rescorla, A. J. (2012). Effect of lime solids and natural organic matter on geosmin removal via powdered activated carbon. A thesis submitted to the Faculty of the University of Minnesota.
- Rosa, J. M., Fileti, A. M. F., Tambourgi, E. B., & Santana, J. C. C. (2015). Dyeing of cotton with reactive dyestuffs: the continuous reuse of textile wastewater effluent treated by ultraviolet/hydrogen peroxide homogeneous photocatalysis. *Journal of Cleaner Production*, *90*, 60–65.
- Ruan, E. D., Aalhus, J. L., Summerfelt, S. T., Davidson, J., Swift, B., & Juárez, M. (2013). Determination of off-flavor compounds, 2-methylisoborneol and geosmin, in salmon fillets using stir bar sorptive extraction–thermal desorption coupled with gas chromatography–mass spectrometry. *Journal of Chromatography A*, *1321*, 133–136.
- Ruan, E. D., Aalhus, J., & Juarez, M. (2014). Sensitive analysis of off-flavor compounds, geosmin and 2-methylisoborneol, in water and farmed sturgeon by using stir bar sorptive extraction coupled with thermal desorption and gas chromatography–mass spectrometry. *Journal of Chromatography & Separation Techniques*, *5*(3), 228–232.
- Sarathy, S. R., & Mohseni, M. (2016). An overview of UV-based advanced oxidation processes for drinking water treatment. *IUVA News*, *7*, 1–12.
- Sarker, P., Pilote, A., Auffret, M., Proulx, É., Villemur, R., Deschamps, M., & Vandenberg, G. (2014). Reducing geosmin off-flavor compounds and waste outputs through dietary phosphorus management in rainbow trout aquaculture. *Aquaculture Environment Interactions*, *6*(1), 105–117.
- Sauvé, S., & Desrosiers, M. (2014). A review of what is an emerging contaminant. *Chemistry Central Journal*, *8*(1), 1–7.
- Schrader, K. K., Davidson, J. W., & Summerfelt, S. T. (2014). Evaluation of the impact of nitrate-nitrogen levels in recirculating aquaculture systems on concentrations of the off-flavor compounds geosmin and 2-methylisoborneol in water and rainbow trout (*Oncorhynchus mykiss*). *Aquacultural Engineering*, *57*, 126–130.
- Seckler, F. S. S., Margarida, M., & Rosemeire, A. L. (2013). Interference of iron as a coagulant on MIB removal by powdered activated carbon adsorption for low turbidity waters. *Journal of Environmental Sciences*, *25*(8), 1575–1582.
- Shan, G., Fu, Y., Chu, X., Chang, C., & Zhu, L. (2015). Highly active magnetic bismuth tungstate/magnetite composite under visible light irradiation in the presence of hydrogen peroxide. *Journal of Colloid and Interface Science*, *444*, 123–131.
- Son, M., Cho, D., Lim, J. H., Park, J., Hong, S., Ko, H. J., & Park, T. H. (2015). Real-time monitoring of geosmin and 2-methylisoborneol, representative odor compounds in water pollution using bioelectronics nose with human like performance. *Biosensors and Bioelectronics*, *74*, 199–206.
- Song, W., & O’Shea, K. E. (2007). Ultrasonically induced degradation of 2-methylisoborneol and geosmin. *Water Research*, *41*, 2672–2678.
- Srinivasan, R., & Sorial, G. A. (2011). Treatment of taste and odor causing compounds 2-methyl isoborneol and geosmin in drinking water: A critical review. *Journal of Environmental Sciences*, *23*(1), 1–13.
- Su, M., Yu, J., Zhang, J., Chen, H., An, W., Vogt, R., Andersen, T., Jia, D., Wang, J., & Yang, M. (2013). MIB-producing cyanobacteria (*Planktothrix sp.*) in a drinking water reservoir: Distribution and odor producing potential. *Water Research*, *444*–453.
- Summers, R. S., Kim, S. M., Shimabuku, K., Chae, S. H., & Corwin, C. J. (2013). Granular activated carbon adsorption of MIB in the presence of dissolved organic matter. *Water Research*, *7*, 3507–3513.
- Sun, D., Yu, J., Yang, M., An, W., Zhao, Y., Lu, N., Yuan, S., & Zhang, D. (2014). Occurrence of odor problems in drinking water of major cities across China. *Frontiers of Environmental Science & Engineering*, *8*(3), 411–416.
- Sun, W., Jia, R., & Gao, B. (2012). Simultaneous analysis of five taste and odor compounds in surface water using solid-phase extraction and gas chromatography-mass. *Frontiers of Environmental Science & Engineering*, *6*(1), 66–74.
- Sun, X., Zhang, Y., Shi, L. X., Chen, X. H., & Tang, X. (2018). Removing Typical Odorants in Drinking Water by Vacuum Ultraviolet Combined with Chlorine. *Huan jing ke xue= Huanjing kexue*, *39*(4), 1654–1660.
- Talaiekhazani, A., Bagheri, M., Goli, A., & Khoozani, M. R. T. (2016). An overview of principles of odor production, emission, and control methods in wastewater collection and treatment systems. *Journal of Environmental Management*, *170*, 186–206.
- Urase, T., & Sasaki, Y. (2013). Occurrence of earthy and musty odor compounds (geosmin, 2-methylisoborneol and 2,4,6-trichloroanisole) in biologically treated wastewater. *Water Science and Technology*, *68*(9), 1969–1975.
- US EPA, (2013). Presentations EPA Webinar Human Health Risks Associated with Cyanobacteria and Cyanotoxins Exposure, May 23, 2013
- van Rensburg, S. J., Barnard, S., & Krüger, M. (2016). Challenges in the potable water industry due to changes in source water quality: case study of Midvaal Water Company, South Africa. *Water SA*, *42*, 633–640.
- Visentin, F., Bhartia, S., Mohseni, M., Dorner, S., & Barbeau, B. (2019). Performance of Vacuum UV (VUV) for the degradation of MC-LR, geosmin, and MIB from cyanobacteria-impacted waters. *Environmental Science: Water Research & Technology*, *5*(11), 2048–2058.
- Wang, D., Bolton, J. R., Andrews, S. A., & Hofmann, R. (2015a). UV/chlorine control of drinking water taste and odour at pilot and full-scale. *Chemosphere*, *136*, 239–244.
- Wang, Q., Zietzschmann, F., Yu, J., Hofman, R., An, W., Yang, M., & Rietveld, L. C. (2020). Projecting competition between 2-methylisoborneol and natural organic matter in adsorption onto activated carbon from ozonated source waters. *Water Research*, *173*, 115574.

- Wang, R., Lia, D., Jin, C. X., & Yang, B. W. (2015b). Seasonal occurrence and species specificity of fishy and musty odor in Huajiang Reservoir in winter, China. *Water Resources and Industry*, 11, 13–26.
- Wang, Y., Yu, J., Zhang, D., & Yang, M. (2014). Addition of hydrogen peroxide for the simultaneous control of bromate and odor during advanced drinking water treatment using ozone. *Journal of Environmental Sciences*, 26(3), 550–554.
- Wang, Z., & Li, R. (2015). Effects of light and temperature on the odor production of 2-methylisoborneol-producing *Pseudanabaena* sp. and geosmin-producing *Anabaena ucrainica* (cyanobacteria). *Biochemical Systematics and Ecology*, 58, 219–226.
- Wang, Z., Shao, J., Xu, Y., Yan, B., & Li, R. (2015c). Genetic basis for geosmin production by the water bloom-forming cyanobacterium, *Anabaena ucrainica*. *Water*, 7, 175–187.
- Wen-Hsing, H., Wei-Nung, H., Gen-Shuh, W., Shu-Tung, H., & Tsair, L. (2012). Effect of pH on the analysis of 2-MIB and geosmin in water. *Water, Air, & Soil Pollution*, 223(2), 1–15.
- World Health Organization (WHO). (2014). *Progress on drinking water and sanitation: 2014 Update*. WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation.
- World Health Organization (WHO). (2015). *Progress on Drinking Water and Sanitation-2015 update and MDG assessment*. WHO Press, World Health Organization, 20 Avenue Appia, 1211 Geneva 27, Switzerland
- Wright, E., Daurie, H., & Gagnon, G. A. (2014). Development and validation of an SPE-GC-MS/MS taste and odour method for analysis in surface water. *International Journal of Environmental Analytical Chemistry*, 94(13), 1302–1316.
- Wu, D., & Duirk, S. E. (2013). Quantitative analysis of earthy and musty odors in drinking water sources impacted by wastewater and algal derived contaminants. *Chemosphere*, 91, 1495–1501.
- Xia, P., Zhang, S., Yu, J., Ye, H., Zhang, D., Jiang, L., Wang, Z., & Yin, D. (2020). Complex odor control based on ozonation/GAC advanced treatment: optimization and application in one full-scale water treatment plant. *Environmental Sciences Europe*, 32(1), 1–12.
- Yu, J., Yang, F., Hung, W., Liu, C., Yang, M., & Lin, T. (2016). Prediction of powdered activated carbon doses for 2-MIB removal in drinking water treatment using a simplified HSDM approach. *Chemosphere*, 156, 374–382.
- Yu, S., Xiao, Q., Zhu, B., Zhong, X., Xu, Y., Su, G., & Chen, M. (2014). Gas chromatography–mass spectrometry determination of earthy-musty odorous compounds in waters by two phase hollow-fiber liquid-phase microextraction using polyvinylidene fluoride fibers. *Journal of Chromatography A*, 1329, 45–51.
- Yuan, B., Li, F., Xu, D., & Fu, M. (2013a). Comparison of two methods for the determination of geosmin and 2-methylisoborneol in algae samples by stable isotope dilution assay through purge-and-trap or headspace solid-phase microextraction combined with GC/MS. *Analytical Methods*, 5(7), 1739–1746.
- Yuan, B., Xu, D., Li, F., & Fu, M. L. (2013b). Removal efficiency and possible pathway of odor compounds (2-methylisoborneol and geosmin) by ozonation. *Separation and Purification Technology*, 117, 53–58.
- Zamyadi, A., Henderson, R. K., Stuetz, R., Newcombe, G., Newtown, K., & Gladman, B. (2016). Cyanobacterial management in full-scale water treatment and recycling processes: reactive dosing following intensive monitoring. *Environmental Science: Water Research & Technology*, 2(5), 362–375.
- Zamyadi, A., Henderson, R., Stuetz, R., Hofmann, R., Ho, L., & Newcombe, G. (2015). Fate of geosmin and 2-methylisoborneol in full-scale water treatment plants. *Water Research*, 83, 171–183.
- Zhang, C., Fang, Z., Liu, W., Tian, F., & Bai, M. (2016a). Rapid removal of bacterial endotoxin and natural organic matter in water by dielectric barrier discharge plasma: Efficiency and toxicity assessment. *Journal of Hazardous Material*, 318, 15–23.
- Zhang, T., Xue, Y., Li, Z., Wang, Y., Yang, W., & Xue, C. (2016b). Effects of ozone on the removal of geosmin and the physicochemical properties of fish meat from bighead carp (*Hypophthalmichthys nobilis*). *Innovative Food Science & Emerging Technologies*, 34, 16–23.
- Zoschke, K., Dietrich, N., Bornick, H., & Worch, E. (2012). UV-based advanced oxidation processes for the treatment of odour compounds: efficiency and by-product formation. *Water Research*, 46, 5365–5373.
- Zoschke, K., Engel, C., Beornick, H., & Worch, E. (2011). Adsorption of geosmin and 2-methylisoborneol onto powdered activated carbon at non-equilibrium conditions: influence of NOM and process modelling. *Water Research*, 45, 4544–4550.
- Zuo, P., Wang, L., Yang, Z., Lee, H., & Li, H. (2016). Rapid and simultaneous determination of ten off-flavour compounds in water by head space solid phase micro-extraction and gas chromatography-mass spectroscopy. *Journal of Central South University*, 23(1), 59–67.

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