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REVIEW ARTICLE

Volatile Mediated Interactions Between Bacteria and Fungi in the Soil

Uta Effmert · Janine Kalderás · René Warnke · Birgit Piechulla

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Abstract Soil is one of the major habitats of bacteria and fungi. In this arena their interactions are part of a communication network that keeps microhabitats in balance. Prominent mediator molecules of these inter- and intraorganismic relationships are inorganic and organic microbial volatile compounds (mVOCs). In this review the state of the art regarding the wealth of mVOC emission is presented. To date, ca. 300 bacteria and fungi were described as VOC producers and approximately 800 mVOCs were compiled in DOVE-MO (database of volatiles emitted by microorganisms). Furthermore, this paper summarizes morphological and phenotypical alterations and reactions that occur in the organisms due to the presence of mVOCs. These effects might provide clues for elucidating the biological and ecological significance of mVOC emissions and will help to unravel the entirety of belowground, volatile-wired' interactions.

Keywords Bacteria · Fungi · Soil · Volatiles · Volatile mediated interactions

Introduction

Inter- and intra-organismal communication strategies are symbolized by the three monkeys: the deaf, the mute, and the blind. Interestingly, one major communication path was not featured: the sense of smell. This is surprising since the sense of smell is well-established in many animals and plants. Vertebrates and invertebrates are able to detect minute amounts of volatiles even over very long distances; plants use volatiles to communicate with their pollinators as well as with plants of the same species or other plants (Baldwin et al., 2006; Dobson, 2006; Heil and Walters, 2009) (Fig. 1). The infochemicals used for these inter- and intra-organismal interactions are low molecular mass compounds with high vapor pressures, low boiling points, and a lipophilic character. All of these features facilitate evaporation. Consequently, these compounds disperse easily in the atmosphere and thus play essential biological/ecological roles in aboveground habitats. It was only recently recognized that belowground organisms are also opulent volatile producers and emitters. Therefore, a new research area focuses on volatile-based interactions in the soil. Here, we first describe the habitat soil with its characteristic structural prerequisites in relation to volatile-based communications. Then, we present a summary of volatile emissions of microbes (bacteria and fungi). In the final section, we discuss volatile-based bacterial and fungal interactions.

The Habitat Soil

The tremendous diversity of the bacterial and fungal kingdoms is paralleled by the heterogeneity of habitats these organisms are able to occupy. They appear ubiquitously around the world, successfully colonizing ecological niches and microhabitats (Dighton, 2003; Hawksworth and Mueller, 2005; Gasch, 2007). One of the major habitats for fungi and bacteria is soil, where they occur as free living organisms on the soil surface, in the soil core, or in association with belowground parts of living plants or organic material derived from dead plants and animals (Forster, 1988). Soil itself is a complex blend of weathered minerals and organic material mixed with biota. Fungi and bacteria hereby play a substantial role in the

U. Effmert · J. Kalderás · R. Warnke · B. Piechulla (✉)
Institute of Biological Sciences, University of Rostock,
Albert-Einstein-Str. 3,
18059 Rostock, Germany
e-mail: birgit.piechulla@uni-rostock.de

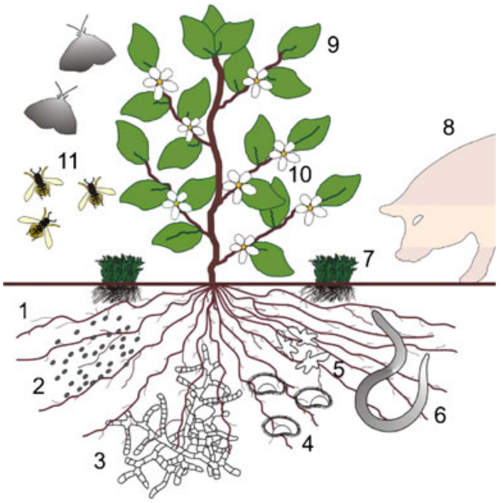


Fig. 1 Schematic presentation of organisms involved in volatile interactions above- and belowground (drawn by Marco Kai). 1 plant root, 2 bacteria, 3 fungi, 4 ciliates, 5 amoeba, 6 nematodes, 7 moos, 8 wild boar, 9 plant leaves, 10 plant flowers, 11 insects

decomposition and breakdown of organic as well as inorganic materials, respectively (Dighton, 2003). These biomineralization processes contribute substantially to soil production, generating a continuous flow of nutrients for plant primary production. Therefore, functional soils should be regarded as a balanced complement of abiotic (mineral and organic) and biotic components (Nakas and Klein, 1980; Dighton, 2003). As part of the microbiotic soil community, fungi and bacteria form dynamic and enduring communities that are integrated into even more complex microecosystems, or they arise as transient communities to secondarily colonize substrates as long as degradable nutrients are available.

Soil Properties Influence Microenvironments Belowground

Microbial colonization of soil is determined mainly by its physicochemical properties (Dequiedt et al., 2011). These properties are influenced by texture, carbon content, and microstructure, which in turn affect the formation of macroaggregates and subsequently soil parameters such as porosity or air and water content. Soil texture is determined by its inorganic components and describes the proportional distribution of mineral particle sizes: sand (0.05–2 mm), silt (2–50 μm), and clay (<2 μm) (Cehnu and Stotzky, 2002; Brown, 2003; Conklin, 2005; Schafer, 2006). Texture, mineral composition, and particle shape give rise to certain particle arrangements (microaggregates) that determine soil microstructures (Cehnu and Stotzky, 2002; Alekseeva, 2007). These microstructures and the presence of organic matter contribute to the assembly and stabilization of macroaggregates >0.25 mm in size (Forster, 1988; Ranjard and Richaume, 2001). As a result, a complex network of void spaces is formed in soil, i.e., soil pores that can account for up to 50 % of the total soil volume (Ranjard and Richaume, 2001; Conklin, 2005; Standing and Killham, 2007). Their ability to retain water varies with their size and shape, so they are filled with different amounts of water and air. Depending on the air and water content, the chemical composition of aggregates, and the circulation within the pore network, numerous heterogenic microenvironments for microbial life are created. These vary in nutrient supply, aeration, availability of water, ionic composition, minerals, pH, redox potential, and surface composition (Forster, 1988; Ranjard and Richaume, 2001; Nannipieri et al., 2003).

Microhabitats Belowground

Microorganisms congregate in soil pores that provide a suitable microenvironment. Bacteria rely on the presence of organic and inorganic solutes in the aqueous phase of pores and on particle surfaces. The heterogeneity of these various microhabitats is probably the reason for the huge bacterial diversity in soil. Although the number of bacterial cells per gram of soil can easily exceed 10^{10} and estimates of the numbers of different species range from 10^3 to 10^5, only a rather small proportion of soils is actually colonized by bacteria (Gans et al. 2005; Roesch et al. 2007; citations in Heuer and Smalla 2012). Bacteria may occur as free living organisms, but are usually attached to solid surfaces as scattered individual cells, microcolonies, or biofilms. Fungi inhabit the same locations but other pore sizes. Water saturated micropores (Ø<10 μm) are reserved for bacterial communities, where they escape predation and the effects of fungal antibiotics. Because of their size, fungi settle in macropores (Ø>10 μm) found between and within macroaggregates. In addition, fungal hyphae can extend through aerated water-unsaturated pores to reach new pores and exploit new nutrient resources (Forster, 1988; Cehnu and Stotzky, 2002). The latter is especially important since soil in its entirety represents a nutrient-depleted habitat for microorganisms. Consequently, microorganisms aggregate near any suitable nutrient source, which creates colonization hotspots. Therefore, bacteria and fungi have to compete for the same resources and undergo interspecies interactions. On the macroscale, plant litter like dead leaves, stems, roots, wood, and bark as well as animal remains and fecal material are important sources of biodegradable organic material, while on the microscale cell-wall remains, lipids, polysaccharides, proteins, DNA and RNA, and metabolites contribute to temporary microhabitats (Forster, 1988; Nannipieri et al., 2003). The most lively and enduring microhabitat is the living plant root, which releases a wide variety of soluble, insoluble, or volatile metabolites that attract an exceptionally dense and diverse population of microbiota, including bacteria and fungi (Koske and Gemma, 1992; Chen et al., 2004; Gregory, 2006; Brimecombe et al., 2007; Nannipieri et al., 2007; Hussain and Hasnain, 2011). Bacteria adhere to the root surface itself (rhizoplane) and colonize a narrow soil zone around the plant root (rhizosphere) (Lenc et al., 2011). They benefit from a constant flow of organic substrates, but in return promote plant growth by providing soluble inorganic nutrients and producing growth-promoting factors (Brimecombe et al., 2007; Nannipieri et al., 2007; Compant et al., 2010). A special role is attributed to antagonistic bacteria, which are able to suppress the growth of various plant pathogenic fungi (Bhattacharyya and Jha, 2011). Mycorrhizal fungi (see Jung et al., 2012, this issue) also benefit from nutrients supplied by the plant root. More than 95 % of short roots of most terrestrial plants are colonized by symbiotic fungi, and these mycorrhizal fungi are surrounded by complex microbial communities. So called mycorrhiza helper bacteria (MHB) support mycorrhiza formation (Frey-Klett et al., 2007; Bonfante and Anca, 2009; Rigamonte et al., 2010). In addition, plant roots not only host beneficial but also attract detrimental organisms such as phytopathogens, which may harm plants and microbiota as well. Therefore, mycorrhizal fungi, their associated bacteria as well as rhizobacteria have to deal with a very complex and competitive rhizomicrobial milieu (Anderson, 1992; Bianciotto et al., 1996; Miransari, 2011). Bacteria and fungi closely intermingle in the mycorrhizosphere and mutually influence survival and colonization success as well as pathogenesis and virulence (Wargo and Hogan, 2006; Minerdi et al., 2008).

Volatiles as Medium for Interactions Belowground

Factors that regulate the dynamics and balance of symbiosis, cooperation, competition, and also coexistence in microbial communities have been investigated intensively. Phenomena like quorum-sensing and quorum-quenching (see Hartmann and Schikora, 2012, this issue), the impact of rhizobacterial and fungal antibiotics, effector molecules, and excreted enzymes have been recognized as effective regulatory principles (Walker et al., 2003, 2004; Chernin et al., 2011). The possible role of volatiles in bacterial-fungal interactions has been neglected for many years despite earlier reports on effective microbial volatiles (Stotzky and Schenk, 1976; Koske and Gemma, 1992). Prerequisite for volatile effectiveness is their release, emanation and distribution, and their perception by a target organism. This is ensured by the physicochemical properties of volatiles (low molecular weight, high vapor pressure, low boiling point), which facilitate distribution even over long distances (Farmer, 2001; Baldwin et al., 2006; Heil and Ton, 2008). However, does this also occur in soils? Yes, it does. Volatile distribution belowground takes place by diffusion and advection (Minnich and Schumacher, 1993). Volatiles can move through the network of soil pores since they are active in both gas and liquid phases and capable of revolatization after passing through water-saturated pores (Koske and Gemma, 1992; Aochi and Farmer, 2005; Asensio et al., 2008). However, due to their high vapor pressure, volatiles move primarily by vapor diffusion (Minnich and Schumacher, 1993). These processes are all influenced by inherent chemical properties of the volatile itself and physicochemical properties of the surrounding soil, which affect adsorption, desorption, and degradation. Adsorption/desorption depends on the polarity of the compound, the soil texture and spatial architecture, and the presence of water. On the microscale, increasing humidity reduces the adsorption of nonpolar volatiles to mineral surfaces; on the macroscale, nonpolar volatiles are increasingly sorbed by organic matter in moist or wet soils (Minnich and Schumacher, 1993; Ruiz et al., 1998; Aochi and Farmer, 2005; Insam and Seewald, 2010). Volatile compounds also are amenable to biodegradation. Owen et al. (2007) found rapid degradation of geraniol in the rhizosphere of *Populus tremula*, an observation they attributed to the activity of soil microorganisms. However, compared to compounds solely soluble in water, volatiles are less likely to be quickly biodegraded (Koske and Gemma, 1992). Mineral surfaces may serve as catalysts for chemical reactions that contribute to abiotic degradation. Highly specific clay surfaces react with volatiles that carry polar functional groups. Furthermore, volatiles also may be exposed to free-radical oxidation (Minnich and Schumacher, 1993; Insam and Seewald, 2010). Measurements of volatile exchange rates have revealed low volatile emission from soil, supporting the assumption that soil acts as a volatile sink (Stotzky and Schenck, 1976; Asensio et al., 2007).

Microbial Volatile Emission

A large number of bacterial species presently are known, and it is estimated that this number could reach a million (10^6). While many microorganisms have been isolated from aboveground habitats (i.e., plants, human skin and intestines, animals, and refuse, sewage, and aquatic habitats), a rich source of bacteria is the terrestrial and belowground biotope. Metagenomic approaches have demonstrated that the microbial diversity is larger in soils than in marine sediments or aquatic habitats (Will et al., 2010; Daniel, 2011). The capacity of bacteria and fungi to decompose, mineralize, and accumulate organic matter is extraordinary and has a significant impact on the carbon, nitrogen, phosphate and sulfur biogeochemical cycles (Naeem, 1997). Some of the metabolized compounds are emitted as volatile products that are readily utilized by other organisms of the microbial food chain or released into the underground

Table 1 Producers and users of microbial volatiles

Producer/emitters →	compound	→ user/receiver	function
Inorganic			
No microorganism known	CO	Carboxydotrophic bacteria (*Hydrogenomonas carboxydovorans*, *Selberia carboxyhydrogena Oligotropha carboxidovorans Carboxydothermus hydrogenoformans*)	Electron donor, carbon source
Heterotrophic microbes	CO_2	Chemolitho (hydrogen-, sulfur-, ammonia-, nitrite-. Fe^{2+}-oxidizing)- and oxygenic (cyanobacteria) and anoxygenic (Rhodospirillaceae, Chromatiaceae, Chlorobiaceae, Chloroflexaceae) photoautotrophic bacteria	Carbon source
		Methanogenic archaea (*Methanobacterium ruminatium, M. thermoautrophicum*) and homoacetogenic bacteria (*Clostridium aceticum, C. ljungdahlii*)	Electron acceptor (methane or acetate production)
Facultative and obligate anaerobic bacteria (clostridia, enterobacteria)	H_2	Chemolitho (hydrogen-oxidizing)- and anoxygenic (Rhodospirillaceae, Chromatiaceae, Chlorobiaceae, Chloroflexaceae) photoautotrophic bacteria	Electron donor
		Methanogenic archaea (*Methanobacterium ruminatium, M. thermoautrophicum*) and homoacetogenic bacteria (*Clostridium aceticum, C. ljungdahlii*)	
Cyanobacteria (*Synechococcus, Synechcystis*)	O_2	Aerobic microorganisms	Electron acceptor
Proteolytic clostridia and some aerobic chemoorganotrophic proteobacteria (*Serratia odorifera* 4Rx13, *Serratia plymuthica* HRO C48, *Pseudomonas fluorescens* L13-6-12, *Pseudomonas* trivialis 3Re2-7, *Stenotrophomonas rhizophila* P69, *Xanthomonas campestris* pv. *vesicatoria* 85-10)	NH_3 (NH_4^+)	Many microorganisms Ammonia-oxidizing bacteria (Nitrosomonas, Nitrosospira, Nitrosococcus)	Nitrogen source, olfaction, antibiotic resistance, toxic compound, electron donor
Ammonia-oxidizing bacteria (*Nitrosomonas, Nitrosospira, Nitrosococcus*)	NO_2^-	Nitrite-oxidizing bacteria (Nitrobacter, Nitrospina, Nitrococcus)	Electron donor, nitrogen source
Denitrifying bacteria (*Alcaligenes faecalis, Bacillus licheniformis, Paracoccus denitrificans, Pseudomonas stutzeri, Thiobacillus denitrificans*)	N_2	Nitrogen-fixing bacteria and archaea (*Rhizobium, Bradyrhizobium, Azorhizobium, Frankia, Klebsiella, Clostridium, Methanosarcina, Methanospirillum*)	Nitrogen source
Some proteobacteria (*Pseudomonas fluorescens, P. trivialis, Chromobacterium, Rhizobium*)	HCN		Defense compound, quorum sensing
Sulfate-reducing bacteria (*Desulfovibrio, Desulfomonas, Desulfotomaculum*)	$H_2S/S/SO_3^{2-}$	Chemolitho (sulfur-oxidizing)- and anoxygenic (Chromatiaceae, Chlorobiaceae) photoautotrophic bacteria	Electron donor, amino acid biosynthesis, defense compound
Organic			
Methanogenic archaea	CH_4	Obligate methylotrophic bacteria	Electron donor, carbon source
Many bacteria, see Table 2	Alkanes, alkenes	Aerobic microorganisms	Carbon source
Clostridium spp., *Pseudomonas* spp., *Streptomyces* spp.	ethylene		
Yeast; several bacteria, see Table 2	CH_3OH		

Table 1 (continued)

Producer/emitters →	compound	→ user/receiver	function
		Obligate and faculative methylotrophic bacteria methanogenic archaea	Electron donor, carbon source, electron acceptor
Yeast, facultative and obligate anaerobic bacteria (e.g. clostridia, enterobacteria, lactic acid bacteria); several bacteria and fungi, see Tables 2 and 3	C_2H_5OH	Heterotrophic bacteria (acetic acid bacteria, *Clostridium kluyveri*)	Electron donor, carbon source
Clostridium spp., *Bacillus* spp., *Lactobacillus* spp., *Salmonella* spp., *Shigella* spp., *Streptomyces* spp.; many other bacteria and fungi, see Tables 2 and 3	Butanol	Heterotrophic bacteria	Electron donor, carbon source
Many bacteria and fungi, see Tables 2 and 3	Low molecular mass alcohols	Heterotrophic bacteria	Carbon source
Enterobacteria, bacilli, clostridia	Acetoin, 2,3-butanediol	Heterotrophic bacteria	Electron donor, carbon source
	CH_2O	obligate and faculative methylotrophic bacteria	electron donor, carbon source
Many bacteria and fungi, see Tables 2 and 3	Low molecular mass aldehydes and ketones	Heterotrophic bacteria	Carbon source
Clostridia and other bacteria, see Table 2; fungi see Table 2	Acetone	Heterotrophic bacteria	Electron donor, carbon source
Facultative and obligate anaerobic bacteria (clostridia, enterobacteria, lactic acid bacteria), many bacteria and fungi, see Tables 2 and 3	$CHOOH$, CH_3COOH, CH_3CH_2COOH, $CH_3CH_2CH_2COOH$, low molecular mass acids	Heterotrophic bacteria and fungi	Electron donor, carbon source
Alcaligenes spp., *Bacillus* spp., *Pseudomonas* spp., *Stenotrophomonas* spp.; many other bacteria see Table 2, few fungi see Table 3	Methylamine and other amines	Obligate and faculative methylotrophic bacteria methanogenic archaea	Electron donor, carbon source
Streptomyces spp.; see Table 2	Geosmin		
Alcaligenes spp., Chondromyces spp., Paenibacillus spp., Serratia spp.; many other bacteria see Table 2	Pyrazines		
Enterobacteria, *Pseudomonas* spp.	Indole		Signaling (indirect?)
Streptomyces spp., *Bacillus* spp., *Pseudomonas* spp., *Tuber* spp.; many other bacteria and fungi, see Tables 2 and 3	Dimethyldisulfide, trimethyldisulfide	Marine sulfur-oxidizing bacteria (*Thiobacillus thioparus*) obligate and faculative methylotrophic bacteria *(Hyphomicrobium)*	Carbon and energy source
Gram negative bacteria (*Pseudomonas fluorescens, Serratia liquefaciens*)	N-acyl-l-homoserine lactones (AHL) (e.g. C4-HSL,C6-HSL, C10HSL)	Gram negative bacteria (*Pseudomonas aeruginosa*, *Agrobacterium tumefaciens*	Quorum sensing signal > biofilm formation
Gram positive bacteria *Streptomyces*	Gamma-butyrolactones	Gram positive bacteria	Quorum sensing signal
Condromyces spp., *Leuconostoc* spp., *Roseobacter* spp.,*Lactobacillus* spp., *Serratia* spp.; many other bacteria, see Table 2	ß-phenylethanol		
	Aromatic compounds	Aerobic and anaerobic bacteria	Carbon source
Serratia odorifera 4Rx13, *S. plymuthica* HRO-C48	Sodorifen		

The table presents examples of microorganisms that synthesize or use inorganic or organic volatile compounds. Summarized from G. Gottschalk, 1986; Fuchs. 2007; and DOVE-MO (Kalderas, 2011) habitat (Table 1). Soil microorganisms produce large quantities of highly diverse volatiles (Stotzky and Schenck, 1976; Linton and Wright, 1993; Leff and Fierer, 2008; Insam and Seewald, 2010 and citations therein). Volatile metabolites also are produced by the root system of plants, but in this review these sources will not be considered. Instead, the focus lies on bacterial and fungal volatile emissions and uptakes (Kesselmeier and Staudt, 1999; Wenke et al., 2009). The volatile compounds can be of organic (volatile organic compounds, VOCs) or inorganic nature, both presumably important for this habitat and capable of influencing organismic communities (McNeal and Herbert, 2009). The functions of the volatiles are diverse, e.g., i) they play a role in the food chain of the microbial loop because they are assimilated and incorporated into organic matter (bioconversion), ii) they influence physiological processes (e.g., laccase activity, nitrification, nitrogen mineralization), iii) they function as electron acceptors or donors to support metabolic reactions, iv) they play a role in quorum sensing/quenching, v) they act as defense compounds, vi) they are used as communication signals, or vii) their functions remain so far elusive (Table 1).

Volatiles Emitted from Bacteria

Inorganic Volatiles

Some producers and users of inorganic volatiles are summarized in Table 1, which is a brief extract from Gottschalk (1986) and Fuchs (2007). **Carbon dioxide** is a major inorganic volatile produced by all heterotrophic living organisms, and indeed much of the CO_2 in the atmosphere originates from the huge microbial populations on earth, in both soil and aquatic habitats. Atmospheric CO_2 is assimilated primarily by plants and oxygenic and anoxygenic phototrophic bacteria (cyanobacteria, *Rhodospirillaceae* [purple nonsulfur bacteria], *Chromatiaceae* [purple sulfur bacteria], *Chlorobiaceae* [green sulfur bacteria], and *Chloroflexaceae* [green nonsulfur bacteria]). The characteristic Calvin reactions and enzymes also are present in soil bacteria, such as *Rhodospirillum rubrum, Thiobacillus intermedius, Ralstonia eutrophus*, *Pseudomonas facilis*, to name a few. Chemolithotrophic microorganisms use ATP and the reducing power of inorganic substrates for the reduction of CO_2. CO_2 also is used by methanogenic bacteria such as *Methanobacterium ruminatium* and *Methanobacterium thermoautrophicum* for CH_4 production (Gottschalk, 1986).

Anthropogenically released **carbon monoxide** results from incomplete reduction of wood and polymers of dead organic material, while microbial CO production is unknown. Aerobically grown *Hydrogenomonas carboxydovorans* and *Selberia carboxyhydrogena* can live on CO by oxidizing it to CO_2. Some bacteria (e.g., *Rhodospeudomonas sphaeroides, Methylosinus, Methylocystis*) use the serine-isocitrate lyase pathway to form oxaloacetate from phosphoenol pyruvate (PEP) and CO_2 (PEP carboxylase). As a result of this pathway, acetyl-CoA and finally succinate are formed from CH_2O and CO_2. Chemolithotrophic and phototrophic bacteria have in common the formation of cell material via CO_2 reduction by using the reducing power from inorganic compounds. Energy sources can be H_2, sulfide, ammonia, or nitrite.

Hydrogen is formed under anaerobic conditions during the fermentation of carbohydrates to short-chain fatty acids by *Clostridium* spp., *Enterobacteriaceae* (e.g., *Escherichia, Salmonella, Shigella*) and others. A group of chemolithotrophic bacteria (hydrogen-oxidizing bacteria), anoxygenic phototrophic bacteria, as well as methanogenic archaea utilize H_2 as an electron donor.

Well-known volatile-dependent soil bacteria are the free-living and symbiotic **nitrogen**-fixing organisms. The latter are, for example, *Rhizobium* spp. and *Frankia* spp., and exist in partnerships with plants. These bacteria form bacteroids, and consequently, root nodules develop. The product of the nitrogenase is **ammonia**, which is usually not released but is efficiently incorporated into organic compounds by glutamate dehydrogenase, glutamine synthetase, and glutamate synthase. Soil-living clostridia (*Clostridium* spp.) and other bacteria (e.g., *Peptococcus anaerobicus*) ferment amino acids and nucleotides and live from these recycled carbon skeletons as well as ammonia. Recently, it was shown that *Serratia, Pseudomonas, Stenotrophomonas*, and *Xanthomonas*, when grown on complex media (NB or LB), emitted gaseous ammonia (or amines), which was detected in the headspace with Nessler's reagent (Kai et al., 2010; Weise et al., 2012, Weise and Piechulla unpublished). Gaseous ammonia released from bacteria can modify, e.g., the antibiotic resistance of *E. coli* to tetracycline (Bernier et al., 2011). Apparently, increased intracellular polyamine levels alter the membrane permeability to antibiotics as well as resistance to oxidative stress. Another recent publication showed that ammonia could be sensed by *Bacillus licheniformis*, which was considered to be a first indication of bacterial olfaction (Nijland and Burgess, 2010). Although the nitrogen supply is usually a limiting factor in soil, it cannot be excluded that NH_3 emission may occur in nature under confined protein-rich growth conditions (e.g., decomposition of carcasses, lysis of large microbial populations or plant materials, or land spreading of whey in agriculture). The amounts as well as the ecological consequences have not been investigated.

Denitrifying bacteria release nitrogen during respiration and reduction of nitrate (in some cases N_2O instead of N_2 is released). The group of nitrogen-evolving bacteria is quite diverse, including *Alcaligenes faecalis, Bacillus licheniformis, Paracoccus denitrificans*, and *Pseudomonas stutzeri*.

Most soil microorganisms use sulfate as their principal sulfur source, and the intrinsic enzyme system reduces sulfate to sulfide (sulfate assimilation). However, in anaerobic regions in the soil, sulfate is used by *Desulfovibrio, Desulfomonas, Desulfuromonas*, and *Desulfotomaculum* as a terminal electron acceptor, and consequently **hydrogen sulfide** is formed and released (dissimilatory sulfate reduction). The toxic end product H_2S is used by chemolithotrophic bacteria as electron acceptor, e.g., *Thiobacilli*, and H_2S can also be incorporated into O-acetylserine, an intermediate of amino acid biosynthesis. Furthermore, it also has been shown that H_2S production in soil is due to the presence of cysteine (Morra and Dick, 1991). Only recently it was demonstrated that H_2S production acts as a defense mechanism that protects bacteria from antibiotics (Shatalin et al., 2011).

The release of **HCN** from bacteria varies in different species (Stotzky and Schenck, 1976). *Pseudomonas* spp. (e.g., CHA0), *Chromobacterium* and *Rhizobium* typically emit this toxic inorganic volatile, while defective mutants (e.g., CHA207) do not (Blumer and Haas, 2000; Pessi and Haas, 2000; Kai et al., 2010; Blom et al., 2011b). Hydrogen cyanide inhibits several metal-containing enzymes, most significantly the cytochrome c oxidase of the respiratory chain. Therefore, this volatile can be toxic for most aerobic organisms living in the same habitat as Pseudomonades. It was reported that both the RHI/R- as well as the AHL-based quorum sensing system regulate HCN biosynthesis (Winson et al., 1995; Pessi and Haas, 2000). Consequently, bacterial population densities can be controlled by HCN levels.

The distribution and appearance of inorganic gaseous compounds in the soil determine the localization of other soil organisms, e.g., the oxidizers (nitrification) of ammonium occur in the upper sediment layers, followed by nitrate and sulfide oxidizers. In the deeper anaerobic layers, methanogenic and acetogenic bacteria reside. Many of the gaseous compounds are quickly recycled (e.g., H_2) because producers and utilizers appear in nearby soil zones. Compounds emitted in excess are released into the atmosphere, for example, CO_2, N_2, and in some regions H_2S.

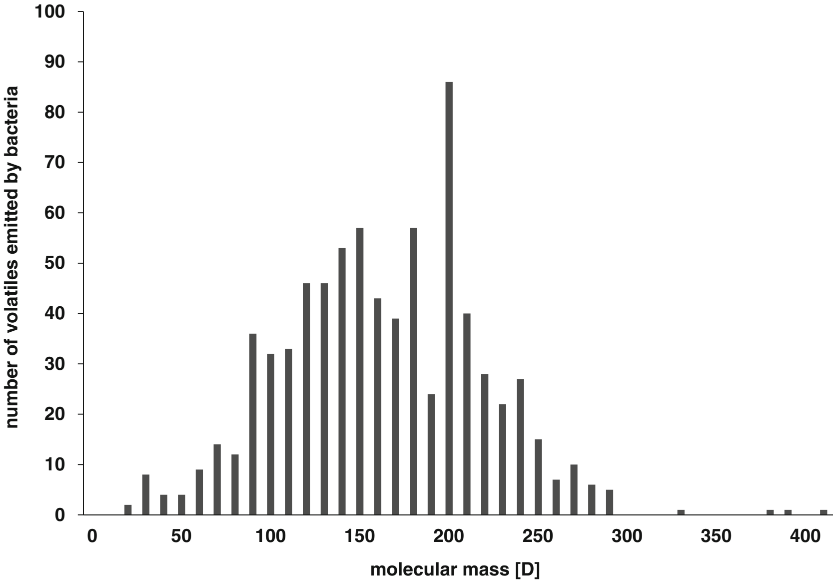
Organic Volatiles (VOCs) (<120 D)

The smallest organic volatile compound is **methane**, the most reduced compound. Its formation is the terminal step in the food chain of methanogenic archaea (Gottschalk, 1986). They utilize CO_2, CH_2O, HCOOH, or CH_3OH and H_2 to synthesize methane. This soil-based methane production is of global importance; for example, tundra and rice fields contribute 40 % of atmospheric methane. In the soil, CH_4 is a good substrate for obligate and facultative methylotrophs, which are often anaerobic organisms that grow in deeper soil layers. Bacterial production of the C_1 volatile **methanol** has been described in *Enterobacteriaceae* such as *Escherichia coli, Shigella flexneri*, and *Salmonella enterica* (Bunge et al., 2008) and in *Xanthomonas campestris* (Weise et al., 2012). Methanol can be metabolized by methylotrophic bacteria including *Hyphomicrobium* species, some *Pseudomonas* species (*P. oxalaticus*), and *Protaminobacter* (Gottschalk, 1986). After an initial conversion into formaldehyde, a condensation with ribulose-5-phosphate forms dihydroxyacetone phosphate in the so–called ribulose-monophosphate cycle in *Methylococcus* and *Methylomonas* species. Yeasts, *Zymomonas mobilis*, lactic acid bacteria, and clostridia form **ethanol** (Gottschalk, 1986). Ethanol together with acetate is a good substrate for *Clostridium kluyveri*. **Butanol** and **acetone** are emitted e.g., by *Clostridium acetobutylicum* when enzymes of this pathway are activated under low pH conditions (Lütke-Eversloh and Bahl, 2011). Butanol also is formed by various microorganisms, and is considered a volatile organic compound (VOC). In the presence of butyrate and e.g., during glucose depletion butanol is a preferred product of butyrate metabolism. Many clostridia reduce acetone to isopropanol. **Acetoin** and **2,3-butanediol** typically are produced during incomplete oxidation by *Bacillus* spp. (Gottschalk, 1986). Formed from pyruvate via α-acetolactate, both compounds are released under glucose abundance and taken up when glucose is depleted. Acetoin and 2,3-butanediol then can serve as a source for ATP production needed during the sporulation process. Butanediol production also is carried out by *Enterobacteriaceae* e.g., *Serratia*, *Enterobacter*, and *Erwinia*. Small molecular weight acids such as formate, acetate, propionate and butyrate are typical mixed acid fermentation products synthesized by *Enterobacteriaceae*, *Clostridia*, *Propionibacteria*, and e.g., *Megasphaera elsdenii* (Gottschalk, 1986). Small organic acids are utilized by many heterotrophic soil microorganisms.

Volatile Organic Compounds (>120 D) Emitted from Bacteria and Fungi

It is well-known that bacteria emit small molecular weight organic volatiles (<120 D, see above), but the frequent release of other compounds (120 to ca. 300 D) by microorganisms has only recently attracted attention. A literature search allowed the compilation of around 800 VOCs emitted by bacteria and fungi. Most compounds are in the range from 130 to 210 D (Fig. 2). In the 'database of volatiles emitted by microorganisms (DOVE-MO),' all VOC emitting microorganisms were compiled, including those in soil (literature search till December 2010, Kalderas, 2011). Since the origin of the microbes often was not well-documented, or it was difficult to assign microorganisms to a single habitat, we compiled all VOC emitting microorganims in DOVE-MO (Database of volatiles emitted by microorganisms) and present them in alphabetical order (bacteria: Table 2, fungi: Table 3). In total, 671 different VOCs are emitted by 212 bacterial species, and

Fig. 2 Distribution of molecular masses of bacterial volatile organic compounds (VOCs)



335 VOCs from 96 fungal species are known. It is expected that future investigations in this new and developing research area will rapidly add organisms and VOCs to this database.

The volatile spectra of the microbes can be simple (<10 VOCs) as well as very complex (>50 VOCs) (e.g., Kai et al., 2007, 2010). Approximately 50 bacterial and ca. 30 fungal species presently are known that emit complex volatile mixtures. The number of detectable volatiles in a species blend increases when various techniques are applied (e.g., dynamic headspace volatile capture in open and closed airflow systems, different trapping materials, solid phase microextraction (SPME), gas chromatography combined with mass spectrometry (GC/MS), proton transfer reaction/mass spectrometry (PTR-MS), selected ion flow tube/mass spectrometry (SIFT-MS), secondary electron spray ionization/mass spectroscopy (SESI-MS), as well as analytical chemistry) (summarized in Wenke et al., 2012). Furthermore, the effects of growth media and conditions on the emission spectra have to be considered (Fiddaman and Rossall, 1994; Kai et al., 2010; Blom et al., 2011a).

The compiled information of volatile-producing microorganisms and their emission profiles was used to search for characteristic VOCs emitted by certain bacterial or fungal genera. The dominant classes of compounds emitted by fungi are alcohols (e.g., isomers of butanol, pentanol, octanol), hydrocarbons, ketones, terpenes, alkanes, and alkenes (Chiron and Michelot, 2005, Table 3). Prominantly emitted VOCs from bacteria are alcohols, alkanes, alkenes, and ketones, followed by esters and pyrazines, lactones, and sulfides (Wenke et al., 2012, Table 2). Some examples are given. *Streptomyces* species are especially rich in sesquiterpenes (Citron et al. 2012) and preferentially emit methylated short-chain alcohols and acids, while *Pseudomonas* species release C9-C16 alkanes/alkenes (Table 2). The product profiles of *Bacteroides* spp. and *Lactobacillus* spp. are rich in various C4 to C16 methylated carboxylic acids, C4 to C14 carboxylic acids, and small methylated alcohols (Table 2). Short-chain and long-chain acids are well-known carbon sources for many microorganisms, but the role of low molecular mass ketones and alcohols in the metabolic food chain is less clear (Table 1). N-acyl-l-homoserine lactones (AHL) are preferentially used as infochemicals (Ryan and Dow, 2008; Dickschat, 2009). Methylamine and other amines serve as good electron donors and carbon sources for many methylotrophic bacteria and methanogenic bacteria. The emission of indole from enterobacteria is well-known, but its ecological relevance is still speculative; an effect in indirect signaling has been indicated (Ryan and Dow, 2008). The sulfur containing compounds dimethyldisulfide (DMDS) and dimethyltrisulfide (DMTS) are often emitted from bacteria and fungi (Tables 2 and 3). While the organic sulfur compounds dimethylsulfide (DMS) and dimethylpropionate (DMSP) play central roles in the global sulfur cycles. This is apparently not the case for DMDS and DMTS (Schäfer et al., 2010). A clear picture on the biological or ecological relevance of the latter compounds is still missing since contrasting results have been obtained. DMDS had inhibitory effects on *Arabidopsis thaliana* in dual culture assays (IC_{50}: 2.5 μmol) (Kai et al., 2010), while in another study it was shown that it could protect plants against fungal pathogens due to the induction of systemic resistance (Huang et al., 2012).

Prominent in bacterial emission profiles are pyrazines and β-phenylethanol. However, their biological functions are presently elusive. Even less understood is the biological and ecological relevance of the emission of extraordinary structures such as the terpene geosmin and sodorifen (Gerber and Lechevalier, 1965; Dickschat et al.,

Table 2 Compilation of VOC producing bacteria

Species	Tax ID (NCBI)	Volatile Synonym	References
Acinetobacter calcoaceticus	471	Sulfoacetaldehyde	Schulz and Dickschat, 2007
Actinobacillus actinomycetemcomitans	714	Acetic acid	Kurita-Ochiai et al., 1995
Aeromonas veronii	654	Dimethylselenide, Dimethyldisulfide, Methaneselenol, Dimethylselenenylsulfide	Schulz and Dickschat, 2007
Alcaligenes faecalis	511	Acetamide, Benzaldehyde, Phenylacetaldehyde, Methanamine, Benzothiazole, Methylpyrazine, 1-Butanamine, Dodecane, Dimethyldisulfide, Nonadecane,1-Decene, 2,5-Dimethylpyrazine	Zou et al., 2007
		Methanethiol, Dimethylsulfide	Schulz and Dickschat, 2007
Alcaligenes spp.	507	3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide, 2-Methylmercaptoethanol	
Alteromonas spp.	226	Methyliodide	
Anabaena spp.	1163	Geosmin	
Arctic sea ice associated bacterium ARK10141	196850	Tridecan-2-one, Dimethyldisulfide, Dimethyltrisulfide, Trimethylpyrazine, Hexadecan-2-one, 2,5-Dimethylpyrazine, Pentadecan-2-one, Tetradecan-2-one, 13-Methyltetradecan-2-one, 13-Methyltetradecan-3-one	Dickschat et al., 2005c
Arctic sea ice associated bacterium ARK10146	196852	Benzaldehyde, Dimethyldisulfide, Dimethyltrisulfide, Trimethylpyrazine, 2,5-Dimethylpyrazine, Pentadecan-2-one, Tetradecan-2-one, 13-Methyltetradecan-2-one, 13-Methyltetradecan-3-one	
Arctic sea ice bacterium ARK10044	196844	Tridecan-2-one, Hexadecyl acetate, Trimethylpyrazine, Hexadecan-2-one, 2,5-Dimethylpyrazine, Pentadecan-2-one, Tetradecan-2-one, 13-Methyltetradecan-2-one	
Arctic sea ice bacterium ARK10063	196865	Benzaldehyde, Menthol, Camphor, Clovene, para-Menth-1-en-4-ol, alpha-Terpineol, Trimethylpyrazine, Dihydroactinidiolide, 2,5-Dimethylpyrazine, Pentadecan-2-one, Borneol, Isolongifolene, beta-Ionone 5,6-epoxide, beta-Ionone 5,6-epoxide, beta-Caryophyllene, 13-Methyltetradecan-2-one	
Arctic sea ice bacterium ARK10223	196854	Benzaldehyde, Tridecan-2-one, Trimethylpyrazine, 2,5-Dimethylpyrazine, Pentadecan-2-one, Tetradecan-2-one, 13-Methyltetradecan-2-one	
Arctic sea ice bacterium ARK10267	196855	Benzaldehyde, Benzyl alcohol, Phenol, Camphor, 2-Phenylethanol, Furfural, Acetophenone, Methylpyrazine, Clovene, Calamenene, para-Menth-1-en-4-ol Tridecan-2-one, Tetramethylpyrazine, alpha-Terpineol, Dodecan-2-one, 3-Ethyl-2,5-dimethylpyrazine, 2-Ethyl-3,5-dimethylpyrazine, Trimethylpyrazine, Ethyltrimethylpyrazine, Hexadecan-2-one, 2,5-Dimethylpyrazine, Tetradecan-2-one, Isolongifolene, Cadina-1(10),6,8-triene, Geranylacetone, beta-Caryophyllene, 2,5-Diethyl-3,6-dimethylpyrazine, 13-Methyltetradecan-2-one, 11-Methyldodecan-2-one, 2,6-Diethyl-3,5-dimethylpyrazine	
Arthrobacter globiformis	1665	Phenylacetaldehyde, 2-Phenylethylamine	Schulz and Dickschat, 2007
Arthrobacter nitroguajacolicus	211146	Acetamide, Benzaldehyde, Phenylacetaldehyde, Methanamine, Benzothiazole, Methylpyrazine, 1-Butanamine, Dodecane, Dimethyldisulfide Nonadecane, 1-Decene, 2,5-Dimethylpyrazine	Zou et al., 2007
Azoarcus evansii	59406	Phenylacetate	Schulz and Dickschat, 2007
Bacillus amyloliquefaciens	1390	Acetoin, 2,3-Butanediol	Ryu et al., 2003; Farag et al., 2006
		Acetone Benzaldehyde, 1-Butanol, 2,3-Butanedione, Ethanol, Glyoxylic acid, Methanethiol, 1-Pentanol, Acetylene, Isoprene, 2-Methyl -1-propanol, 2-Butanone, Diethylacetic acid, 2-Methylbutanal, Cyclohexane, Dodecane, 2-Methyl-1-butanol, Ethyl acetate, 3-Methylbutanoic acid, 2-Methylfuran, Hexadecane, 3-Methylbutanal, Dimethyldisulfide, 1-Undecene, Tetrahydro-2,5-dimethylfuran, Undecane, 2-Ethylfuran, Dimethyltrisulfide, 2-Pentylfuran, 3-Methyl-1-butanol, Acetic acid butyl ester, Butanol-3-methyl acetate, 1-Methoxy-3-methylbutane, 2-Hydroxy-3-pentanone, 2,4-Hexadienal	Farag et al., 2006
Bacillus popilliae	78057	N-3-Methylbutylidene-3-methylbutylamine, N-Phenylmethylene-2-methylpropylamine, N-Phenylmethylene-3-methylbutylamine	Schulz and Dickschat, 2007
		N-Isopentylideneisopentylamine	Dickschat et al., 2005b
Bacillus pumilus	1408	n-Hexadecanoic acid, Diethylphthalate, 3-Methyl-1-butanol, oleic acid, 8-Methyl-1-decene, 3,4-Dimethyl-5-hexen-3-ol, (*E*)-2-Octenal, 2,4-Decadienal, (*Z*)-2-Heptenal	Wei-wei et al., 2008

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
Bacillus simplex	1478	Propanone, Benzaldehyde, Phenol, Benzenacetaldehyde, Propionic acid, 1-Hexadecanol, Phenylethanone, Cyclohexene, Benzene ethanol, Nonane, 2-Undecanone, Decanal, Dodecane, Hexadecane, Dimethyldisulfide, Tetradecane, 2-Nonanone, Terpineol, 2-Octanol, Trimethylpyrazine	Gu et al., 2007
Bacillus spp.	1386	Acetic acid, Acetoin, Isoprene, 3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide, 2,3,5,6-Tetramethylpyrazine, 2-Methylmercaptoethanol, (2R,3R)-Butane-2,3-diol	Schulz and Dickschat, 2007
		Acetamide, Phenylacetaldehyde, Methaneamine, Benzothiazole, Methylpyrazine, 1-Butanamine, Dodecane, Nonadecane, 1-Decene, 2,5-Dimethylpyrazine	Zou et al., 2007
		2,3-Butanediol, Acetoin	Ryu et al., 2003
		Octanal, n-Hexadecanoic acid, Diethylphthalate, Octadecanoic acid, Heptanol, 2-Pentylfuran, Nonanal, 2-Methyl-7-oxabicyclo[2.2.1] heptane, Oleic acid, (*E*)-2-Octenal, (*E*)-2-nonenal, (*E*)-2-decenal, 2,4-Decadienal, 2-Undecenal, (*Z*)-2-Heptenal	Wei-wei et al., 2008
		Acetone, 2,3-Butanedione, Ethanol, Glyoxylic acid, Methanethiol, 1-Pentanol, Acetylene, Isoprene, 2-Methyl-1-propanol, 2-Butanone, Diethylacetic acid, 2-Methylbutanal, Benzaldehyde, 1-Butanol, 2,3-Butanediol, Acetoin, Cyclohexene, Dodecane, 2-Methyl-1-butanol, Ethyl acetate, 3-Methylbutanoic acid, 2-Methylfuran, Hexadecane, 3-Methylbutanal, Dimethyldisulfide, 1-Undecene, Tetrahydro-2,5-dimethylfuran, Dimethyltrisulfide, 2-Pentylfuran, 3-Methyl-1-butanol, Acetic acid butyl ester, 3-Methyl-butanol acetate, 2-Hydroxy-3-pentanone, 2,4-Hexadienal	Farag et al., 2006
		Benzaldehyde, Propanone, Phenol, 1-Hexadecanol, Benzenacetaldehyde, Propionic acid, Benzeneethanol, Phenylethanone, Cyclohexene, Decanal, Dodecane, Hexadecane, Dimethyldisulfide, Tetradecane, Nonane, 2-Nonananone, 2-Undecanone,Terpineol, 2-Octanol, Trimethylpyrazine	Gu et al., 2007
Bacillus weihenstephanensis	86662	Propanone, Benzaldehyde, Phenol, Benzenacetaldehyde, Propionic acid, 1-Hexadecanol, Benzeneethanol, Phenylethanone, Cyclohexene, Nonane, 2-Undecanone, Decanal, Dodecane, Hexadecane, Dimethyldisulfide, Tetradecane, 2-Nonanone, Terpineol, 2-Octanol, Trimethylpyrazine	
Bacteroides bivius	28125	Acetic acid	Wiggins et al., 1985
Bacteroides distasonis	823	Acetic acid, Propionic acid, Isobutyric acid, Isovaleric acid	
Bacteroides fragilis	817	Acetate, Succinate, Isobutyrate, Isovalerate	Hinton and Hume, 1995
		Hexadecanoic acid, Tetradecanoic acid, 12-Methyltetradecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-methylhexadecanoic acid, 3-Hydroxyhexadecanoic acid	Brondz and Olsen, 1991
Bacteroides gracilis	824	Hexadecanoic acid, Dodecanoic acid, Octadecanoic acid, Tetradecanoic acid, 3-Hydroxytetradecanoic acid, 3-Hydroxyhexadecanoic acid, Hexadecenoic acid	
Bacteroides ovatus	28116	Acetic acid, Propionic acid, Isovaleric acid	Wiggins et al., 1985
Bacteroides thetaiotaomicron	818	Acetic acid, Propionic acid, Isobutyric acid, Isovaleric acid	
Bacteroides ureolyticus	827	Hexadecanoic acid, Dodecanoic acid, Octadecanoic acid, Tetradecanoic acid, 3-Hydroxytetradecanoic acid, 3-Hydroxyhexadecanoic acid, Hexadecenoic acid	Brondz and Olsen, 1991
Bacteroides vulgatus	821	Acetic acid, Propionic acid, Isobutyric acid, Isovaleric acid	Wiggins et al., 1985
Brevibacterium linens	1703	Methanethiol, S-Methylthiobutyrate, S-Methylthio-2-methyl butyrate, S-Methyl thioacetate, S-Methyl thiocaproate, S-Methylthio-3-methyl butyrate, S-Methyl thiopropionate, S-Methylthio-2-methyl propionate, S-Methyl thiovalerate	Schulz and Dickschat, 2007
Calothrix parietina	32054	Octanal, Decanal, 6-Methyl-5-hepten-2-one, beta-Cyclocitral, Heptadecane, Limonene, Heptadecene, Nonanal, 2,6,6-Trimethylcyclo-hex-2-en-1-one, 8-Methylheptadecane, Dihydro-beta-ionone, beta-Ionone, beta-Ionone-5,6-epoxide	Höckelmann and Jüttner, 2004
Calothrix spp.	1186	Cresol, Skatole, Sulcatone, beta-Cyclocitral, 2,2,6-Trimethylcyclohexanone, Sulcatol, Dihydroactinidiolide, 2-Hydroxy-2,6,6-trimethylcyclohexan-1-one, Dihydro-beta-ionone, beta-Ionone, (Z)-5-Heptadecene, Geosmin, beta-Ionone-5,6-epoxide	Schulz and Dickschat, 2007
		Octanal, Decanal, Heptadecane, Limonene, Nonanal, Geosmin, beta-Ionone-5,6-epoxide	Höckelmann and Jüttner, 2004
Campylobacter fetus	196	Hexadecanoic acid, Dodecanoic acid, Octadecanoic acid, Tetradecanoic acid, 3-Hydroxytetradecanoic acid, 3-Hydroxyhexadecanoic acid, Hexadecenoic acid	Brondz and Olsen, 1991
Capnocytophaga ochracea	1018	Acetic acid, Propionic acid, Isovaleric acid	Kurita-Ochiai et al., 1995
Carnobacterium divergens	2748		Ercolini et al., 2009

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Toluene, Menthol, Hexadecanol, Dibutylphthalate, Hexanal, Carbondisulfide, Isobornylacetate, Linalool, alpha-Pinene, 2-Ethylphenol, 4-Methylguaiacol, ortho-Dimethylbenzene, tert-Butylcyclohexanol, 2-Ethyl-1-hexanol, Ethyloctanoate, para-Dimethylbenzene, 4-Methylthiophenol, 1-Propanethiol, Decanal, 1-Undecanol, 1-Dodecanol, Citronellylacetate, 1-Hexadecene, Methoxybenzenethiol, 2-Nonanone, 1-Tetradecene, Decane, delta-Nonalactone, 1-Octen-3-ol, 2-Butyl-1-octanol, 2-Pentylthiophene, Limonene, 2-Ethylhexyl-2-ethyl hexanoate, 2-Dodecanol, 2-Ethylhexanal, Ethylhexanoate, Nonanal, Tetradecanal, Butylhydroxytoluene, Isotridecanol, Terbutylcyclohexyl acetate, Decenyl acetate, 2-Methyl-1-dodecanol, Hexyl formate, Ethenyl decanoate, Undecanthiol, 2-Methyl-1-undecanol, 1-Nonen-3-ol, Limoneneoxide, 9,12-Tetradecadien-1-ol acetate, 3-Hydroxydodecanoic acid, 2-Hexyl-1-decanol, 4-Methoxybenzhydrol, Tetradecen-1-ol, 5-Undecene, 5-Methyl-1,5-hexadien-3-ol, Dodecyl hexanoate, 5-Butyl-4-nonene, 2-Methyl-2-decene, 6-Methyl-1-octanol, Tetradecen-1-ol acetate, 4-Methylundecene, 8-Methyl-1-undecene, 2,3-Epoxygeranyl acetate, 2-Hexyl-1-octanol, 2-Ethyldodecanol, 2-Methyl-2-dodecene, 2-Buten-1-ol, Dodecenal, 2-Octen-1-ol, 5-Octadecene, 9-Octadecene, Tetradecenoic acid,	
Carnobacterium maltaromaticum	2751	2-Ethyl-1-hexanol, 2-Nonanone, 2-Ethylhexanal, 2-Hexyl-1-octanol, 2-Buten-1-ol	
Chondromyces crocatus	52	Benzylalcohol, 2-Phenylethanol, endo-Bornyl acetate, Benzothiazol, 1,4-Dimethoxybenzol,, 2,5-Dimethylpyrazine, 2-Methoxy-3-(2-methylpropyl)pyrazine, 2-Methoxy-3-(1-methylethyl)pyrazine, (1-Methylethyl)pyrazine, beta-Copaene, 2-Methoxy-3-(1-methylpropyl)pyrazine, alpha-Elemene, Dimethyl-(1-methylethyl)pyrazine, 2-(1-Hydroxy-2-methylpropyl)-3-methoxypyrazine, Eremophilene, 1,4-Cadinadiene, Zonarene, Bicycloelemene, 2,5-bis-(1-Methylethyl)pyrazine, 2-(1-Methylethenyl)-5-(1-methylethyl)pyrazine, 2,5-Bis(2-methylpropyl)pyrazine, (1R,6S,10S)-6,10-Dimethylbicyclo[4.4.0]decan-3-one, 2,6-bis-(1-Methylethyl)pyrazine, beta-Ylangene, Methyl salicylate, 1-Phenylethanol, Anisol, 2-Aminoacetophenone, Methyl 2-methoxy benzoate, 2-(Methoxymethyl)furan, alpha-Muurolene, (-)-Germacrene D, (6S,10S)-6,10-Dimethylbicyclo[4.4.0]dec-1-en-3-one, (1R,6R,10R)-6,10-Dimethylbicyclo[4.4.0]decan-3-one, (1(10)*E*,5*E*)-Germacradien-11-ol, Methyl anthranilate, Nonanal, 2-Methyl-3-methoxypyrazine, 2-Methyl-5-(1-methylethyl)pyrazine, Cubenol, 3-Methoxy-2,5-dimethylpyrazine, 3-Methoxy-2,6-dimethylpyrazine, 2-Methyl-6-(1-methylethyl)pyrazine, 6,10-Dimethylbicyclo[4.4.0]decan-3-ol, Geosmin	Schulz et al., 2004
		Methyl salicylate, 1-Phenylethanol, Anisol, 2-Aminoacetophenone, Methyl 2-methoxy benzoate, 2-(Methoxymethyl)furan, alpha-Muurolene, (-)-Germacrene D, (6S,10S)-6,10-Dimethylbicyclo[4.4.0]dec-1-en-3-one, (1R,6R,10R)-6,10-Dimethylbicyclo[4.4.0]decan-3-one, (1(10)E,5E)-Germacradien-11-ol, Geosmin, 4-Methoxyacetophenone, Methyl 4-methoxy benzoate, Furfuryl 3-methyl butanoate, 2-Aminobenzaldehyde, Methyl anthranilate, Nonanal, 1,4-Dimethoxybenzene, 4-Phenylbutanone, Isopropylpyrazine, 2-Methyl-5-isopropylpyrazine, alpha-Eudesmol, 2-Methoxy-3-(1-hydroxy-2-methylpropyl)pyrazine, 2,5-Diisopropylpyrazine, 2-Isopropyl-5-isopropenylpyrazine, 2-Isopropyl-5-buten-2-yl-pyrazine, Eremophilene, 2,5-Diisobutylpyrazine, (1S,6R,10R)-6,10-Dimethylbicyclo[4.4.0]decan-3-one, 2-Methyl-6-isopropylpyrazine, 2,6-Diisopropylpyrazine	Schulz and Dickschat, 2007
		4-Phenyl-2-butanone, 2-Methoxy-3-methylpyrazine, 1-epi-Cubenol, alpha-Eudesmol, 5-Methyl-2-(1-methylethyl)pyrazine, 3-Methoxy-2,5-bis(1-methylpropyl)pyrazine, Methoxydi-(1-methylethyl)pyrazine, 3-Methoxy-2-(1-methylpropyl)-5-(2-methylpropyl)pyrazine, 2-Butan-2-yl-5-propan-2-yl-pyrazine, 3-Methoxy-5-(2-methylpropyl)-2-propan-2-yl-pyrazine, 3-Methoxy-2,5-bis(2-methylpropyl)pyrazine, 5-Butan-2-yl-3-methoxy-2-propan-2-yl-pyrazine, 5-Butan-2-yl-3-methoxy-2-methyl-pyrazine, 3-Methoxy-2-methyl-5-(2-methylpropyl)pyrazine, 6-Methyl-2-(1-methylethyl)pyrazine, (1S,6S,10S)-6,10-Dimethylbicyclo[4.4.0]decan-3-one, Methyl salicylate, 1-Phenylethanol, Anisol, 2-Aminoacetophenone, Methyl 2-methoxy benzoate, 2-(Methoxymethyl)furan, alpha-Muurolene, (-)-Germacrene D, (6S,10S)-6,10-Dimethylbicyclo[4.4.0]dec-1-en-3-one, (1R,6R,10R)-6,10-Dimethylbicyclo[4.4.0]decan-3-one, (1(10)*E*,5*E*)-Germacradien-11-ol, 4-Methoxyacetophenone, Methyl 4-methoxy benzoate, Furfuryl 3-methyl butanoate, 2-Aminobenzaldehyde, Benzylalcohol, 2-Phenylethanol, endo-Bornyl acetate, Benzothiazol, 1,4-Dimethoxybenzol,, 2,5-Dimethylpyrazine, 2-Methoxy-3-(2-methylpropyl)pyrazine, 2-Methoxy-3-(1-methylethyl)pyrazine, (1-Methylethyl)pyrazine, beta-Copaene, 2-Methoxy-3-(1-methylpropyl)pyrazine, alpha-Elemene, Dimethyl-(1-methylethyl)pyrazine, 2-(1-Hydroxy-2-methylpropyl)-3-methoxypyrazine, Eremophilene, 1,4-Cadinadiene, Zonarene, Bicycloelemene, 2,5-bis-(1-Methylethyl)pyrazine, 2-(1-Methylethenyl)-5-(1-methylethyl)pyrazine, 2,5-Bis(2-methylpropyl)pyrazine, (1R,6S,10S)-6,10-Dimethylbicyclo[4.4.0]decan-3-one, 2,6-bis-(1-Methylethyl)pyrazine, beta-Ylangene, Geosmin	Dickschat et al., 2005e
		Alpha-Muurolene, Cadina-1,4-diene, Geosmin	Dickschat et al., 2005d

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
Citrobacter freundii	546	Methanethiol, Phenol, Dimethylselenenylsulfide	Schulz and Dickschat, 2007
Citrobacter spp.	544	2-Phenylethanol, 3-Methylbutyl propionate, 3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide, 3-Methylbutyl acetate, 2-Methylmercaptoethanol	
Clostridium bifermentans	1490	Acetic acid, Propionic acid, Isovaleric acid, Isocaproic acid	Wiggins et al., 1985
Clostridium butyricum	1492	Acetic acid, Butyric acid	
Clostridium cadaveris	1529	Acetic acid, Butyric acid, Propionic acid	
Clostridium collagenovorans	29357	Dimethylselenium, Dimethyldiselenium, Dimethyltellurium, Trimethylbismuth, Trimethylstibine, Trimethylarsine	Michalke et al., 2000
		Trimethylbismuth, Trimethylstibine, Trimethylarsine	Schulz and Dickschat, 2007
Clostridium fallax	1533	Acetic acid, Butyric acid	Wiggins et al., 1985
Clostridium histolyticum	1498	Acetic acid	
Clostridium sporogenes	1509	Acetic acid, Butyric acid, Propionic acid, Isobutyric acid, Valeric acid, Isovaleric acid, Isocaproic acid	
Clostridium spp.	1485	Acetic Acid, Acetoin, 2,3-Butanediol, Butyric acid, Formic acid, Ethanol, Methanol, Propionic Acid, Dimethylsulfide, Ethylene, Isobutanol, Acrylic acid, Isobutyric acid, Valeric acid, Caproic acid, Isovaleric acid, Isocaproic acid, Isopentanol, Crotonic acid,	Stotzky and Schenck, 1976
Clostridium tertium	1559	Acetic acid, Butyric acid	Wiggins et al., 1985
Cytophaga spp.	978	3,3,7,7-Tetramethyl-1,2,5-trithiepane, 3,3,6,6-Tetramethyl-1,2,5-trithiepane, 4,4-Dimethyltrithiolane, 4,4,6,6-Tetramethyl-1,2,5-trithiepane, 3,3,8,8-Tetramethyl-1,2,5,6-tetrathiocane, 2-Methylpropane-1,2-dithiol, 3,3,7,7-Tetramethyl-1,2,5,6-tetrathiocane, 5,5-Dimethyltetrathiane,	Sobik et al., 2007
Desulfovibrio acrylicus	41791	Methanethiol, Dimethylsulfide	Schulz and Dickschat, 2007
Desulfovibrio gigas	879	Dimethylselenium, Dimethyldiselenium, Dimethyltellurium, Trimethylarsine	Michalke et al., 2000
		Trimethylarsine	Schulz and Dickschat, 2007
Desulfovibrio vulgaris	881	Dimethylselenium, Dimethyldiselenium, Trimethylstibine, Trimethylarsine	Michalke et al., 2000
		Trimethylstibine, Trimethylarsine	Schulz and Dickschat, 2007
Dinoroseobacter shibae	215813	2-Phenylethanol, 4-Octanolide, 4-Nonanolide, 4-Undecanolide, 4-Heptanolide, Undecanal, Dodecanal, Butyl benzoate, Benzylcyanide, 1-Nonanol, 6-Methyl-5-hepten-2-one, 4-Hexanolide, 4-Decanolide, Tetramethylpyrazine, 4-Dodecanolide, S-Methylmethanethiosulfonate, 5-Nonanolide, Dimethyltrisulfide, 2-Methyl-4-pentanolide, 4-Methylquinazoline, 3-Methyl-4-pentanolide, 2-Butyl-3,6-dimethylpyrazine, 3-Butyl-2,5-dimethylpyrazine, Geranylacetone	Dickschat et al., 2005f
		S-Methylmethanethiosulfonate, S-Methylmethanethiosulfinate	Schulz and Dickschat, 2007
		2-Ethyl-5-methylpyrazine, 2-Ethyl-3,6-dimethylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, 5-Methyl-2-(1-methylethyl) pyrazine, Methylmethylthiomethyldisulfide	Dickschat et al., 2005e
Dinoroseobacter spp.	309512	4-Butanolide, Octan-4-olide, Nonan-4-olide, Undecan-4-olide, Heptan-4-olide, 4-Pentanolide, Butyl benzoate, Hexan-4-olide, Decan-4-olide, Dodecan-4-olide, 2-Methylpentan-4-olide, Tetradecan-4-olide, 3-Methylpentan-4-olide	Schulz and Dickschat, 2007
Enterobacter agglomerans	549	1-(2-Pyridinyl)ethanone	
Enterobacter cloacae	550	Dimethylselenide	
Enterobacter spp.	547	Acetoin, Indole, 2-Phenylethanol, Hydroxypropanone, 3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide, 2-Methylmercaptoethanol	
Escherichia coli	562	Acetic acid, Methanol, Acetaldehyde, Acetone, 1-Butanol, Methanethiol, 2-Methyl-1-butanol, Ethanol, Indole	Bunge et al., 2008
		Acetoin, 2,3-Butanediol, 2,3-Butanedione, Glyoxylic acid, Acetylene, Isoprene, 1-Propanol-2-methyl, 2-Butanone, Diethylacetic acid, Dodecane, Ethyl acetate, 3-Methylbutanoic acid, 2-Methylfuran, Hexadecane, 3-Methylbutanal, Dimethyldisulfide, 1-Undecene, Tetrahydro-2,5-dimethylfuran, 1-Undecane, Dimethyltrisulfide, 2-Pentylfuran, 3-Methyl-1-butanol, Acetic acid butyl ester, 3-Methylbutyl acetate, 2-Hydroxy-3-pentanone, 2,4-Hexadienal, Acetone, 1-Butanol, Methanethiol, 2-Methyl-1-butanol, Ethanol	Farag et al., 2006
		Ethanol, Indole, Acetonitrile	Zhu et al., 2010

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Indole	Schulz and Dickschat, 2007; Ryan and Dow, 2008
Escherichia spp.	561	2-Phenylethanol, Ethyl octanoate, 1-Decene	Schulz and Dickschat, 2007
Flavobacterium spp.	237	Ethanol, Dimethyldisulfide	Freeman et al., 1976
Fossombronia pusilla	34161	Geosmin	Dickschat et al., 2005a
Fusobacterium nucleatum	851	Acetic acid, Butyric acid, Propionic acid, Valeric acid, Isovaleric acid	Kurita-Ochiai et al., 1995
		Methanethiol, L-Methionine	Schulz and Dickschat, 2007
Geobacillus stearothermophilus	1422	Dimethylselenide, Dimethyldiselenide, Dimethyltelluride, Dimethylditelluride, Methanetellurol	
Halomonas venusta	44935	(S)-2-Methoxy-3-(1-methylpropyl)pyrazine	
Jannaschia helgolandensis	188906	5-Methyl-2-(1-methylethyl)pyrazine	Dickschat et al., 2005e
Klebsiella oxytoca	571	Dimethyldisulfide, Dimethyltrisulfide	Schulz and Dickschat, 2007
Klebsiella pneumoniae	573	Phenol, 2-Methyl-5-isopropylpyrazine	
Klebsiella spp.	570	Acetoin, Indole, 2-Phenylethanol, 2-(Hydroxymethyl)furan, 1-Phenylpropan-2-one, Ethyl butanoate, 3-Methylbutyl butanoate, Methylpropyl acetate, 3-(Methylsulfanyl)propan-1-ol, Pentyl butanoate, Hexan-2-one, 2-Methylbutyl acetate, Dimethyldisulfide, 3-Methylbutyl acetate, 2-Methylmercaptoethanol	
Lactobacillus brevis	1580	3-Methylthiopropionate, Methanethiol, 3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide, Methional	
Lactobacillus casei	1582	Acetic acid, Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	Tracey and Britz, 1989
Lactobacillus fermentum	1613	L-Cystathionine	Schulz and Dickschat, 2007
Lactobacillus hilgardii	1588	3-Methylthiopropionate, Methanethiol, 3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide	
Lactobacillus lactis	29397	alpha-keto-gamma-methylthiobutyric acid, Methanethiol, Methional, Methylmercaptoacetaldehyde	
Lactobacillus plantarum	1590	Acetic acid, Acetoin, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol, Benzaldehyde	Tracey and Britz, 1989
		3-Methylthiopropionate, Methanethiol, Phenylpyruvate, L-Phenylalanine, 3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide, Benzaldehyde	Schulz and Dickschat, 2007
Lactobacillus spp.	1578	Methanethiol, Dimethylsulfide, Dimethyldisulfide, Dimethyltrisulfide	
Lactococcus lactis	1358	Acetic acid, Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	Tracey and Britz, 1989
		L-Cystathionine, S-Methyl thiobutyrate, S-Methylthio-2-methyl butyrate, S-Methyl thioacetate, S-Methyl thiocaproate, S-Methyl thio-3-methyl butyrate, S-Methyl thiopropionate, S-Methylthio-2-methyl propionate, S-Methyl thiovalerate	Schulz and Dickschat, 2007
Lactococcus spp.	1357	Methanethiol, Phenyl pyruvate, Phenylacetaldehyde, Dimethylsulfide, L-Phenylalanine, Dimethyldisulfide, Dimethyltrisulfide	
Leuconostoc cremoris	33965	Acetic acid, Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	Tracey and Britz, 1989
Leuconostoc dextranicum	33966	Acetic acid, Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
Leuconostoc mesenteroides	1245	Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	
Leuconostoc oenos	1247	Acetic acid, Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	
Leuconostoc paramesenteroides	1249	Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	
Loktanella hongkongensis	278132	Tetramethylpyrazine, 2-Ethyl-5-methylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, 5-Methyl-2-(1-methylethyl)pyrazine, 2,5-Dimethyl-3-(3-methylbutyl)pyrazine, 3-Butyl-2,5-dimethylpyrazine	Dickschat et al., 2005e
Loktanella spp.	245186	Indole, 4-Butanolide, Octan-4-olide, Nonan-4-olide, Undecan-4-olide, Heptan-4-olide, 4-Pentanolide, S-Methyl methanethiosulfonate, 4-(Methylsulfanyl)butan-2-one, S-Methylmethanethiosulfinate, Tetradecan-4-olide, Tropone, Methyl 2-furancarboxylate, 1-Phenylpropan-1,2-dione, Hexan-4-olide, Decan-4-olide, Dodecan-4-olide, 3-Methylbutan-4-olide, S-Methyl thiopropionate	Schulz and Dickschat, 2007
		Indole, 2-Phenylethanol, 4-Nonanolide, 4-Pentanolide, Undecanal, 1-Tetradecanol, Benzycyanide, 6-Methyl-5-hepten-2-one, Dimethyltrisulfide, 2-Ethyl-3,6-dimethylpyrazine, 4-Methylthio-2-butanone, Methylmethylthiomethyldisulfide, 4-Methylquinazoline, 2-Isopentyl-3,6-dimethylpyrazine, 2-Butyl-3,6-dimethylpyrazine, Tetramethylpyrazine, Geranylacetone, 1-Phenylpropan-1,2-dione, Hexan-4-olide, Decan-4-olide, Dodecan-4-olide, 3-Methylbutan-4-olide, S-Methyl thiopropionate	Dickschat et al., 2005f
Lyngbya spp.	28073	Geosmin	Schulz and Dickschat, 2007
Lysobacter gummosus	262324	Acetamide, Benzaldehyde, Phenylacetaldehyde, Methanamine, Benzothiazole, Methylpyrazine, 1-Butanamine, Dodecane, Dimethyldisulfide, Nonadecane, 1-Decene, 2,5-Dimethylpyrazine	Zou et al., 2007
Methanobacterium formicicum	2162	Stibine, Dimethylselenium, Trimethylbismuth, Trimethylstibine, Dimethyldiselenium, Dimethyltellurium, Trimethylarsines, Dimethylstibine, Monomethylstibine, Monomethylarsine, Dimethylarsine	Michalke et al., 2000
		Trimethylbismuth, Monomethylarsine, Dimethylarsine	Schulz and Dickschat, 2007
Methanobacterium spp.	2160	Trimethylarsine, Dimethylarsine	Stotzky and Schenck, 1976
Methanobacterium thermoautotrophicum	145262	Trimethylstibine	Michalke et al., 2000
Methanosarcina barkeri	2208	Dimethylselenium, Trimethylstibine, Dimethyldiselenium	
Methylobacterium spp.	407	Methyliodide	Schulz and Dickschat, 2007
Microbacterium oxydans	82380	Propanone, Benzaldehyde, Phenol, Benzenacetaldehyde, Propionic acid, 1-Hexadecanol, Benzeneethanol, Phenylethanone, Cyclohexene, Nonane, 2-Undecanone, Decanal, Dodecane, Hexadecane, Dimethyldisulfide, Tetradecane, 2-Nonanone, Terpineol, 2-Octanol, Trimethylpyrazine	Gu et al., 2007
Microbacterium thermosphactum	2756	Ethanol, Methanol	Freeman et al., 1976
Myxococcus spp.	32	5-Methylhexan-3-ol, 7-Methyloctan-3-one, 5-Methyl-4-hexen-3-one	Schulz and Dickschat, 2007
Myxococcus xanthus	34	2-Phenylethanol, Benzothiazole, Benzylcyanide, 6-Methyl-5-hepten-2-one, Butyl propionate, 5-Methylhexan-3-ol, 5-Methylhexan-3-one, Tridecane, 2-Acetylfuran, Dimethyltrisulfide, Butyl acetate, 7-Methyloctan-3-one, 5-Methylhex-4-en-3-one, Cyanoisoquinoline, (3S)-Decan-3-ol, 4-Methylquinoline, 2-Aminoacetophenone, Decan-3-one, Nonan-3-one, Undecan-3-one, Dimethyltetrasulfide, Octan-3-one, Geranylacetone, Geosmin, (-)-Germacrene D, 9-Methyldecan-3-one, (1(10)E,5E)-Germacradien-11-ol	Dickschat et al., 2004
		Sulcatone, Undecan-3-ol, (S)-Decan-3-ol, Isolepidozene, Octalinhydrocarbon, 4-Methylquinoline, 2-Aminoacetophenone, Decan-3-one, Nonan-3-one, Undecan-3-one, Dimethyltetrasulfide, Octan-3-one, Geranylacetone, Geosmin, (-)-Germacrene D, 9-Methyldecan-3-one, (1(10)E,5E)-Germacradien-11-ol	Schulz and Dickschat, 2007

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Geosmin	Dickschat et al., 2005d
		(-)-Germacrene D, 9-Methyldecan-3-one, (1(10)E,5E)-Germacradien-11-ol	Dickschat et al., 2005a
		8,10-Dimethyl-1-octalin, (1(10)E,5E)-Germacradien-11-ol, Geosmin	Nawrath et al., 2008
Nannocystis exedens	54	Benzylalcohol, Hexadecan-1-ol, 2-Phenylethanol, Isobornyl acetate, Benzothiazole, Ethyl 2-methyl propionate, Heptan-4-olide, 2-Butyl acetate, 4-Pentanolide, Ethyl-3-methyl butyrate, Dodecan-1-ol, Tetradecan-1-ol, Benzylnitrile, Pinanol, 2-Aminoacetophenone, Methyl-2-furan carboxylate, Hexan-4-olide, (-)-2-Methylisoborneol, Limonene, Ethyl-2-methyl butyrate, Diethyl succinate, Borneol, 1-Phenyldecan-1-one, 2-Methylenebornane, 2-Methyl-2-bornene, 2,5-Dimethyl-3-(1-methylethyl)pyrazine, Germacrene D, (6S,10S)-6,10-Dimethylbicyclo[4.4.0]dec-1-en-3-one, 2,5-Di-(1-methylethyl)pyrazine, 2-(1-Methylethenyl)-5-(1-methylethyl)pyrazine, 2,5-Di-(1-methylpropyl)pyrazine, 5-(1-Methylethyl)-2-(1-methylpropyl)pyrazine, (1(10)E,5E)-Germacradien-11-ol, beta-Ylangene, Geosmin	Dickschat et al., 2007
		2-Furanmethanol, Geosmin	Schulz and Dickschat, 2007
		Geosmin	Schulz et al., 2004; Dickschat et al.,2005a, d
		8,10-Dimethyl-1-octalin	Nawrath et al., 2008
Nannocystis exedens subsp. *cinnabarina*	54	2-Phenylethanol	Dickschat et al., 2007
Oceanibulbus indolifex	225422	2-Ethyl-5-methylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, 5-Methyl-2-(1-methylethyl)pyrazine	Dickschat et al., 2005e
Octadecabacter spp.	53945	Benzaldehyde, 2-Acetylfuran, 2,5-Dimethylpyrazine, 4-(Methylsulfanyl)butan-2-one	Dickschat et al., 2005a
		4-(Methylsulfanyl)butan-2-one, (R)-4-(Methylsulfanyl)butan-2-ol	Schulz and Dickschat, 2007
Oenococcus oeni	1247	3-Methylthiopropionate, Methanethiol, 3-(Methylsulfanyl)propan-1-ol, Dimethyldisulfide, Methional	
Oscillatoria chalybea	41313	2-Methylisoborneol	
Oscillatoria spp.	1158	2-Methylisoborneol, Geosmin	
Paenibacillus polymyxa	1406	n-Hexadecanoic acid, Octadecanoic acid, Diethylphthalate, Hexadecanoic acid methyl ester, Octadecanoic acid methyl ester, Azulene, Di-2-propenyltrisulfide,, Diallyldisulfide, Tetradecanal, 1,3-Dithiole-2-thione, Oleic acid, (Z)-9-Hexadecenoic acid methyl ester, 2,4-Decadienal, 2-Undecenal	Wei-wei et al., 2008
		Isopropylpyrazine, 2-(2-Methylpropyl)pyrazine, 2-Methyl-5-isopropylpyrazine, 2,6-Diisobutylpyrazine, 2,5-Diisopropylpyrazine, 2-Isopropyl-5-buten-2-yl-pyrazine, 2,5-Diisobutylpyrazine, 2-Methyl-5-isobutylpyrazine, 2-Methyl-6-isopropylpyrazine, 2,6-Diisopropylpyrazine	Schulz and Dickschat, 2007
		2,5-Dimethyl-3-(2-methylpropyl)pyrazine	Dickschat et al., 2005e
Parasporobacterium paucivorans	115544	Methanethiol, Dimethylsulfide	Schulz and Dickschat, 2007
Pediococcus damnosus	51663	Acetic acid, Acetoin, Benzaldehyde, Benzenemethanol, Butanoic acid, Octanoic acid, Decanoic acid, Dodecanoic acid, 2-Phenylethanol, Isobutanol, Ethyl-2-hydroxy propionate, Pentanoic acid, Heptanoic acid, Nonanoic acid, Hexanoic acid, 3-(Methylthio)-1-propanol, Tetradecanoic acid, 3-Methyl-2-butanol, alpha,alpha-Dimethylbenzenemethanol, Isoamylalcohol	Tracey and Britz, 1989
Phormidium spp.	1198	Octanal, alpha-Pinene, 2-Heptanone, Decanal, 6-Methyl-5-hepten-2-one, beta-Cyclocitral, 2-Tridecanone, Heptadecane, 2-Decanone, 6-Methylheptan-2-one, Limonene, Heptadecene, 7-Methylheptadecane, Nonanal, 1-Octen-3-one, 2,6,6-Trimethylcyclo-hex-2-en-1-one, 8-Methylheptadecane, 2-Decenal, Geosmin, Dihydro-beta-ionone, beta-Ionone, beta-Ionone-5,6-epoxide	Höckelmann et al., 2004
		Sulcatone, Dihydroactinidiolide, 2-Hydroxy-2,6,6-trimethylcyclohexan-1-one, Tetrahydroionone, Dihydro-beta-ionol, 4-Oxodihydro-beta-ionone, Geosmin, Dihydro-beta-ionone, beta-Ionone, beta-Ionone-5,6-epoxide	Schulz and Dickschat, 2007
Photobacterium spp.	657	Methyl iodide	
Plantibacter spp.	190323	Methyl iodide	
Plectonema spp.	1183		

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Octanal, Decanal, 6-Methyl-5-hepten-2-one, Heptadecane, Limonene, 7-Methylheptadecane, Nonanal, 2,6,6-Trimethylcyclo-hex-2-en-1-one, 8-Methylheptadecane, Beta-Cyclocitral, Dihydro-beta-ionone, beta-Ionone, beta-Ionone-5,6-epoxide	Höckelmann and Jüttner, 2004
		Sulcatone, Beta-Cyclocitral, Dihydro-beta-ionone, beta-Ionone, beta-Ionone-5,6-epoxide, 2,2,6-Trimethylcyclohexanone, Sulcatol, Dihydroactinidiolide, 2-Hydroxy-2,6,6-trimethylcyclohexan-1-one, beta-Cyclogeraniol, Dihydro-beta-ionol	Schulz and Dickschat, 2007
Porphyromonas endodontalis	28124	Hexadecanoic acid, Tetradecanoic acid, 12-Methyltetradecanoic acid, 11-Methyldodecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-Methylhexadecanoic acid, 3-Hydroxypentadecanoic acid, 3-Hydroxyhexadecanoic acid	Brondz and Olsen, 1991
Porphyromonas gingivalis	837	Acetic acid, Butyric acid, Propionic acid, Isobutyric acid, Valeric acid, Isovaleric acid	Kurita-Ochiai et al., 1995
		Methanethiol	Schulz and Dickschat, 2007
Prevotella buccae	28126	Hexadecanoic acid, Tetradecanoic acid, 12-Methyltridecanoic acid, 12-Methyltetradecanoic acid, 14-Methylhexadecanoic acid, 11-Methyldodecanoic acid, 14-Methylpentadecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-Methylhexadecanoic acid, 15-Methylhexadecanoic acid, 3-Hydroxypentadecanoic acid, 3-Hydroxyhexadecanoic acid, 10-Methyldodecanoic acid	Brondz and Olsen, 1991
Prevotella disiens	28130	Hexadecanoic acid, Tetradecanoic acid, 12-Methyltridecanoic acid, 12-Methyltetradecanoic acid, 14-Methylhexadecanoic acid, 11-Methyldodecanoic acid, 14-Methylpentadecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-Methylhexadecanoic acid, 15-Methylhexadecanoic acid, 3-Hydroxypentadecanoic acid, 3-Hydroxyhexadecanoic acid, 10-Methyldodecanoic acid	
Prevotella heparinolyticus	28113	Hexadecanoic acid, Tetradecanoic acid, 12-Methyltetradecanoic acid, 11-Methyldodecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-Methylhexadecanoic acid, 15-Methylhexadecanoic acid, 3-Hydroxypentadecanoic acid, 3-Hydroxyhexadecanoic acid, 10-Methyldodecanoic acid	
Prevotella intermedia	28131	Acetic acid, Butyric acid, Isobutyric acid, Isovaleric acid	Kurita-Ochiai et al., 1995
Prevotella loescheii	840	Acetic acid, Butyric acid, Propionic acid, Isobutyric acid, Valeric acid, Isovaleric acid	
Prevotella oralis	28134	Hexadecanoic acid, Tetradecanoic acid, 12-Methyltridecanoic acid, 12-Methyltetradecanoic acid, 14-Methylhexadecanoic acid, 11-Methyldodecanoic acid, 14-Methylpentadecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-Methylhexadecanoic acid, 15-Methylhexadecanoic acid, 3-Hydroxypentadecanoic acid, 3-Hydroxyhexadecanoic acid	Brondz and Olsen, 1991
Prevotella oris	28135	Hexadecanoic acid, Tetradecanoic acid, 12-Methyltridecanoic acid, 12-Methyltetradecanoic acid, 14-Methylhexadecanoic acid, 11-Methyldodecanoic acid, 14-Methylpentadecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-Methylhexadecanoic acid, 15-Methylhexadecanoic acid, 3-Hydroxypentadecanoic acid, 3-Hydroxyhexadecanoic acid, 10-Methyldodecanoic acid	
Prevotella spp.	838	11-Methyldodecanoic acid, 13-Methyltetradecanoic acid	
Prevotella veroralis	28137	Hexadecanoic acid, Tetradecanoic acid, 12-Methyltridecanoic acid, 12-Methyltetradecanoic acid, 11-Methyldodecanoic acid, 14-Methylpentadecanoic acid, 13-Methyltetradecanoic acid, 3-Hydroxy-15-Methylhexadecanoic acid, 3-Hydroxyhexadecanoic acid, 10-Methyldodecanoic acid	
Pseudoalteromonas spp.	53246	Methyliodide	Schulz and Dickschat, 2007
Pseudomonas aeruginosa	287	Ethyleneglycol, Acetic acid, Acetone, Ethanol, Indole, 4-Methylphenol, Acetonitrile, 2-Pentanone, 2-Aminoacetophenone	Zhu et al., 2010
		Butanol, 2-Undecanone, Dimethyldisulfide, 2-Nonanone, Dimethyltrisulfide, Isopentanol, Undecene, 2-Aminoacetophenone	Labows et al., 1980
Pseudomonas aurantiaca	86192	Benzaldehyde, Benzothiazole, 2-Ethyl-1-hexanol, Phenylenediamine, Cyclohexanol, 2-Methylpyrazine, Nonane, 2-Undecanone, Decanol, Dodecane, Pyrazine, 2-Tridecanone, Tetradecane, Pentadecane, Nonadecane, 1-Undecene, Undecane, 1-Heptadecanol, Decane, 4-Octylbenzoic acid, Dimethyltrisulfide, Nonanal, Hexadecane	Fernando et al., 2005
Pseudomonas cepacia	292	Dimethyldisulfide, Dimethyltrisulfide	Labows et al., 1980
Pseudomonas chlororaphis	587753		Fernando et al., 2005

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Benzaldehyde, Benzothiazole, 2-Ethyl-1-hexanol, Phenylenediamine, Cyclohexanol, 2-Methylpyrazine, Nonane, 2-Undecanone, Decanol, Dodecane, Pyrazine, 2-Tridecanone, Tetradecane, Pentadecane, Nonadecane, 1-Undecene, Undecane, 1-Heptadecanol, Decane, 4-Octylbenzoic acid, Dimethyltrisulfide, Nonanal, Hexadecane	
		Benzothiazole	Schulz and Dickschat, 2007
Pseudomonas corrugata	47879	Benzaldehyde, Benzothiazole, 2-Ethyl-1-hexanol, Phenylenediamine, Cyclohexanol, 2-Methylpyrazine, Nonane, 2-Undecanone, Decanol, Dodecane, Pyrazine, 2-Tridecanone, Tetradecane, Pentadecane, Nonadecane, 1-Undecene, Undecane, 1-Heptadecanol, Decane, 4-Octylbenzoic acid, Dimethyltrisulfide, Nonanal, Hexadecane	Fernando et al., 2005
Pseudomonas doudoroffii	84158	Methanethiol, Dimethylsulfide	Schulz and Dickschat, 2007
Pseudomonas fluorescens	294	Acetoin	Lee et al., 1979; Pittard et al.,1982
		Benzaldehyde	Lee et al., 1979; Fernando et al., 2005
		2,3-Butanediol, 1-Butanol, 2,3-Butanedione, Glyoxylic acid, 1-Pentanol, Acetylene, Isoprene, 2-Methyl-1-propanol, Diethylacetic acid, 2-Methylbutanal, Cyclohexane, 2-Methyl-1-butanol, 2-Methylfuran, Hexadecane, Tetrahydro-2,5-dimethylfuran, 3-Methyl-1-butanol, Butanol-3-methyl acetate, 2-Hydroxy-3-pentanone, 2,4-Hexadienal, Benzaldehyde, Acetoin, Ethanol, Methanethiol, 2-Butanone, Dodecane, Undecane, Methylbutanal, Dimethyldisulfide, 1-Undecene, Dimethyltrisulfide	Farag et al., 2006
		Butanol, Isopentanol, Dimethyltrisulfide	Labows et al., 1980
		Ethanol, Methanol, Methyl propionate, Dimethylsulfide, Dimethyldisulfide, Methylthiol acetate	Freeman et al., 1976
		Methanethiol, 2-Butanone, Dimethylsulfide, Toluene, 2-Nonanone, 4-Methyl-2,6-di-tert-butylphenol, Dimethyldisulfide, 1-Undecene, Dimethyltrisulfide, Nonanal, Methylthiol acetate, 2-Butanol, 3-Octanone, Dimethylbenzenes, Ethylmethyldisulfide, 2-Octanol, 1-Nonene, Cycloheptene, 4-Octanone, 2-Pentanone, 2-Heptanone, Trimethylbenzene, 3-Pentanone	Pittard et al., 1982
		Toluene, 2-Nonanone, 4-Methyl-2,6-di-tert-butylphenol, Methyl propionate, Methyl isothiocyanate, Methyl-2-methyl butyrate, Methylpent-2-enoate, Methylbutanal, Dimethyldisulfide, 1-Undecene, Dimethyltrisulfide, Methylthiol acetate	Lee et al., 1979
		Benzothiazole, 2-Ethyl-1-hexanol, Phenylenediamine, Cyclohexanol, 2-Methylpyrazine, Nonane, 2-Undecanone, Decanol, Tetradecane, Pentadecane, Nonadecane, 1-Heptadecanol, Decane, 4-Octylbenzoic acid, Hexadecane, 2-Tridecanone, Pyrazine, Dodecane, Undecane, 1-Undecene, Dimethyltrisulfide, Nonanal	Fernando et al., 2005
		Dimethyltelluride	Schulz and Dickschat, 2007
		Undecene	Kai et al., 2007
Pseudomonas fragi	296	Acetaldehyde, Ethylalcohol, Methylmercaptan, Butanone, Ethyl butyrate, Ethyl hexanoate, Dimethylsulfide, Ethyl acetate, Dimethyldisulfide	Miller et al., 1973
		Ethanol, Methanol, Methyl acetate, Dimethylsulfide, Ethyl acetate, Dimethyldisulfide	Freeman et al., 1976
		Toluene, Menthol, Dibutylphthalate, Hexanal, Carbondisulfide, Linalool, alpha-Pinene, 2-Ethylphenol, 4-Methylguaiacol, 2-Ethyl-1,3-hexandiol, ortho-Dimethylbenzene, para-Dimethylbenzene, 1-Butene, 2,4,4-Trimethyl-1-pentene, Decanal, Dodecene, 10-Undecenal, 1-Dodecanol, 4(1,1,3,3-Tetramethylbutyl)phenol, 1-Nonanol, Citronellyl acetate, 1-Hexadecene, 2-Undecanol, alpha-Terpineol, 1-Octen-3-ol, 2-Butyl-1-octanol, 1,9-Nonanediol, 2-Pentylthiophene, Limonene, 2-Ethylhexyl-2-ethyl hexanoate, 2-Dodecanol, Tridecanal, Nonanal, Butylhydroxytoluene, Decenyl acetate, 2-Methyl-1-dodecanol, Hexadecanediol, 2-Methyl-1-decanol, 1-Nonen-3-ol, 1,2-Dodecanediol, 3-Hydroxydodecanoic acid, 2-Methyl-3-buten-1-ol, 2-Hexyl-1-decanol, 4-Methoxybenzhydrol, 2-Pentadecanol, Tetradecen-1-ol, Dodecyl hexanoate, 5-Butyl-4-nonene, 2-Methyl-2-decene, 5-Methylundecene, 2,3-Epoxygeranyl acetate, 2-Ethyldodecanol, 2-Ethyl-1-decanol, 2-Methyl-2-dodecene, Dodecenal, 3-Tetradecene, 3-Decen-2-one, Undecene, 6-Dodecenol, 2,5-Octanedione, 2-Methylundecanthiol, 2-Butyloctenal	Ercolini et al., 2009
Pseudomonas maltophilia	40324	Butanol, 2-Undecanone, Dimethyldisulfide, Dimethyltrisulfide, Isopentanol	Labows et al., 1980
Pseudomonas putida	303		Lee et al., 1979

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Acetone, 4-Methyl-2,6-di-tert-butylphenol, Methylthiol acetate, 2-Nonanone, 2-Butanone, Toluene, Benzaldehyde, Methyl benzoate, Methyl isothiocyanate, Methyl butanal, Methylpent-2-enoate, 1-Undecene, Dimethyldisulfide, Dimethyltrisulfide	
		Butanol, Isopentanol, 2-Undecanone, Dimethyldisulfide, Dimethyltrisulfide	Labows et al., 1980
		Ethanol, Heptadiene, Methanol, Dimethyldisulfide	Freeman et al., 1976
		Methanethiol, 3-Pentanone, 2-Pentanone, 2-Heptanone, Trimethylbenzene, 4-Octanone, n-Nonanal, Ethylmethyldisulfide, 3-Octanone, Dimethylbenzenes, Acetone, 4-Methyl-2,6-di-tert-butylphenol, Methylthiol acetate, 2-Nonanone, 2-Butanone, Toluene, Carbondisulfide, Dimethyldisulfide, Dimethyltrisulfide	Pittard et al., 1982
		Phenylacetate, Carbondisulfide	Schulz and Dickschat, 2007
Pseudomonas putrefaciens	24	Butanol, Dimethyltrisulfide, Isopentanol, Dimethyldisulfide	Labows et al., 1980
		Ethanol, Methylmercaptan, Methanol, Dimethyldisulfide	Freeman et al., 1976
Pseudomonas solanacearum	305	Ethylene	Stotzky and Schenk, 1976
Pseudomonas spp.	286	Methylmercaptan, Methyl acetate, Ethylbenzene, Ethyl acetate, Dimethyldisulfide, Xylene, Dimethylsulfide	Freeman et al., 1976
		Methyliodide, 1-Undecene, Dimethylselenenylsulfide	Schulz and Dickschat, 2007
		Methylthiol n-butyrate	Pittard et al., 1982
		6-Methyl-1-octanol, Tetradecen-1-ol acetate, 4-Methylundecene	Ercolini et al., 2009
Pseudomonas taetrolens	47884	2-Methoxy-3-(1-methylethyl)pyrazine	Schulz and Dickschat, 2007
Pseudomonas trivialis	200450	Undecadiene, Benzyloxybenzonitrile, Undecene	Kai et al., 2007
Pseudonocardia spp.	1847	Isoprene	Schulz and Dickschat, 2007
Rhizobium spp.	379	Methyliodide	
Rhodobacter sphaeroides	1063	Dimethylselenide	
Rhodococcus spp.	1827	Methyliodide	
Rhodocyclus tenuis	1066	Dimethylselenide, Dimethyltelluride	
Rhodospirillum rubrum	1085		
Rivularia spp.	373984	2-Heptanone, 6-Methyl-5-hepten-2-one, beta-Cyclocitral, 2-Tridecanone, 2-Decanone, Limonene, 2,6,6-Trimethylcyclohex-2-en-1-one, 8-Methylheptadecane, beta-Ionone-5,6-epoxide, Geosmin	Höckelmann et al., 2004
		Sulcatone, Geosmin	Schulz and Dickschat, 2007
Roseobacter gallaeciensis	60890	2-Ethyl-5-methylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, 5-Methyl-2-(1-methylethyl)pyrazine	Dickschat et al., 2005a
Roseobacter spp.	2433	Methanethiol, Dimethylsulfide, 2-Phenylethanol	Schulz and Dickschat, 2007
Roseovarius spp.	74030	Methyliodide, Diiodomethane, Triiodomethane, Chloroiodomethane	
Saccharomonospora spp.	1851	Isoprene	
Salmonella enterica	28901	Acetic acid, Acetaldehyde, 1-Butanol, Ethanol, Methanethiol, Methanol, 2-Butanone, 2-Methyl-1-butanol	Bunge et al., 2008
Salmonella enterica serovar typhimurium	90371	Ethyleneglycol, Acetic acid, Acetone, Butanol, Ethanol, Indole, 4-Methylphenol, Acetonitrile, 2-Pentanone, Pyrimidine, 2-Nonanone, Isopentanol	Zhu et al., 2010
Serratia marcescens	615	Propanone, Benzaldehyde, Phenol, Benzenacetaldehyde, Propionic acid, 1-Hexadecanol, Benzeneethanol, Phenylethanone, Cyclohexene, Nonane, 2-Undecanone, Decanal, Dodecane, Hexadecane, Dimethyldisulfide, Tetradecane, 2-Nonanone, Terpineol, 2-Octanol, Trimethylpyrazine	Gu et al., 2007
Serratia odorifera 4Rx13	618	Beta-Phenylethanol, Dimethyldisulfide, Dimethyltrisulfide, Methantiol, ‚Sodorifen’	Kai et al., 2007 and 2010
Serratia plymuthica HROC48	82996	Beta-Phenylethanol, Benzylnitrile, trans-9-Hexadecene-1-ol	Kai et al., 2007
Serratia proteamaculans	28151	Toluene, Menthol, Hexanal, Carbondisulfide, Linalool, alpha-Pinene, 2-Ethylphenol, 4-Methylguaiacol, ortho-Dimethylbenzene, Ethyl octanoate, para-Dimethylbenzene, 1-Propanethiol, Ethyl decanoate, Citronellyl acetate, 1-	Ercolini et al., 2009

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Methyl-2,1-methylethylbenzene, Methylethylsulfide, 1-Hexadecene, 2-Hexen-1-ol, alpha-Terpineol, 1-Octen-3-ol, 2-Pentylthiophene, Limonene, 2-Ethylhexyl-2-ethyl hexanoate, 2-Dodecanol, Ethyl nonanoate, 3-Methyl-1-butanol, Ethyl hexanoate, Isoamyl acetate, Butylhydroxytoluene, Decenyl acetate, 2-Hexen-1-ol propanoate, Linalyl propanoate, Borneol, 1-Nonen-3-ol, 3-Hydroxydodecanoic acid, 4-Methoxybenzhydrol, Tetradecen-1-ol, Dodecyl hexanoate, 3-Octanone, 5-Butyl-4-nonene, 6-Methyl-1-octanol, Tetradecen-1-ol acetate, 4-Methylundecene, 2,3-Epoxygeranyl acetate, 4-Hydroxy-3-methylbutanal, Dodecenal, trans-2-Hexen-1-ol, 2-Octen-1-ol, 2-Nonen-1-ol	
Serratia spp.	613	Acetic acid, 3-Hydroxy-2-butanone, 2-Propanone, Ethanol, 1,2-Benzenedicarboxylic acid, 2-Propanol, 2-Methyl-1-propanol, 2-Butanone, 2-Methyl-propanoic acid, 1,2-Dimethylbenzene, 2-Ethyl-1-hexanol, 2-Pentanone, Acetic acid ethenyl ester, 2-Heptanone, 2-Undecanone, 2-Methyl-butanoic acid, Ethyl acetate, 3-Methyl-butanoic acid, 2-Nonanone, Undecane, 2-Dodecanone, 2,5-Dimethylpyrazine, Limonene, Dimethyldisulfide, Dimethyltrisulfide	Bruce et al., 2004
		Acetoin, Undecan-2-one, Nonan-2-one, Dodecan-2-one, Dimethyldisulfide, Dimethyltrisulfide	Schulz and Dickschat, 2007
Shewanella spp.	22	Methyliodide, 1-Undecene	
Shigella flexneri	623	Acetic acid, Acetaldehyde, Acetone, 1-Butanol, Ethanol, Indole, Methanethiol, Methanol, 2-Methyl-1-butanol	Bunge et al., 2008
Sphingomonas spp.	13687	Methyliodide	Schulz and Dickschat, 2007
Spirulina platensis	118562	beta-Ionone-5,6-epoxide	
Sporosarcina ginsengisoli	363855	Acetamide, Benzaldehyde, Phenylacetaldehyde, Methanamine, Benzothiazole, Methylpyrazine, 1-Butanamine, Dodecane, Dimethyldisulfide, Nonadecane, 1-Decene, 2,5-Dimethylpyrazine	Zou et al., 2007
Staphylococcus aureus	1280	Ethyleneglycol, Acetic acid, Acetone, Butanol, Ethanol, 4-Methylphenol, 2-Aminoacetophenone, 2-Pentanone, Pyrimidine, 2-Nonanone, Isopentanol	Zhu et al., 2010
Staphylococcus epidermidis	1282	Beta-Phenylethanol, Dodecanal	Kai et al., 2007
Staphylococcus spp.	1279	Acetic acid, Acetoin, Butanoic acid, Butanedione, Propanoic acid, 2-Methylpropanal, 2-Methylbutanal, 3-Methylbutanal, Pentane-2,3-dione	Schulz and Dickschat, 2007
Staphylococcus xylosus	1288	Acetic acid, Acetaldehyde, 2-Hydroxy-3-butanone, Acetone, Benzaldehyde, Butanoic acid, 3-(Methylthio)-propanoic acid, Lactic acid, 2,3-Butanedione, Ethanol, Benzeneacetaldehyde, Benzeneacetic acid, Propanoic acid, 2-Propanol, 2-Phenylethanol, 2-Methylpropanol, 2-Methylpropanal, 2-Butanone, 2-Methylpropanoic acid, 2-Methylbutanal, Acetophenone, 2-Phenylethyl acetate, 2-Methylbutanol, 3-Methylbutanal, 2,3-Pentanedione, Dimethyldisulfide, 3-(Methylthio)-propanal, 2,5-Dimethylpyrazine, 3-Methylbutanol, 3-Methyl-1-butyl acetate, 2-Methylbutanoic acid, 3-Methylbutanoic acid,, 3-Methylbut-2-en-1-ol,, 3-Methylbut-3-en-1-ol,, 2-Methyltetrahydrothiophen-3-one	Beck et al., 2002
		3-Methylmercapto propionate, Phenylacetaldehyde, Phenyl acetate, 2-Phenylethanol, Methylpropanoic acid, 2-Methylbutanoic acid, 3-Methylbutanoic acid,, 3-Methylbut-2-en-1-ol,, 3-Methylbut-3-en-1-ol,, 2-Methyltetrahydrothiophen-3-one	Schulz and Dickschat, 2007
Stappia marina	281252	Tetramethylpyrazine, 2-Ethyl-5-methylpyrazine, 5-Methyl-2-(1-methylethyl)pyrazine	Dickschat et al., 2005e
Stenotrophomonas maltophilia	40324	Acetamide, Benzaldehyde, Phenylacetaldehyde, Methanamine, Benzothiazole, Methylpyrazine, 1-Butanamine, Nonadecane, 1-Decene, 2,5-Dimethylpyrazine	Zou et al., 2007
		Propanone, Benzaldehyde, Phenol, Benzenacetaldehyde, Propionic acid, 1-Hexadecanol, Benzeneethanol, Phenylethanone, Cyclohexene, Nonane, 2-Undecanone, Decanal, Hexadecane, Tetradecane, 2-Nonanone, Terpineol, 2-Octanol, Trimethylpyrazine	Gu et al., 2007
		Dodecane, Dimethyldisulfide	Zou et al., 2007; Gu et al., 2007
Stenotrophomonas rhizophila	216778	beta-Phenylethanol	Kai et al., 2007
		Dodecanal	
Stigmatella aurantiaca	41	Benzaldehyde, Benzylalcohol, Butyl acetate, Dimethyltrisulfide, Menthol, Hexadecan-1-ol, 2-Phenylethanol, 2-Methoxy-1,1'-biphenyl, Methyl benzoate, 4-Butanolide, Acetophenone, 4-Pentanolide, Undecan-2-one, Tetradecan-1-ol, 2-Methylbutyric acid, 6-Methylhept-5-en-2-one, 3-Methylbutyric acid, para-Menth-1-en-3-ol, Butyl propionate, Pent-2-en-4-olide, Pentadecan-1-ol, Methyl 3-methyl crotonate, 2-Acetylfuran, Undecan-2-ol, beta-Copaene, Guaioxide, 13-Methyltetradecan-1-ol, Tetradecan-4-olide, N-Isopentylacetamide, N-Isopentylideneisopentylamine, 6,10-Dimethylbicyclo[4.4.0]dec-1-ene, N-Isopentylformamide, (E,E)-Farnesol, N-(2-Phenylethylidene)isopentylamine, Geranylacetone, Methyl-2-methyl crotonate, 2-Methyltetradecan-4-one, beta-Ylangene, Methyl salicylate, 4-	Dickschat et al., 2005b

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Methylquinoline, Hexahydrofarnesylacetone, Nonadecan-10-one, 5-Methylhexan-3-one, Dodecan-3-one, alpha-Terpineol, S-Methylmethanethiosulfonate, Dihydroactinidiolide, 1-Phenylundecan-1-one, 1-Phenylnonan-1-one, 1-Phenyldecan-1-one, beta-Eudesmol, 6,10-Dimethylundeca-5,9-dien-2-ol, Dodecan-3-ol, Methyl-5-methyl hexanoate, Nerolidol, Germacrene D, Valerianol, Geosmin, (1(10)E,5E)-Germacradien-11-ol	
		Methyl salicylate, 4-Methylquinoline, Hexahydrofarnesylacetone, Nonadecan-10-one, 5-Methylhexan-3-one, Dodecan-3-one, alpha-Terpineol, S-Methylmethanethiosulfonate, Dihydroactinidiolide, 1-Phenylundecan-1-one, 1-Phenylnonan-1-one, 1-Phenyldecan-1-one, beta-Eudesmol, 6,10-Dimethylundeca-5,9-dien-2-ol, Dodecan-3-ol, Methyl-5-methyl hexanoate, Nerolidol, Germacrene D, Valerianol, Menthol, 2-Methylisoborneol, S-Methylmethanethiosulfinate, N-(3-Methylbutyl)acetamide, N-3-Methylbutylidene-3-methylbutylamine, N-(3-Methylbutyl)formamide, Farnesol, N-(2-Phenylethylidene)-3-methylbutylamine, p-Meth-1-en-4-ol, Rosifoliol, Isolepidozene, Octalinhydrocarbon, Geosmin, Stigmolone, (1(10)E,5E)-Germacradien-11-ol	Schulz and Dickschat, 2007
		Geosmin	Dickschat et al., 2005c
		Stigmolone	Schulz et al., 2004; Dickschat et al., 2007
		(1(10)E,5E)-Germacradien-11-ol, Geosmin	Dickschat et al., 2005d
Stigmatella spp.	40	Methyl benzoate, 4-Butanolide, Octan-4-olide, Nonan-4-olide, Undecan-4-olide, Heptan-4-olide, 4-Pentanolide, Hexan-4-olide, Decan-4-olide, Methyl 3-methylbut-2-enoate, Dodecan-4-olide, Methyl 2-methylbut-2-enoate, Tetradecan-4-olide	Schulz and Dickschat, 2007
Streptomyces albidoflavus	1886	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, Dimethyltrisulfide, 3-Methyl-1-butanol, Ethanethioic acid S-methyl ester, Geosmin	Schöller et al., 2002
		Geosmin, S-Methyl thiobutyrate, S-Methyl thioacetate, S-Methyl thio-3-methylbutyrate, S-Methyl thiopropionate, Albaflavenone	Schulz and Dickschat, 2007
Streptomyces albus	1888	Acetone, 1-Butanol, Cyclopentanone, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylbutanoic acid methyl ester, Dimethyltrisulfide, 3-Methyl-1-butanol, Ethanethioic acid S-methyl ester, Geosmin	Schöller et al., 2002
		Camphor, 3-Methylbut-3-en-1-ol, Geosmin	Schulz and Dickschat, 2007
Streptomyces antibioticus	1890	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, 3-Methylbutanoic acid methyl ester, Methyl butyrate, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylbutanoic acid methyl ester, Dimethyltrisulfide, 3-Methyl-1-butanol, Geosmin	Schöller et al., 2002
		Geosmin	Schulz and Dickschat, 2007
Streptomyces aureofaciens	1894	Acetone, 1-Butanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, 3-Methylbutanoic acid methyl ester, Methyl butyrate, Dimethyldisulfide, 2-Methylbutanoic acid methyl ester, 2-Methylisoborneol, Dimethyltrisulfide, Geosmin, 3-Methyl-1-butanol	Schöller et al., 2002
Streptomyces caviscabies	90079	Linalool, 4-Methylquinoline, 2-Aminoacetophenone, 3-Methylbut-2-en-1-ol, 3-Methylbut-3-en-1-ol, 6-Methylheptan-2-one, gamma-Muurolene, 5-Methylheptan-2-one, Dimethyltetrasulfide, S-Methyl thiobenzoate, Dimethylpentasulfide, alpha-Muurolene, (E)-4,8-Dimethylnona-1,3,7-triene, 2-Methyl-2-bornene, Isothujone, delta-Cadinene, Geraniol, Cadina-1,4-diene, cis-Calamenene, Kelsoene, alpha-Gurjunene, (1(10)E,5E)-Germacradien-11-ol, 10-Methylundecan-5-olide, 10-Methylundecan-4-olide, 10-Methyldodecan-4-olide, 10-Methyldodecan-5-olide, 10-Methylundec-2-en-4-olide, 10-Methyldodec-2-en-4-olide, 10-Methylundec-3-en-4-olide, 10-Methyldodec-3-en-4-olide, beta-Muurolene	Schulz and Dickschat, 2007
Streptomyces citreus	67288	4-Methylpent-3-en-2-one, 3-Methylpentan-2-ol, 3-Methylbutan-2-ol, 2-Acetylfuran, Limonene, Geosmin, beta-Myrcene, delta-Elemene, delta-Cadinene, Geraniol, Bicyclogermacrene, Germacrene D, beta-Gurjunene, beta-Elemene, Dihydroagarofuran, (1(10)E,5E)-Germacradien-11-ol	
Streptomyces coelicolor	1902	Acetone, 1-Butanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, Methyl butyrate, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylbutanoic acid methyl ester, Dimethyltrisulfide, 3-Methyl-1-butanol, Ethanethioic acid S-methyl ester, Dimethyltetrasulfide, Geosmin	Schöller et al., 2002
		Geosmin	Dickschat et al., 2005a
		(1(10)E,5E)-Germacradien-11-ol	Schulz and Dickschat, 2007

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
Streptomyces diastatochromogenes	42236	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylisoborneol, Dimethyltrisulfide, Geosmin, 3-Methyl-1-butanol	Schöller et al., 2002
Streptomyces griseus	1911	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylbutanoic acid methyl ester, 2-Methylisoborneol, Dimethyltrisulfide, 3-Methyl-1-butanol, Ethanethioic acid S-methyl ester, Geosmin, Dimethyltetrasulfide	
		Alpha-Pinene, Beta-Pinene, S-Methyl thiobutyrate, Dimethyltetrasulfide	Schulz and Dickschat, 2007
		Geosmin	Dickschat et al., 2005a; Nawrath et al., 2008
		beta-Gurjunene	Dickschat et al., 2005d
Streptomyces hirsutus	35620	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, 3-Methylbutanoic acid methyl ester, Methyl butyrate, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, Dimethyltrisulfide, Geosmin, 3-Methyl-1-butanol, Ethanethioic acid S-methyl ester, Dimethyltetrasulfide	Schöller et al., 2002
Streptomyces hygroscopicus	1912	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, Cyclopentanone, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, 3-Methylbutanoic acid methyl ester, Methyl butyrate, Dimethyldisulfide, 2-Methylbutanoic acid methyl ester, 2-Methylisoborneol, Dimethyltrisulfide, Geosmin, 3-Methyl-1-butanol, Dimethyltetrasulfide	
Streptomyces lateritius	67313	Propanone, Benzaldehyde, Phenol, Benzenacetaldehyde, Propionic acid, 1-Hexadecanol, Benzeneethanol, Phenylethanone, Cyclohexene, Nonane, 2-Undecanone, Decanal, Dodecane, Hexadecane, Dimethyldisulfide, Tetradecane, 2-Nonanone, Terpineol, 2-Octanol, Trimethylpyrazine	Gu et al., 2007
Streptomyces lavendulae	1914	(-)-2-Methylisoborneol	Dickschat et al., 2007
Streptomyces murinus	33900	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, Methyl butyrate, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylbutanoic acid methyl ester, 2-Methylisoborneol, Geosmin, 3-Methyl-1-butanol	Schöller et al., 2002
Streptomyces olivaceus	47716	Acetone, 1-Butanol, 2-Phenylethanol, 2-Methyl-1-propanol, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylisoborneol, Dimethyltrisulfide, Geosmin, 3-Methyl-1-butanol	
Streptomyces platensis	58346	Butanoic acid 2-methyl ester, 1a,2,3,3a,4,5,6,7b-Octahydro-1,1,3a,7-tetramethyl-1H-cyclopropa[a]naphthalene, trans-1,10-Dimethyl-trans-9-decalol, 5-Methoxy-1,3-dimethyl-1H-pyrazole, 1,1,4,4-Tetramethyl-2,5-dimethylene- cyclohexane, 3,3,7,11-Tetramethyltricyclo [5.4.0.0 (4,11)] undecan-1-ol, 2-(2,4-Dimethoxybenzylidenehydrazino)-N-ethyl-2-oxo-acetamide,	Wan et al., 2008
Streptomyces rishiriensis	68264	Acetone, 1-Butanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, Dimethyltrisulfide, Geosmin, 3-Methyl-1-butanol	Schöller et al., 2002
Streptomyces spp.	1883	Acetoin, Butane-2,3-diol, Isoprene, Methyl benzoate, 2-(Hydroxymethyl)furan, Hexanoic acid, 3-Methylfuran, S-Methyl thioacetate, Pentalenene, Germacrene A, Protoilludene, Benzylalcohol, Benzothiazole, 2-Phenylethyl acetate, 1-Phenylpropan-2-one, Benzyl acetate, 4-Methylquinoline, 3-Methylbut-2-en-1-ol, 2-Phenylpropan-2-ol, Dimethyldisulfide, 3-Methylbut-3-en-1-ol, Dodecan-4-olide, Butylphenyl acetate, Dimethyltetrasulfide, 4-Methylhexan-1-ol, 4-Methylquinazoline, 2-Phenylethanol, 2-Methylisoborneol, Dimethyltrisulfide, Geosmin	Schulz and Dickschat, 2007
		Acetone, 1-Butanol, Isoprene, Cyclopentanone, 2-Methyl-1-butanol, 3-Methyl-1-butanol, 2-Phenylethanol, 2-Methylisoborneol, Dimethyltrisulfide, Geosmin	Schöller et al., 2002
		Vinylguaiacol, Hexadecanoic acid, Octadecanoic acid, Methyl-4-hydroxy benzoate, Heptadecanoic acid, Tetradecanoic acid, Pentadecanoic acid, 12-Methyltetradecanoic acid, 14-Methylhexadecanoic acid, 14-Methylpentadecanoic acid, 13-Methyltetradecanoic acid, 15-Methylhexadecanoic acid, 12-Methyltridecanoic acid, Pentadecenoic acid, 9-Octadecenoic acid, Squalene, 9-Hexadecenoic acid, (R)-10-methyl-6-undecanolide, (6R,10S)-10-methyl-6-dodecanolide, 2-Phenylethanol, Geosmin	Stritzke et al., 2004
		Benzophenone, Isobornyl acetate, Linalool, Ethyl-2-methyl propionate, Methylpyrazine, Heptan-2-one, Hexan-1-ol, Benzylcyanide, 6-Methylhept-5-en-2-one, 2-Aminoacetophenone, 6-Methylheptan-2-one, 2-Acetylfuran, gamma-Muurolene, Heptane-2,5-dione, Geranylacetone, 5-Methylheptan-2-one, Butyl acetate, Cyclooctasulfur, S-Methyl thiobenzoate, Dimethylpentasulfide, Guaioxide, Methyl methylthiomethyl disulfide, alpha-Muurolene, Isolongifolene, Citronellylacetone, (E)-4,8-Dimethylnona-1,3,7-triene, 2-Methyl-2-bornene, Isothujone, delta-Cadinene, 1-epi-	Dickschat et al., 2005d

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
		Cubenol, 2-Methoxy-3-(1-methylpropyl)pyrazine, Geraniol, Cadina-1,4-diene, cis-Calamenene, beta-Gurjunene, Kelsoene, alpha-Gurjunene, 10-Methylundecan-5-olide, 10-Methylundecan-4-olide, 10-Methyldodecan-4-olide, 10-Methyldodecan-5-olide, 10-Methylundec-2-en-4-olide, 10-Methyldodec-2-en-4-olide, 10-Methylundec-3-en-4-olide, 10-Methyldodec-3-en-4-olide, beta-Muurolene, Benzylalcohol, Benzothiazole, 2-Phenylethyl acetate, 1-Phenylpropan-2-one, Benzyl acetate, 4-Methylquinoline, 3-Methylbut-2-en-1-ol, 2-Phenylpropan-2-ol, Dimethyldisulfide, 3-Methylbut-3-en-1-ol, Dodecan-4-olide, Butylphenyl acetate, Dimethyltetrasulfide, 4-Methylhexan-1-ol, 4-Methylquinazoline, 2-Phenylethanol, 2-Methylisoborneol, Dimethyltrisulfide, (1(10)*E*,5*E*)-Germacradien-11-ol, Geosmin	
		Ethylene	Stotzky and Schenk, 1976
		Butyrolactone	Ryan and Dow JM, 2008
		Geosmin	Dickschat et al., 2007
		(1(10)*E*,5*E*)-Germacradien-11-ol, 8,10-Dimethyl-1-octalin	Nawrath et al., 2008
Streptomyces sulphureus	47758	Geosmin	Schulz and Dickschat, 2007
Streptomyces thermoviolaceus	1952	Acetone, 1-Butanol, 2-Phenylethanol, Isoprene, 2-Methyl-1-propanol, Cyclopentanone, 2-Methyl-1-butanol, 2-Methylpropanoic acid methyl ester, Methylbutyrate, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 2-Methylbutanoic acid methyl ester, Dimethyltrisulfide, Geosmin, 3-Methyl-1-butanol, Ethanethioic acid S-methyl ester	Schöller et al., 2002
Sulfitobacter dubius	218673	Tetramethylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, 2,5-Dimethyl-3-(3-methylbutyl)pyrazine, 3-Butyl-2,5-dimethylpyrazine	Dickschat et al., 2005e
Sulfitobacter pontiacus	60137	Tetramethylpyrazine, 2-Ethyl-5-methylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, Ethyltrimethylpyrazine, 5-Methyl-2-(1-methylethyl)pyrazine, 2,5-Dimethyl-3-(3-methylbutyl)pyrazine, 2,5-Dimethyl-3-(2-methylpropyl)pyrazine, 3-Butyl-2,5-dimethylpyrazine, 2,5-Dimethyl-3-methylsulfanylpyrazine	
		2,5-Dimethyl-3-methylsulfanylpyrazine	Schulz and Dickschat, 2007
Sulfitobacter spp.	60136	2-Ethyl-5-methylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, 5-Methyl-2-(1-methylethyl)pyrazine	Dickschat et al., 2005e
		2-(3-Methylbutyl)-3,6-dimethylpyrazine, 2-Isobutyl-3,6-dimethylpyrazine, 2-Butyl-3,6-dimethylpyrazine, 2-(2-Methylbutyl)-3,6-dimethylpyrazine, 2,5-Dimethyl-3-methylsulfanylpyrazine	Schulz and Dickschat, 2007
Thermoactinomyces spp.	2023	Isoprene, 2-Methylfuran	
Thermomonospora fusca	2021	5-Methylhexan-3-one, S-Methyl thiobutyrate	
Thermomonospora spp.	2019	Isoprene	
Tolypothrix distorta	119534	Octanal, alpha-Pinene, 2-Heptanone, Decanal, 6-Methyl-5-hepten-2-one, beta-Cyclocitral, 2-Tridecanone, Heptadecane, 2-Decanone, 6-Methylheptan-2-one, Limonene, Heptadecene, Geosmin, 7-Methylheptadecane, Nonanal, 1-Octen-3-one, 8-Methylheptadecane, beta-Ionone, 2-Decenal, beta-Ionone-5,6-epoxide	Höckelmann et al., 2004
Tolypothrix spp.	111782	Sulcatone	Schulz and Dickschat, 2007
Treponema denticola	158	Methanethiol, L-Methionine	
Variovorax spp.	34072	Methyliodide	
Veillonella spp.	29465	Acetate, Succinate, Isobutyrate, Isovalerate	Hinton and Hume, 1995
Vibrio spp.	662	Methyliodide	Schulz and Dickschat, 2007
Wolinella curva	200	Hexadecanoic acid, Dodecanoic acid, Octadecanoic acid, Tetradecanoic acid, 3-Hydroxytetradecanoic acid, 3-Hydroxyhexadecanoic acid, Hexadecenoic acid	Brondz and Olsen, 1991
Wolinella recta	203	Hexadecanoic acid, Dodecanoic acid, Octadecanoic acid, Tetradecanoic acid, 3-Hydroxytetradecanoic acid, 3-Hydroxyhexadecanoic acid, Hexadecenoic acid	
Wolinella succinogenes	844	Hexadecanoic acid, Dodecanoic acid, Octadecanoic acid, Tetradecanoic acid, 3-Hydroxytetradecanoic acid, 3-Hydroxyhexadecanoic acid, Hexadecenoic acid	
Xanthomonas campestris pv. *campestris*	340	Butyrolactone, cis-11-Methyl-2-dodecenoic acid	Ryan and Dow JM, 2008
	316273		Weise et al., 2012

Table 2 (continued)

Species	Tax ID (NCBI)	Volatile Synonym	References
Xanthomonas campestris pv. *vesicatoria* 85-10		Hexan-2-one, 2-Methylpropyl acetate, n-Octane, 5-Methylhexan-2-one, 2-Methylbutyl acetate, 3-Methylbutyl acetate, Heptan-2-one, 2,5-Dimethylpyrazine, 2-Methylpropyl propionate, n-Nonane, 6-Methylheptan-2-one, 5-Methylheptan-2-one, 2-Methylbutyl propionate, 3-Methylbutyl propionate, Octan-2-one, 2,3,5-Trimethylpyrazine, Hexyl acetate, Benzylalcohol, 3-Methylbutyl 3-methylbutyrate, Acetophenone, 7-Methyloctan-2-one, Nonan-2-one, 2-Phenylethanol, 8-Methylnonan-2-one, 7-Methylnonan-2-one, 8-Methylnonan-2-ol, 7-Methylnonan-2-ol, Decan-2-one, 2-Phenylethyl acetate, 9-Methyldecan-2-one, Undecan-2-one, Undecan-2-ol, 3,6-Dimethyl-2-(3-methylbutyl)pyrazine, 10-Methylundecan-2-one, 9-Methylundecan-2-one, 10-Methylundecan-2-ol, 9-Methylundecan-2-ol, Dodecan-2-one, Geranylacetone, 11-Methyldodecan-2-one, Tridecan-2-one, Tridecan-2-ol, 12-Methyltridecan-2-one, 11-Methyltridecan-2-one, 12-Methyltridecan-2-ol, 11-Methyltridecan-2-ol, Tetradecan-2-ol, 13-Methyltetradecan-2-one, Pentadecen-2-one, Pentadecan-2-one, 14-Methylpentadecan-2-one, 13-Methylpentadecan-2-one	
Zoogloea spp.	349	Methyliodide	Schulz and Dickschat, 2007

The name of the volatile producing species corresponds to a taxonomy ID (http://www.ncbi.nlm.nih.gov/taxonomy)

2005a; von Reuss et al., 2010). It is, for example, not known whether these volatiles act as communication signals or are used as carbon sources. Important future tasks are, therefore, elucidation of the plethora of bacterial and fungal VOCs and determination of their chemical structures and biological and ecological roles.

Volatile Mediated Bacterial-Fungal Interactions

Bacterial and fungal volatiles may play multiple roles in microbial communities belowground. Although volatiles can serve as nutrient sources, under highly competitive but symbiotic conditions they are particularly important for antibiosis and signaling, and may serve as regulative principles in any ecosystem. Subsequently, interactions between bacteria and fungi can be beneficial or detrimental. In the latter situation, the term microbiostasis is used to describe the inability of bacteria and/or fungi to multiply in natural soils (Ho and Ko, 1982). Although nutrient depletion or suboptimal environmental conditions also may account for this effect, the involvement of microbial biogenic inhibitors, including volatiles, in microbiosis is widely accepted (Hora and Baker, 1972; Griffin et al., 1975; Stotzky and Schenck, 1976 and citations therein; Chuankun et al., 2004; Zou et al., 2007; Garbeva et al., 2011). The role of volatiles in signaling events within microbial communities has not yet been well-studied. Wheatley (2002) described volatiles as info-chemicals that could mediate bacterial and fungal interactions. This was also proposed by Bending et al. (2006) for the mycorrhizal community. Fungi and plants produce volatile signal molecules that bacteria in the mycorrhizhospere may also synthesize, thereby affecting mycorrhiza formation. A similar situation has been described for the rhizobacterial community (Chernin et al., 2011). Volatiles of *Pseudomonas fluorescens* and *Serratia plymuthica* inhibited quorum-sensing in various other bacteria such as *Agrobacterium*, *Chromobacterium*, *Pectobacterium*, and *Pseudomonas* due to suppression of the transcription of N-acyl-homoserine lactone synthase genes.

Effects of Bacterial Volatiles on Fungi

Influence of Bacterial Volatiles on Germination and Mycelial Growth

The phenomenon of fungistasis was first described by Dobbs and Hinson (1953), which can be due to the negative influence of bacterial volatiles on germination and growth of soil-borne fungi. McCain (1966) showed that volatiles produced by *Streptomyces griseus* induced early sclerotia formation in *Sclerotium cepivorum* and *Rhizoctonia solani*, and

Table 3 Compilation of VOC producing fungi

Species	Tax ID (NCBI)	VOC Synonym	References
Acremonium obclavatum	132114	Acetone, Benzene, Ethanol, 2-Butanone, 2-Ethylhexanol, Pentane, Cyclohexane, Limonene, Arsenous acid, Cyclotrisiloxane	Ezeonu et al., 1994
Agaricus bisporus	5341	Isovaleric acid	Stotzky and Schenk, 1976
Agaricus campestris	56157	2,3-Dimethyl-1-pentene	
Alternaria alternata	5599	2-Methylpropanol, 2-Ethylhexanol, 2-Methylbutanol, 1-Octen-3-ol, 3-Methylbutanol, Methyl-2-ethyl hexanoate, 3-Octanone	van Lancker et al., 2008
Alternaria spp.	5598	1-Octen-3-ol, 3-Methylbutanol, 3-Octanone, 2-Octen-1-ol	Kaminski et al., 1974
		Ethylbenzene, 1-Penten-3-ol, 2-Methyl-1-propanol, 2-Methyl-1-butanol, 3-Methylfuran, Thujopsene, Dimethylbenzene	Börjesson et al., 1992
		Methoxybenzene, 1-Ethyl-2-methylbenzene, 1-Octen-3-ol, 3-Methyl-1-heptene, 2-Methyl-1-propanol, 2-Methyl-1-butanol, 3-Methyl-1-butanol, Hexanoic acid ethyl ester, 3-Cyclohepten-1-one, 3-Octanone, 2,3,5-Trimethylfuran, 1,3,6-Octatriene	Fischer et al., 1999
Aspergillus clavatus	5057	Ethylene	Stotzky and Schenk, 1976
Aspergillus flavus	5059	1-Octanol, 3-Octanol, 1-Octen-3-ol, 3-Methylbutanol, 3-Octanone	
		Nitromethane, 2-Methyl-1-propanol, Ethylbenzene, 1-Penten-3-ol, 3-Methylfuran, Limonene, Thujopsene, 1,3-Octadiene, Dimethylbenzene	Börjesson et al., 1992
Aspergillus fumigatus	746128	2-Methyl-1-propanol, Camphene, Alpha-Pinene, 2-Methyl-1-butanol, 3-Methyl-1-butanol, Citronellol, Limonene, alpha-Farnesene, trans-beta-Farnesene	Fischer et al., 1999
		Methylbenzoate, 2-Ethyl-1-hexanol, 2-Pentanone, 2-Heptanone, Butoxyethoxyethanol, 3-Octanol, 2-Nonanone, 1-Octen-3-ol, 2-Pentanol, 3-Octanone, 2-Nonen-1-ol, 3-Methyl-1-butanol	Matysika et al., 2008
Aspergillus glaucus	40379	1-Octen-3-ol, 2,4-Pentadione, 3-Octanone	Menetrez and Foarde, 2002
Aspergillus niger	5061	2-Methyl-1-propanol, Styrene, 2-Pentanone, Ethylacetate, 1,3-Pentadiene, 2-Pentanol, 3-Methyl-1-butanol	Nieminen et al., 2008
		2-Methyl-1-propanol, 2-Pentanone, 2-Heptanone, 3-Octanol, 3-Octanone, 3-Methylfuran, 1-Octen-3-ol, Pentadecene, Ethyltiglate, 1,3-Nonadiene, iso-Amyltiglate, 2-Pentanol, 3-Methyl-1-butanol	Matysika et al., 2008
		3-Octanol, 1-Octen-3-ol, 3-Methylbutanol, 2-Octen-1-ol, 3-Octanone	Kaminski et al., 1974
Aspergillus ochraceus	40380	1-Octanol, 3-Octanol, 1-Octen-3-ol, 3-Methylbutanol, 3-Octanone, 2-Octen-1-ol	Kaminski et al., 1974
Aspergillus oryzae	5062		
Aspergillus parasiticus	5067		
Aspergillus spp.	5052	Dimethylselenide	Stotzky and Schenk, 1976
Aspergillus versicolor	46472	Benzene, Ethanol, Methylbenzene, Cyclotetrasiloxane, Xylene, Cyclotrisiloxane, 2-Ethylhexanol, 1,3-Dimethoxybenzene, Limonene	Ezeonu et al., 1994
		Ethylbenzene, 1-Penten-3-ol, Thujopsene, Dimethylbenzene, 3-Methylfuran, Limonene, 2-Methyl-1-propanol, 3-Methyl-1-butanol, 1,3-Octadiene	Börjesson et al., 1992
		Anisole, 1-Octene, 3-Methoxyanisole, 3-Methyl-2-butanone, 3-Methyl-2-pentanone, Dimethyldisulfide, 3-Methyl-3-buten-1-ol, 1,3-Pentadiene, 4-Methyl-3-hexanone, 3-Octanone, 3-Methylfuran, 2-Ethylhexanol, 3-Octanol, 1-Octen-3-ol, 2-Methyl-1-propanol, 5-Ethyl-4-methyl-3-heptanone	Sunesson et al., 1995
		2-Ethyl-1-hexanol, 2-Pentanone, 2-Heptanone, 2,6-di-tert-Butyl-p-benzoquinone, 2-Nonanone, 2-Pentanol, 3-Octanone, 1,3-Dimethoxybenzene, 3-Octanol, 1-Octen-3-ol, 1,3-Octadiene, 5-Ethyl-4-methyl-3-heptanone	Matysika et al., 2008
		2-Methyl-1-butanol, 6-Methyl-2-heptanone, alpha-Muurolene, γ- Curcumene, 1-Octen-3-ol Limonene, 3-Methyl-1-butanol	Fischer et al., 1999

Table 3 (continued)

Species	Tax ID (NCBI)	VOC Synonym	References
		2-Methylbutanol, 3-Methylbutanol, Methyl-2-ethyl hexanoate, 2-Ethylhexanol, 1-Octen-3-ol, 1,3-Octadiene	van Lancker et al., 2008
		1,3-Dimethoxybenzene, 3-Octanol, 1-Octen-3-ol	Menetrez and Foarde, 2002
		2-Methyl-1-propanol	Wilkins et al., 2000
Aureobasidium pullulans	5580	Ethanol	Stotzky and Schenk, 1976
Bjerkandera adusta	5331	Phenyl pyruvate, 2-Hydroxy-3-phenylpropionic acid, Cinnamic acid,	Schulz and Dickschat, 2007
Blastomyces dermatitidis	5039	Ethylene	Stotzky and Schenk, 1976
Boletus variegatus	48592	Acetoin, Ethanol, Isobutanol, Isobutyric acid, 3-Methylbutanol	
Candida humicola	109387	Dimethylselenide, Trimethylarsine, Dimethylarsine	
Candida tropicalis	5482	Acetic acid, Acetaldehyde, Acetone, 1-Butanol, Ethanol, Methanethiol, Methanol, 2-Butanone, 2-Methyl-1-butanol	Bunge et al., 2008
Cephalosporium spp.	81097	3-Octanol, 1-Octen-3-ol, 3-Methylbutanol, 3-Octanone, 2-Octen-1-ol	Kaminski et al., 1974
Ceratocystis fagacearum	72029	Acetaldehyde, Ethyl propionate, Propyl acetate, Isobutyl acetate, Methyl isovalerate, Methyl butyrate, Butyl acetate	Lin and Phelan, 1992
Ceratocystis fimbriata	5158	Ethylene	Stotzky and Schenk, 1976
Ceratocystis spp.	5157	Acetone, Ethanol, Formaldehyde, 2-Methylpropanal, 2-Methylbutanal, Furfural, 2-Heptanone, Ethyl acetate, 2-Hexenal	
Cladosporium cladosporoides	29917	Phenylethylalcohol, 1-Pentanol, 2-Pentanone, 2-Heptanone, 1-Octene, 3-Octanol, 3-Methyl-3-buten-1-ol, 1-Octen-3-ol, 2-Pentanol, Pentadecene, 3-Methyl-1-butanol, 3-Octanone, 1,3-Nonadiene, Tetradecene	Matysika et al., 2008
		3-Pentanone, 1-Octene, 3-Methylfuran	Sunesson et al., 1995
Cladosporium sphaerospermum	92950	Alpha-Humulene, Tetramethyltetrahydrofuran	Menetrez and Foarde, 2002
Cladosporium spp.	5498	2-Pentanone	Nieminen et al., 2008
Daedalea juniperina	239201	Anisaldehyde	Stotzky and Schenk, 1976
Dipodascus aggregatus	44075	Ethyl propionate, Ethyl acetate	
Emericella nidulans	162425	2-Methyl-1-propanol, 2-Methyl-1-butanol, alpha-Terpinolene, 1-Octen-3-ol, Limonene, 3-Methyl-1-butanol, 2,3-Dimethyl-butanoic acid methyl ester, Cyclooctene	Fischer et al., 1999
Emericella spp.	5071	Styrene, 2-Pentanone, 2-Heptanone, 2-Pentanol, 3-Methyl-1-butanol, 1,3-Pentadiene	Nieminen et al., 2008
Fistulina hepatica (Schaeffer: Fr.)	40457	Benzaldehyde, 1-Butanol, Butanoic acid, Octanal, 1-Octanol, Hexadecanoic acid, Phenylacetaldehyde, Phenylacetic acid, 1,8-Cineole, Decanoic acid, Hexanal, Linalool, 2-Methyl-1-propanol, 2-Methyl-propanoic acid, Benzoic acid methyl ester, 2-Methyl-pentanoic acid, 2-Ethyl-1-hexanol, Citronellal, Pentanoic acid, Nonanoic acid, 1-Dodecanol, Methyl stearate, Hexanoic acid, 6-Methyl-5-hepten-2-one, Sabinene, 1-Octen-3-ol, Limonene, Isopropyl dodecanoate, 4-Hydroxy-4-methyl-2-pentanone, Isoamylalcohol, 1-Octen-3-one, (+)-Cuparene, Bisabololoxide B, (E)-2-Methyl-2-butenoic acid, 3-Octanone, Cinnamicaldehyde, (Z)-2-Methyl-2-butenoic acid, (E)-2-Heptenal, (E)-2-Octenal, (E)-Nerolidol	Wu et al., 2005
Fomes annosus	13563	Hexa-1,3,5-triene	Stotzky and Schenk, 1976
Fomes pomaceus	123902	Methylbromides	
Fomes spp.	40441	Ethanol, Methylbromides, Methylchloride, Isobutanol	
Fusarium sambucinum	5128	Beta-Santalene, beta-Himachalene, beta-Chamigrene, alpha-Bergamotene, Acoradiene, Ar-Curcumene, Elixene, Trichodiene, Longifolene, beta-Bisabolene, beta-Selinene, Di-epi-alpha-Cedrene, alpha-Farnesene, beta-Farnesene	Jelen et al., 1995

Table 3 (continued)

Species	Tax ID (NCBI)	VOC Synonym	References
Fusarium spp.	5506	1-Octen-3-ol, 3-Methylbutanol, 3-Octanone	Kaminski et al., 1974
Mucor hiemalis	64493	Ethylene	Stotzky and Schenk, 1976
Mucor plumbeus	97098	2-Methyl-1-propanol, 2-Pentanone, Ethyl acetate, Ethyl-2-methyl butyrate, 3-Methyl-1-butanol	Nieminen et al., 2008
Muscodor albus	152623	Acetone, Phenylethylalcohol, 2-Methyl-1-propanol,, 2-Butanone, Acetic acid, methyl ester, 2-Methyl-propanoic acid, Tetrahydrofuran,, Acetic acid ethyl ester, 2-Methylfuran, 2-Methylpropanoic acid methyl ester, 3-Methyl-1-butanol acetate, 4-Nonanone, Aciphyllene, Caryophyllene	Atmosukarto et al., 2005
Muscodor fengyangensis	910323	Phenylethylalcohol, 2-Methyl-propanoic acid, 3-Methyl-6-(1-methylethyl)- 2-cyclohexen-1-one, alpha-Phellandrene, Acetic acid 2-phenylethyl ester, Acetic acid 2-methylpropyl ester, 1-Ethenyl-1-methyl-2,4-bis(1-methylethenyl)-,[1S-(1-alpha,2-beta.,4-beta)]- cyclohexane, 2-Methylpropanoic acid methyl ester, beta-Phellandrene, Caryophylleneoxide, 3-Methyl-1-butanol, 3-Methyl-1-butanol acetate, 3,5-Dimethoxytoluene, 2-Cyclohexen-1-ol, cis-3-Methyl-6-(1-methylethyl)-2-Cyclohexen-1-ol, trans-3-methyl-6-(1-methylethyl)-2-Cyclohexen-1-ol, 2,6-Dimethyl-6-(4-methyl-3-pentenyl)-bicyclo[3.1.1]hept-2-ene, 2,6-Dimethyl-6-(4-methyl-3-pentenyl)-bicyclo[3.1.1]hept-2-ene, 1-Methyl-4-[5-methyl-1-methylene-4-hexenyl)-[S]- cyclohexene, cis-1-Methyl-4-(1-methylethyl)-2-cyclohexen-1-ol, Isoaromadendrene epoxide, Diepicedrene-1-oxide, 2-Methylene-4,8,8-trimethyl-4-vinyl-bicyclo[5.2.0]nonane, 3,3,7,11-Tetramethyl-tricyclo[6.3.0.0(2,4)]undec-8-ene, Caryophyllene, cis-alpha-Bisabolene, Caryophyllene-[I1]	Zhang et al., 2010
Paecilomyces variotii	45996	Acetone, 2-Pentanone, Propylacetate, 2-Heptanone, 1-Hexanol, 3-Methyl-2-pentanone, 2-Hexanone, 1-(1,1-Dimethylethyl)-4-ethylbenzene, 2-Methyl-1-propanol, 3-Methyl-1-butanol, 2,5-Dimethylfuran, 3-Methylfuran, 2,3,5-Trimethylfuran	Sunesson et al., 1996
		Octane, 2-Propanol, 2-Butanone, Methylacetate, Furan, Trimethylbenzene, 2-Methylpropyl formate, 2,4-Dimethylfuran, 1-Methylpropylformate, alpha-Curcumene, 2-Methyl-1,3-pentadiene, 2-Methyl-1-propanol, 3-Methyl-1-butanol, 2-Methyl-1-butanol, 2,5-Dimethylfuran, 3-Methylfuran, Xylene	Sunesson et al., 1995
		alpha-Phellandrene, alpha-Terpinene, beta-Phellandrene, γ-Cadinene, Myrcene, Germacrene B, neo-allo-Ocimene, Megastigma-4,6(e),8(Z)-triene, +alpha-Longipinene, 2-Methyl-1-propanol, 3-Methyl-1-butanol, 2-Methyl-1-butanol, 2,3,5-Trimethylfuran	Fischer et al., 1999
Penicillium aurantiogriseum	36655	Acetic acid, Ethanol, 1-Propanol, 2-Methyl-1-propanol, 3-Methylfuran, 1-Octen-3-ol, 3-Methyl-1-butanol, 3-Octen-2-ol	Börjesson et al., 1990
Penicillium brevicompactum	5074	Acetone, 2-Propanol, 2-Butanone, 3-Pentanone, 3-Methylfuran, 2-Methyl-1-propanol, 2-Methyl-1-butanol	Börjesson et al., 1992
		Styrene, 1-Octen-3-ol, Limonene, 3-Methyl-1-butanol, 2-Methyl-1-propanol, 2-Methyl-1-butanol	Fischer et al., 1999
Penicillium chrysogenum	5076	Acetic acid, Ethanol, 2-Propanol, Isoprene, 2-Methyl-1-propanol, 2-Butanol, 2-Butanone, alpha-Pinene, 3-Pentanone, 1-Pentene, 2-Octanone, 1-Dodecene, 2-Methyl-1-butanol, 2-Heptanol, 3-Pentanol, 2-Hexanone, 1-Hexene, Dimethyldisulfide, 2-Hexanol, 2-Nonanol, 1-Undecene, Methyl-2-methylbutyrate, beta-Pinene, 1-Tridecene, 2-Octanol, Nonadiene, 2-Pentanone, 3-Methyl-1-butanol 2-Heptanone, 1-Octene, 1-Heptene, 2-Nonanone, 1-Pentadecene, 1-Nonene, 1-Octen-3-ol, 1,3-Octadiene	Wilkins et al., 2000
		1-Octanol, 2-Octen-1-ol, 3-Octanol, 1-Octen-3-ol, 3-Methyl-1-butanol, 3-Octanone	Kaminski et al., 1974
		3-Methylanisole, 1,3-Dimethoxybenzene, Hexadecane, 2-Pentanol, Geosmin, 1,4-Dimethoxy-2-methylbenzene, Ethyltiglate, 1,3-Nonadiene, iso-Amyltiglate, 2-Pentanone, 2-Heptanone, 1-Octene, 1-Heptene, 2-Nonanone, 1-Pentadecene, 1-Nonene, 2-Methylbutanol, 3-Octanol, 1-Octen-3-ol, 3-Methyl-1-butanol, 3-Octanone, 1,3-Octadiene, Tetradecene	Matysika et al., 2008
		2-Ethylhexanol, 2-Methylbutanol, 3-Octanol, 1-Octen-3-ol, 3-Methyl-1-butanol, 1,3-Octadiene	van Lancker et al., 2008
		1-Octen-3-ol, 3-Octanone, Tetradecene	Menetrez and Foarde, 2002
Penicillium citrinum	5077	1-Octanol, 3-Octanol, 1-Octen-3-ol, 3-Methylbutanol, 3-Octanone, 2-Octen-1-ol	Kaminski et al., 1974

Table 3 (continued)

Species	Tax ID (NCBI)	VOC Synonym	References
Penicillium clavigerum	29841	2-Methyl-1-propanol, alpha-Terpinene, Styrene, 2-Methyl-1-butanol, Dimethyldisulfide, Limonene, Myrcene, 3-Methyl-1-butanol, Bicyclo-(3.2.1)-octan-2-one, beta-Caryophyllene, beta-Elemene	Fischer et al., 1999
Penicillium commune	36653	Acetone, Dimethylsulfide, Cresol, Camphene, alpha-Pinene, Ethyl propanoate, Ethyl butanoate, Propyl acetate, 2-Methylpropyl acetate, Cyclopentanone, 2-Methyl-1-butanol, Ethyl acetate, Heptane, 3-Methylfuran, beta-Pinene, Limonene, Ethyl-2-methyl butanoate, 3-Methylbutylacetate, Methyl-(1-methylethenyl)benzene, alpha-Curcumene, Ethanthioic acid-S-(2-methyl)butyl ester	Sunesson et al., 1995
		2-Ethyl-1-hexanol, 2-Pentanone, 2-Heptanone, 1-Hexanol, 2-Methyl-1-butanol, 1-Octen-3-ol, Dimethyltrisulfide, Geosmin, 1-Methoxy-4-(1-methylethyl)benzene, 1-Methoxy-3-methylbutane, 3-Octanone	Sunesson et al., 1996
		2-Methyl-1-propanol, 2-Butanone, Methyl acetate, 3-Methylanisole, Dimethyldisulfide, 2,5-Dimethylfuran, 3-Methyl-1-butanol	Sunesson et al., 1995, 1996
Penicillium crustosum	36656	2-Methyl-1-propanol, Styrene, Dodecane, 2,5-Dimethylfuran, 2-Ethylfuran, Limonene, 3-Methyl-1-butanol, 2,3,5-Trimethylfuran	Fischer et al., 1999
Penicillium cyclopium	60167	2-Methyl-1-propanol, 2,5-Dimethylfuran, γ-Cadinene, 2-Methylenebornane, 2-Methyl-2-bornene, 2,3,5-Trimethylfuran, Cyclooctene, Germacrene A	
Penicillium digitatum	36651	Ethane, Ethylene, Acetylene, Propane, Propylene	Stotzky and Schenk, 1976
Penicillium expansum	27334	1-Pentanol, 2-Methyl-1-propanol, 3-Methylanisole, 2-Ethyl-1-hexanol, 2-Pentanone, 2-Heptanone, 2-Methyl-1-butanol, 3-Octanol, Dimethyldisulfide, alpha-Terpineol, 1-Octen-3-ol, 2-Pentanol, 3-Octanone, 1,3-Octadiene	Matysika et al., 2008
		Styrene, 1-Methoxy-3-methylbenzene, Aromadendrene, Elemol, Germacrene B, γ Curcumene, Bicycloelemene	Fischer et al., 1999
		Geosmin	Mattheis and Roberts, 1992
Penicillium funiculosum	28572	1-Octen-3-ol, 3-Methylbutanol, 3-Octanone, 2-Octen-1-ol	Kaminski et al., 1974
Penicillium glabrum	69773	2-Methyl-1-propanol, 2-Butanone, 3-Pentanone, 2-Methyl-1-butanol, 3-Methylfuran, 1-Octen-3-ol, 3-Octanone, 1,3-Octadiene, Dimethylbenzene, Limonene	Börjesson et al., 1992
		Styrene, 2-Methyl-1-butanol, 3-Methyl-1-butanol, Limonene	Fischer et al., 1999
Penicillium italicum	40296	Methylbutenone, Cedrol, Cedrene	Menetrez and Foarde, 2002
Penicillium raistrickii	69783	1-Octen-3-ol, 3-Methylbutanol, 3-Octanone, 2-Octen-1-ol	Kaminski et al., 1974
Penicillium roqueforti	5082	Toluene, 2-Methylpropanoic acid, Acetic acid 2-methylpropyl ester, Heptane, 3-Methyl-1-butanol, Isoamylacetate, 1,3-Octadiene, Xylene	Jelen et al., 1995
		2-Methyl-1-propanol, 2-Methyl-1-butanol, 3-Methylfuran, Dimethylbenzene, Limonene, 3-Octanone, 1,3-Octadiene	Börjesson et al., 1992
		Alpha-Phellandrene, Styrene, 3-Octanol, Undecane, beta-Himachalene, 1-Octene-3-ol, 3-Carene, beta-Myrcene, (+)-2-carene, beta-Patchoulene, Aristolochene, Di-epi-alpha-cedrene, beta-Elemene, beta-Bisabolene, Limonene, 3-Octanone	Jelen 2003
Penicillium spp.	5073	2-Methyl-1-propanol, Styrene, 2-Pentanone, Ethylacetate, 2-Pentanol, Ethyl-2-methylbutyrate, 3-Methyl-1-butanol, 1,3-Pentadiene, 2-Heptanone	Nieminen et al., 2008
		4-Allylanisole, 2-Heptanone	Bjurman et al., 1997
		Dimethylselenide	Stotzky and Schenk, 1976
Penicillium variabile	28576	2-Ethylhexanol, 2-Heptanone, 2-Ethylhexanoic acid, 2-Methylbutanol, Terpinolene, 3-Octanol, 1-Octen-3-ol, 3-Methylbutanol, Methyl-2-ethyl hexanoate, 3-Octanone, 1,3-Octadiene	van Lancker et al., 2008
Penicillium viridicatum	60134	1-Octanol, 3-Octanol, 3-Octanone, 2-Octen-1-ol, 1-Octen-3-ol, 3-Methylbutanol	Kaminski et al., 1974

Table 3 (continued)

Species	Tax ID (NCBI)	VOC Synonym	References
		2-Ethylhexanol, 2-Methylbutanol, 2-Ethylfuran, 2-Pentylfuran, 1,3-Octadiene, 1-Octen-3-ol, 3-Methylbutanol	van Lancker et al., 2008
Phellinus spp.	40470	Benzylalcohol, Methyl salicylate, Phenylethylalcohol, Methyl benzoate, Ethyl benzoate	Stotzky and Schenk, 1976
Phialophora fastigiata	91935	Acetone, 2-Butanone, Methyl benzoate, Cyclopentanone, Methyl-3-methyl butanoate, Dimethyldisulfide, 1-Octen-3-ol, 3-Methyl-1-butanol, 3-Octanone, Caryophyllene	Sunesson et al., 1995
Puccinia graminis var. tritici	5297	Acetaldehyde, Furfural, Trimethylethylene, n-Nonanal, Methyl ferulate	Stotzky and Schenk, 1976
Rhodotorula glutinis	5535	Phenylethylalcohol, 2-Methyl-1-propanol, 3-Methyl-2-butanol	Menetrez and Foarde, 2002
Saccharomyces cerevisiae	4932	Acetic acid, 2-Propanone, 1,2-Benzenedicarboxylic acid, 2-Propanol, Phenylethylalcohol, 2-Methyl-1-propanol, 2-Butanone, 2-Methyl-propanoic acid, 1,2-Dimethylbenzene, 2-Ethyl-1-hexanol, 2-Pentanone, Acetic acid ethenyl ester, 2-Methyl-butanoic acid, Pyrazine, 3-Methyl-butanoic acid, Dimethyldisulfide, Undecane, Limonene, 2,5-Dimethylpyrazine, Ethanol, Ethylacetate	Bruce et al., 2004
		Acetaldehyde, n-Propanol, Isobutanol, Ethanol, Ethylacetate	Stotzky and Schenk, 1976
Schizophyllum commune	5334	Methylmercaptan, Dimethylselenide	Stotzky and Schenk, 1976
Scopulariopsis brevicaulis	40375	Dimethylselenide, Trimethylarsine, Dimethylarsine	
Stachybotrys chartarum	74722	1-Butanol, 2-Propanol, Isoprene, 2-Methyl-1-propanol, 2-Butanol, Methyl benzoate, Anisole, m-Methylanisole, Methyl-2-methyl propionate, Dimethyldisulfide, 3-Methylfuran, o-Methylanisole, Dimethylhexadiene	Wilkins et al., 2000
Staphylococcus xylosus	1288	Pyridine	Matysika et al., 2008
Thielaviopsis basicola	124036	Acetone, Ethanol, Formaldehyde, 2-Methylpropanal, 2-Methylbutanal, Furfural, 2-Heptanone, Ethyl acetate, 2-Hexenal	Stotzky and Schenk, 1976
Tilletia caries	13290	Trimethylamine	Stotzky and Schenk, 1976
Tilletia controversa	13291	Trimethylamine	
Tilletia foetida	157183	Trimethylamine	
Trichoderma atroviride	63577	Phenylethylalcohol, α-Phellandrene, γ-Terpinene, α-Terpinene, 2-Heptanone, 2-Undecanone, β-Phellandrene, α-Terpinolene, 3-Octanol, 2-Nonanone, 1-Octen-3-ol, 2-Pentylfuran, 2-n-Heptylfuran, 6-Pentyl-α-pyrone, α-Bergamotene, α-Zingiberene, 3-Octanone, β-Bisabolene, α-Curcumene, p-Menth-2-en-7-ol, α-Farnesene, β-Farnesene, Nerolidol, γ-Curcumene, β-Sesquiphellandrene	Stoppacher et al., 2010
Trichoderma aureoviride	64502	Acetaldehyde, Acetone, Benzylalcohol, Chloroform, Isobutane, 2-Methyl-1-propanol, 2-Ethyl-4-methyl-1-pentanol, Heptanone, Nonane, Heptane, Decane, 2,4-Dimethylheptane, 3-Methyl-2-hexanol, 7-Octen-4-ol, 5-Methyl-5-hexen-3-ol, 1,3-Hexadien-5-yne	Bruce et al., 2000
Trichoderma pseudokoningii	317029	2-Propanone, Butanal, 1-Butanol, Octane, 1-Propanol, Hexanal, 1-Pentanol, Acetonitrile, 2-Methyl-1-propanol, 2-Butanone, p-Xylene, 2-Methylpentane, Methyl-cyclohexane, Hexane, n-hexane, 2-Octanone, 1-Hexanol, Heptanal, Formic acid heptyl ester, Decanal, 2-Methyl-butanol, Acetic acid ethyl ester, Heptane, Limonene, 3-Methyl-1-butanol, 2-Propyl-1-pentanol, 2-Octen-1-ol, 2,2,4,6,6,-Pentamethyl-3-heptene, 2-Propenylidene-cyclobutene	Wheatley et al., 1997
Trichoderma spp.	5543	Acetaldehyde, Acetone, Ethanol	Stotzky and Schenck, 1976
		Styrene, 2-Pentanone, 3-Methyl-1-butanol, 1,3-Pentadiene	Nieminen et al., 2008
Trichoderma viride	5547	2-Propanone, Benzaldehyde, Butanal, 1-Butanol, Octane, Propanal, 1-Propanol, Isopropyl-alcohol, Hexanal, Acetonitrile, 2-Butanone, Benzothiazole, p-Xylene, Methyl-cyclohexane, 2-Heptanone, Hexane, 2-Octanone, Heptanal, Decanal, 2-Methyl-1-butanol, Acetic acid 2-ethyl ester, Heptane, 6-Methyl-5-hepten-2-one, 3-Methylhexane, 4-Penten-2-ol, Pentadecane, 3-Methyl-1-butanol, Nonanal, 2-Propyl-1-pentanol, 2,4,6-Trimethyl-1-nonene, Caryophyllene, 2-Methyl-1-propanol	Wheatley et al., 1997

Table 3 (continued)

Species	Tax ID (NCBI)	VOC Synonym	References
		2-Propanol, 1-Pentanol, 2-Hexanone, 3-Methylfuran, 2-Methyl-1-propanol	Wilkins et al., 2000
Tuber aestivum	59557	Acetaldehyde, Acetone (2-Propanone), 1-Butanol, Ethanol, 1-Propanol, Dimethylsulfide, 2-Methyl-1-propanol, 2-Butanol, 2-Butanone, Acetic acid methyl ester, Propanoic acid ethyl ester, Propanoic acid propyl ester, 2-Methyl-1-butanol, Acetic acid ethyl ester, Butanoic acid methyl ester, Acetic acid 2-methylbutyl ester, 4-Hydroxy-3-methyl-2-butanone, 2-Methyl-ethyl-butanoic acid	March et al., 2006
Tuber brumale	60458	Acetaldehyde, Acetone (2-Propanone), 1-Butanol, Ethanol, Isopropylalcohol, 2-Methyl-1-propanol, 2-Butanol, 2-Butanone, Acetic acid methyl ester, 1-Methoxy-3-methylbenzene, Propanoic acid ethyl ester, Butanoic acid ethyl ester, Butanoic acid propyl ester, Propanoic acid propyl ester, 2-Methyl-1-butanol, Acetic acid ethyl ester, Butanoic acid methyl ester, Butanoic acid-1-methylpropyl ester, 4-Hydroxy-3-methyl-2-butanone, Butanoic acid 2-methyl-ethyl ester	March et al., 2006
Tuber melanosporum	39416	Acetaldehyde, Acetone (2-Propanone), 1-Butanol, 1-Propanol, Isopropylalcohol, 2-Methyl-1-propanol, Acetic acid methyl ester, Propanoic acid ethyl ester, Butanoic acid propyl ester, Propanoic acid propyl ester, Acetic acid-1-methylethyl ester, 2-Methyl-1-butanol, Acetic acid ethyl ester, Butanoic acid methyl ester, Butanoic acid 2-methyl- methyl ester, 4-Hydroxy-3-methyl-2-butanone, Butanoic acid 2-methyl-ethyl ester, Pentanoic acid 4-methyl- ethyl ester, 2-Methyl-3-ethyl-2-pentene, Ethanol, Dimethylsulfide, 2-Butanol	March et al., 2006
		2-Butanone, 3-Octanol, bis(Methylthio)methane, 1-Octen-3-ol, 1-Octen-3-one, 3-Octanone, Ethanol, Dimethylsulfide, 2-Butanol	Pelusio et al., 1995
Tuber mesentericum	92904	Acetaldehyde, Acetone (2-Propanone), 1-Butanol, Ethanol, 1-Propanol, Dimethylsulfide, 2-Methyl-1-propanol, 2-Butanol, 2-Butanone, Acetic acid methyl ester, 1-methoxy-3-methylbenzene, Propanoic acid ethyl ester, Butanoic acid propyl ester, Propanoic acid propyl ester, 2-Methylbutan-1-ol, Acetic acid ethyl ester, 3-Methyl-butanal, Butanoic acid methyl ester, 2-Methylbutyric acid methyl ester, 2-Methylbutyric acid ethyl ester, 2-Methyl-3-ethyl-2-pentene	March et al., 2006
Tuber rufum	119233	Acetaldehyde, Acetone (2-Propanone), 1-Butanol, Ethanol, Dimethylsulfide, Isopropylalcohol, 2-Butanol, 2-Butanone, Acetic acid methyl ester, Propanoic acid ethyl ester, Butanoic acid ethyl ester, Butanoic acid propyl ester, Propanoic acid propyl ester, 2-Propyl acetate, Acetic acid propyl ester, 2-Methyl-1-butanol, Acetic acid ethyl ester, Propanoic acid methyl ester, Butanoic acid methyl ester, 2-Methylbutyric acid methyl ester, 4-Hydroxy-3-methylbutan-2-one, 2-Methylbutyric acid ethyl ester, Acetic acid butyl ester, N-methylene-ethenamine	March et al., 2006
Ulocladium chartarum	119957	2-Methylpropanol, 2-Pentanone, 2-Heptanone, 2-Ethylhexanoic acid, 2-Methylbutanol, 2-Hexanone, Dimethyldisulfide, 2-Nonanone, 6-Methyl-2-heptanone, 5-Methyl-2-heptanone, 3-Methylbutanol, Methyl 2-ethyl hexanoate	van Lancker et al., 2008

The name of the volatile producing species corresponds to a taxonomy ID (http://www.ncbi.nlm.nih.gov/taxonomy) reduced sporulation in *Gloeosporium aridum*. A strong inhibition of spore germination of *Cladosporium cladosporioides* was caused by but-3-en-2-one produced by *Streptomyces griseoruber* (Herrington et al., 1987). Zou et al. (2007) screened 1080 bacterial isolates for fungistatic activity. A total of 328 isolates belonging to the family of *Rhizobiaceae*, *Xanthomonadaceae*, *Micrococcaceae*, *Alcaligenaceae*, and to the order of *Bacillales* were identified as decreasing germination and mycelial growth of *Paecilomyces lilacinus* and *Pochonia chlamydosporia*. The spore germination of both fungi also was strongly inhibited by soil direct fungistasis and soil volatile fungistasis. Both effects correlated closely with impaired spore germination and disappeared after autoclaving. Several volatiles were identified, and trimethylamine, benzaldehyde, and N,N-dimethyloctylamine showed strong antifungal activity (Chuankun et al., 2004).

In order to identify bacterial isolates specifically antagonistic to plant pathogens, many *in vitro* experiments have been done. The experimental setup had to ensure that only volatile metabolites would influence fungal growth. Split Petri dishes (Fernando et al., 2005; Kai et al., 2007; Vespermann et al., 2007), separated agar patches (Alharbi et al., 2011), or the inversion of one bottom plate over a second one (Bruce et al., 2000) assured the exchange of volatiles solely in the headspace. Vespermann et al. (2007) and Kai et al. (2007 and 2008) conducted a comprehensive investigation using *Bacillus subtilis*, *Pseudomonas fluorescens*, *Pseudomonas trivialis*, *Burkholderia cepacia*, *Staphylococcus epidermidis*, *Stenotrophomonas maltophilia*, *Stenotrophomonas rhizophila*, *Serratia odorifera*, and *Serratia plymuthica* against pathogenic fungi, including *Aspergillus niger*, *Fusarium culmorum*, *Fusarium solani*, *Microdochium bolleyi*, *Paecilomyces carneus*, *Penicillium waksmanii*, *Phoma betae*, *Phoma eupyrena*, *Rhizoctonia solani*, *Sclerotinia sclerotiorum*, *Trichoderma strictipile*, and *Verticillium dahliae*. All rhizobacteria inhibited the mycelial growth of most fungi. The extent of inhibition depended on the individual bacteria-fungus combination. Noticeably, *Fusarium solani* turned out to be resistant against the bacterial volatiles. The spectra of bacterial volatiles produced included many unknown components; however, 2-phenylethanol, 1-undecene, dodecanal, dimethyl disulfide (DMDS), and dimethyl trisulfide (DMTS) could be identified (Kai et al., 2007). DMDS and 1-undecene indeed inhibited the growth of *F. culmorum* when applied as individual compounds in dual-culture tests (Kai et al., 2009). Several other reports also confirmed the antifungal action of volatiles produced by antagonistic rhizobacteria. *Pseudomonas fluorescens* and *Pseudomonas pumila* inhibited most effectively the growth of *Gaeumannomyces graminis* var *tritici*, the cause of take-all disease in wheat (Babaeipoor et al., 2011). *Gluconacetobacter diazotrophicus* decreased the growth of *Fusarium oxysporum* (Logeshwarn et al., 2011), *Bacillus pumilus*, *Bacillus subtilis*, and *Bacillus cereus* hindered growth of *Botrytis mali* (Jamalizadeh et al., 2010), and volatiles produced by *Bacillus subtilis* showed antifungal activity towards *Rhizoctonia solani* and *Pythium ultimum* (Fiddaman and Rossall, 1993) and *Aspergillus alternate*, *Cladosporium oxysporum*, *Fusarium oxysporum*, *Paecilomyces lilacinus*, *Paecilomyces variotii*, and *Pythium afertile* (Chaurasia et al., 2005). *Bacillus* spp. impaired the growth of *Phytophthora sojae*, which causes the soybean damping-off disease (Tehrani et al., 2002). Interestingly, the dual application of *Bacillus pumilus* and the mycorrhizal fungus *Glomus mosseae* improved the growth of mandarin plants, directly attributed in part to growth inhibition of fungal pathogens by rhizobacterial volatiles (Chakraborty et al., 2011). The volatiles 1-octen-3-ol, benzothiazol, and citronellol produced by *Paenibacillus polymyxa* strongly inhibited mycelial growth and impaired germination of eight fungal pathogens, including *Botrytis cinerea* (Zhao et al., 2011). Wan et al. (2008) investigated the effect of headspace volatiles of *Streptomyces plantesis* on phytopathogenic fungi. Two antifungal components were identified: 2-phenylethanol and a phellandrene derivative were responsible for the suppression of mycelial growth of *Rhizoctonia solani*, *Sclerotinia sclerotiorum*, and *Botrytis cinerea*. Ascospore germination was suppressed up to 90 % by volatiles released by *Pseudomonas* sp., which were isolated from canola and soybean plants (Fernando et al., 2005). *Staphylococcus pasteuri* showed a significant antifungal activity *in vitro* against *Tuber borchii* and inhibited ectomycorrhizal formation (Barbieri et al., 2005).

Many *Pseudomonas* species are known to produce HCN as an effective antifungal component (Voisard et al., 1989; Haas and Défago, 2005). Although HCN production could be correlated to fungistasis, its antifungal effect often could only be verified *in vitro*. Rhizobacterial isolates were screened for HCN production and diffusible antifungal metabolites, and tested against *Verticilium dahliae* and *Rhizoctonia solani* in dual-culture tests (Tehrani et al., 2001; Afsharmanesh et al., 2006), and subsequently used in greenhouse experiments. Interestingly, HCN producers showed the highest efficiency when applied to the soil, whereas non-producers were more efficient when applied to seeds. Antifungal properties also have been attributed to gaseous ammonia. Schippers et al. (1982) showed that ammonia release from soil as well as from an ammonium sulfate solution inhibited conidia germination of *Botrytis cinerea* and *Penicillium nigricans*. However, some fungi such as *Fusarium culmorum* and *Verticillium nigrescens* were not affected by ammonia. Furthermore, other volatiles released from the soil decreased conidia germination and tube growth of these two fungi. Similarly, Howell et al. (1988) identified ammonia to be the antifungal component in dual-culture tests using *Enterobacter cloacae*, *Rhizoctonia solani*, and *Pythium ultimum*.

Fungal growth promotion by bacterial volatiles has hardly ever been reported. Mackie and Wheatley (1999) and Wheatley (2002) selected four fungi as representative of a range of several habitats and challenged them *in vitro* with headspace volatiles of a variety of randomly selected soil bacteria. The response was unique for each fungal-bacterial combination, and revealed positive, negative, as well as neutral effects on radial growth of *Trichoderma viride*, *Phanaerochaete magnoliae*, *Phytophthora cryptogea*, and *Gaeumannomyces graminis* var *tritici*. Only *P. cryptogea* exhibited a significant increase in growth upon exposure to volatiles of certain bacterial isolates.

Impact of Bacterial Volatiles on Fungal Morphology

Several reports also have focused on morphological changes in fungi following bacterial volatile treatment. Fiddaman and Rosall (1993) observed abnormal hyphae with deformation and enhanced vacuolation in *Rhizoctonia solani* and *Pythium ultimum* exposed to volatiles produced by *Bacillus subtilis*. The same bacterial species caused hyphal and conidial deformations in *Aspergillus alternaria*, *Cladosporium oxysporum*, *Fusarium osysporum*, *Paecilomyces lilacinus*, *Paecilomyces variotii*, and *Pythium afertile*. Transverse and longitudinal septae completely disappeared in *Aspergillus alternaria*, and conidia became thick-walled and irregular in shape. Conidia formation was sometimes arrested, and in *Cladosporium oxysporum*, conidiophores became vegetative and stunted. Swelling of hyphae, vacuolization, and granulation lead finally to lysis of fungal mycelium in *Fusarium oxysporum*, *Paecilomyces lilacinus*, and *Paecilomyces variotii* (Chaurasia et al., 2005). Swollen terminal cells and bulging intercalary cells also were described for *Tuber borchii* upon exposure to volatiles emitted by *Staphylococcus pasteuri* and, finally, fungal mycelium showed swollen and contorted patterns when treated with 1-octen-3-ol (Barbieri et al., 2005). Benzothiazol caused a more frequent branching of the mycelium and increased conidia production, whereas citronellol only induced a slight hyphal contortion. All three compounds were components of the volatile mix produced by *Paenibacillus polymyxa* (Zhao et al., 2011).

Influence of Bacterial Volatiles on Mycorrhizal Fungi

Mycorrhiza is a complex symbiotic community including plant roots, mycorrhizal fungi, and associated bacteria (see Jung et al., 2012, this issue). Not only their physical contact but also the release of bioactive molecules, including volatiles, apparently play a regulatory role in a mycorrhizal network establishment (Bonfante and Anca, 2009). Associated bacteria comprise primarily the mycorrhiza helper bacteria (MHB) as well as rhizobacteria with beneficial or deleterious functions (Bonfante and Anca, 2009; Miransari, 2011). In 1991, Tylka et al. demonstrated that the MHB *Streptomyces orientalis* stimulated spore germination in *Gigaspora margarita* and *Glomus mossae*. Garbaye and Duponnois (1992) proposed that MHB directly stimulate the growth of *Laccaria laccata* by releasing volatile substances. Volatiles emitted by a bacterial isolate originally associated with *Gigaspora margarita* also promoted *in vitro* host fungus growth (Horii and Ishii, 2006), and volatile and diffusible compounds produced by MHB strains obtained from *Glomus clarum* spores stimulated or arrested spore germination, dependent on the bacterial species. Complete inhibition of spore germination, however, was only related to the volatiles (Xavier and Germida, 2003). Aspray et al. (2006) revealed that stimulation of mycorrhiza formation of *Lactarius rufus* required close proximity or contact. Volatiles of the MHB *Paenibacillus* sp. alone had significant negative effects on mycorrhiza formation. Furthermore, volatiles of the MHB *Streptomyces* spp., which actually promoted growth of the ectomycorrhizal fungus *Amanita muscaria*, did not affect mycelial extension rates (Schrey et al., 2005). The antagonist *Bacillus subtilis* JA inhibited significantly the spore germination and hyphal growth of a monoxenic strain of *Glomus etunicatum* in dual-culture experiments (Xiao et al., 2008), whereas volatiles produced by *Klebsiella pneumonia* promoted hyphae extension distantly located from the germinated spores of *Glomus deserticola*. Both organisms were indigenous to the roots of sea oats (Will and Sylvia, 1990).

Impact of Bacterial Volatiles on Fungal Enzyme Activities and Gene Expression

Mackie and Wheatley (1999) and Wheatley (2002) investigated the effect of bacterial volatiles on physiological properties of fungi by monitoring laccase and tyrosinase activity of *Phanaerochaete magnoliae* and *Trichoderma viride* upon exposure to volatiles of three selected soil bacteria isolates (A, B, C). Laccase activity completely ceased in *P. magnolia* in the presence of isolates A, B, C, whereas tyrosinase activity was inhibited only by the presence of isolate B. Isolate B was the only one to affect laccase activity in *T. viride*. The observed decrease in fungal growth correlated with decreased enzyme synthesis rather than inhibition of enzyme activity (Wheatley, 2002). Laccase activity in *Rhizoctonia solani* was induced after co-cultivation with *Pseudomonas fluorescens*. Due to the experimental setup, it was not possible to distinguish between effects of diffusible and volatile metabolites (Crowe and Olsson, 2001). Inhibition of enzyme activities may also be involved in the complete loss of pigmentation after treatment of *Fusarium oxysporum* with citronellol, a compound emitted by *Paenibacillus polymyxa*

(Zhao et al., 2011). In contrast, Kai et al. (2009) observed a dark discoloration of the agar when fungi were exposed to rhizobacterial volatiles.

At present there are few reports that bacterial volatile components may affect gene expression. Minerdi et al. (2008, 2009) demonstrated an indirect volatile mediated effect of bacteria on fungal gene expression. The antagonistic wild type (WT) strain *Fusarium oxysporum* MSA35 lives in symbiosis with associated bacteria of the genera *Serratia*, *Achromobacter*, *Bacillus*, and *Stenotrophomonas*. Volatiles produced by the WT repressed the expression of two putative virulence genes of a pathogenic *Fusarium oxysporum lactucae* strain. When cured of the bacterial symbionts, the WT turned pathogenic and the sesquiterpene caryophyllene was no longer in the headspace of the cured WT. It also was not found in the headspace of the ectosymbionts, so this volatile seems to mediate a mechanism for the antagonistic properties of the *Fusarium oxysporum* WT. However, caryophyllene is only produced by the WT in the presence of the bacterial symbionts.

Possible Mechanisms of Actions of Volatiles

Presently, little is known about mechanisms of action and detoxification of bacterial volatiles in fungi. It is known that the cyanide ions from HCN are potent inhibitors of many metal-containing enzymes, in particular of copper-containing cytochrome c oxidases (Haas and Défago, 2005). However, it remains unclear how most volatiles develop their activity. One scenario relates to the production of melanin (Kai et al., 2009; Zhao et al., 2011). Melanins are known to reinforce the cell wall or accumulate on the cell surface where they develop antioxidative properties and scavenge free radicals. In fungi, melanins are synthesized via the polyketide synthase pathway (Jacobson, 2000), but phenol oxidizing enzymes such as laccases and tyrosinases may also be involved (Williamson, 1997). Intracellular laccases account for detoxification of chemicals (Champagne and Ramsay, 2010). In this regard, the increase of laccase activities reported by Crowe and Olsson (2001) might result from the presence of eligible volatile substrates, whereas the decrease in laccase and tyrosinase activity reported by Mackie and Wheatley (1999) might be a sign of impaired cell homeostasis. This again demonstrates that a deleterious bacterial volatile can be considered a toxin. Fungal cells respond to it as to any other biotic or abiotic stress factors. Whole-genome expression studies conducted in fungal model organisms including *Saccharomyces cerevisiae*, *Candida albicans*, and *Schizosaccharomyces pombe* have revealed that each species responded to environmental stress with an individual change in gene expression. Some species also expressed a common set of genes, referred to as environmental stress response (ESR) (Gasch, 2007). This can include the response to cell wall stress and/or oxidative and osmotic stress. Compounds like gaseous ammonia could be considered a stress factor, impairing cell homeostasis and triggering ESR. On the other hand, sub-inhibitory concentrations of ammonia might play a part in signaling. Ammonia released from bacterial strains has been shown to stimulate *Bacillus licheniformis* to form biofilms and pigmentation (Nijland and Burgess, 2010) and to increase the antibiotic resistance of various gram-positive and gram-negative bacteria (Bernier et al., 2011). Therefore, the ecological role of microbial volatiles may be intrinsically to serve as a signal molecule within and between species. They may also function as chemical 'manipulators' to alter central metabolic pathways, contribute to nutrient scavenging, and participate in developmental processes (Hibbing et al., 2010). Interestingly, ammonia also has been identified as a long-distance signal in *Candida albicans*, warning the colony of approaching starvation (Palková and Váhová, 2003). In this sense, the mode of actions of microbial volatiles should be assessed in more detail.

Effects of Fungal Volatiles on Bacteria

Bacteriostasis, similar to fungistasis, is the inability of bacteria to multiply in soil (Ho and Ko, 1982). Bacteriostasis is influenced by environmental factors such as nutrient supply and habitat conditions, but active volatile inhibitors also may be involved (Davis, 1976). It is known to date that bacteria produce volatiles that inhibit bacterial growth (Brown, 1973; Ko and Chow, 1977; Acea et al., 1988), and that volatiles produced by fungi also affect fungi (Stotzky and Schenck, 1976; Calvet et al., 1992; McAllister et al., 1996; Bruce et al., 2000; Martinez et al., 2004), but fungal volatiles acting on bacteria has not been reported (to the best of our knowledge).

Ecological Significance of Volatile Mediated Bacterial-Fungal Interactions

Suitable microenvironments in soils attract macro- and microbiota that colonize and form microhabitats, thereby creating dynamic microecosystems. Consequently, at least in densely and diversely populated habitats, bacteria and fungi are involved in a 'networking' community characterized by mutualism, commensalism, cooperation, antagonism, competition, and coexistence (Pal and McSpadden Gardener, 2006). Interactions between organisms can be specific or non-specific, but they are mostly multitrophic, thus keeping the microecosystem in balance. This is especially true for the mycorrhizosphere, where rhizobacteria, including plant growth promoting rhizobacteria, mingle with mycorrhizal fungi and their associated bacteria, free living bacteria and fungi, protozoa (amoeba) or metazoa (nematodes), including many phytopathogenic organisms. In this arena, interactions between bacteria and fungi could have a positive or a negative impact on third parties, which is useful if the weakened party is a pathogen and the strengthened party is a valuable member of the community. It is likely that volatile compounds are involved in these phenomena, since many bacterial volatiles affect phytopathogenic fungi directly or indirectly, i.e., as a result of bacterial-fungal interactions, pathogens are affected. In any case, the plant would benefit. An elucidation of this plant-fungus-bacterium network of interactions opens the way for biological control of plant diseases. An impressive example was given by Cao et al. (2011). They showed *in vitro* and *in vivo* that a GFP-tagged *Bacillus subtilis* strain, originally isolated from the rhizosphere of a non-infested cucumber plant, was able to successfully suppress the growth of *Fusarium oxysporum* f. sp. *cucumerinum* by colonizing the root and persisting on the rhizoplane, which is critical for an effective biocontrol in this case of cucumber wilt. Although not explicitly investigated, the authors proposed antibiosis caused by diffusible agents to be at least one mode of action. This, however, does not exclude volatile agents. Other experiments with a *B. subtilis* strain isolated from the rhizosphere of wheat and soybean showed that bacterial volatiles were involved in the biocontrol of *Botrytis mali* and *Phytophthera sojae*, respectively (Tehrani et al., 2002; Jamalizadeh et al., 2010). However, when using rhizobacteria as biocontrol agents, it is apparently important that the biocontrol strain is indigenous to the treated plant species in order to prevent damage of indigenous beneficial fungi (Will and Sylvia, 1990; Xiao et al., 2008).

Volatiles also might be involved in tritrophic interactions comprising bacteria, fungi, and nematodes. *Paenibacillus polymyxa* and *P. lentimorbus* exhibited strong antifungal activities, thereby interfering with the nematode-fungus interaction *Meloidogyne incognita* - *Fusarium oxysporum*, which significantly reduced nematode infestation of tomato plants (Son et al., 2009). In addition, soil bacteria, including one rhizobacterial strain, enhanced the nematophagous activity of the nematode-trapping fungus *Arthrobotrys oligospora* by increasing trap formation and predaceous activity (Duponnois et al., 1998). Volatile signaling cannot be excluded for either experiment.

In their entirety, the emission patterns of volatile metabolites of a belowground microecosystem reflect the dynamics of the community (McNeal and Herbert, 2009). Variations could be related to changes in the microenvironment such as pH, humidity, temperature, nutrient supply, and resulting changes in metabolic activities of micro- and macrobiota. In this respect, *in vitro* studies of volatile-mediated interactions between bacteria and fungi provide only limited access to the overall picture. Artificial test conditions might produce results that cannot be postulated uncritically for natural conditions. This especially applies to artificial growth media and nutrient supplies that influence metabolic activities as well as to “out of range” concentrations of the volatile mediators emitted (Nannipieri et al., 2003; Blom et al., 2011a). The crucial question is: are these concentrations found in the habitat? Since measurements of volatile concentrations in microhabitats are presently not available, *in vitro* testing is a useful tool to reveal substantial relationships between certain partners that might come into contact in a microecosystem. The consideration of environmental conditions and the verification of *in vitro* derived results in *in situ/in natura* experiments will give an overall picture regarding the role of volatiles in bacterial-fungal interactions and the implications of these interactions in community networks.

Conclusion and Perspectives

Volatiles are only a small proportion of the total number of metabolites produced by living organisms. However, because of their unique properties they are predestined to act as infochemicals in intra- and interspecies communications in the atmosphere as well as in the soil. This paper describes the wealth of microbial volatile emissions. The number of microbial volatiles (presently comprising around 800 compounds) and presumably of those with novel structures will increase significantly as this new research field expands. Just consider i) the large number of bacteria and fungi whose volatile profiles have yet not been obtained, ii) the various growth conditions that determine and alter the VOC profiles, and iii) the huge number of not yet identified or isolated microbes (10^6!!). This foreshadows the potential this research area has and where it may develop in the future. It seems very likely that only the “tip of the iceberg” of possible ‘volatile-wired’ interactions between underground bacteria and fungi (and elsewhere) has been seen. It will be a central task in the future to elucidate the plethora of bacterial and fungal VOCs and determine their biological and ecological roles in the soil. It also is quite likely that the naturally produced VOCs can be used as potent non-invasive indicators to study soil microbial ecosystems, including far-reaching spatiotemporal dynamics and environmental perturbations. Ultimately, these microbial volatiles – individually or in mixtures, chemically synthesized or biologically emitted - with their positive and/or negative effects on other organisms may develop into useful agricultural tools.

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