Microbial Volatile Organic Compounds: Applications and Future Prospects

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ABSTRACT
Microbial volatile organic compounds (MVOCs) are organic compounds having low molecular mass (less than 300 Da) and high vapor pressure due to low boiling point. Microorganisms produce a plethora of volatile compounds that can play a very crucial role in intra- and inter-kingdom interactions. Many volatile organic compounds (VOCs) secreted by microbes associated with soil and plants have been described to be involved in microbial communications. A considerable body of opinion indicates that MVOCs have potential to be utilized as a beneficial and good sustainable approach for diverse areas including agriculture, industrial and health sector. They can induce plant defense systems and inhibit the development of diverse plant pathogens.

Key words: Microbial volatile organic compounds, Sustainable strategy, Inter-kingdom interactions, Plant pathogens, Microbial communications.

INTRODUCTION
Volatile organic compounds, shortly known as VOCs are released by microbes as secondary metabolites. Since the last decade, microbial volatile emissions and their future practical applications have gained increased attention. These compounds are produced by several microorganisms ranging from bacteria to fungi and known as microbial volatile organic compounds (MVOCs).¹ In the VOCs database, 600 microbes are already registered that produces 1,300 volatile compounds.² Bacteria and fungi are engaged in multifaceted interactions (may be beneficial or deleterious) through volatile organic compounds. Fungi produce a wide range of volatile organic chemicals that are involved in a variety of fungus-fungus interactions.³ Microorganisms additionally live in relationship with plants, where they act as an ample source of specific volatile metabolites. At present, 94 different VOCs from microbes (under 10% of the recorded in database) with bioactivity were depicted, and 50 and 57 influence plants and fungi, individually. VOCs are formed as a by-product for the most part in the metabolic oxidation of glucose, from various precursors, for example acetate, amino acids, fatty acids, and keto acids.⁴ The presence of microbial volatiles indicates active growth and sometime associated with health hazards like irritation or inflammatory responses, headache, dizziness, and fatigue.⁵ Microorganisms are directly responsible for the synthesis of VOCs produced by soil. Furthermore, VOCs play an important role in a variety of activities, including inter-organism communication, microbial nutrition cycles, and the rate at which microbes colonize the ecosystem.⁶

The evidences accumulated over the last ten years have shown that bacterial volatiles promote plant growth and inhibit fungal pathogens. It is also confirmed that bacteria themselves have been impacted by volatile compounds released by same or different bacterial species. The bacteria belonging to the similar group produce more similar blends of volatiles as compare to the distantly related ones.⁷,⁸,¹ Bacterial species such as Bacillus sp., Burkholderia sp., Collimonas sp., Pseudomonas sp., Serratia sp., Stenotrophomonas sp. and Streptomyces sp. have been
reported to be as most frequently mVOC producers. Similarly, fungi like Aspergillus sp., Fusarium sp., Mucor sp., and Alternaria sp. are also considered as important volatiles producer.\[^9\] Recently, many endophytic fungi have been found to generate volatile organic compounds (VOCs) while growing on agricultural waste substrates that are best described as hydrocarbons. As both environmentally friendly chemicals and fuels, these compounds have potential uses.

**Microbial volatile organic compounds**

Depending on the different parameters such as growth phase and cultural conditions, bacteria produce broad range of volatile compounds in addition to diffusible substances.\[^{10}\] The significance of volatile organic compounds has become increasingly apparent over the past decade in arbitrating interactions between bacteria and other organisms. Increasing proof indicates that bacteria-emitted volatiles can also affect the development of other organisms such as fungi. Volatiles form bacterial origin has been shown to decrease the growth of fungi in relation to their impact on plant growth and development. The synthesis of HCN by some *Pseudomonas* species, such as *P. fluorescens* CHA0, is a well-known example of volatile-mediated fungal inhibition. Its direct participation has been proven in the biological control of *Thielaviopsis* induced tobacco root rot.\[^11\] Various mechanisms are involved through which bacteria can inhibit fungi. Most of the mechanisms like iron depletion by siderophore production, disturbance of fungal virulence factors, synthesis of antifungal compounds and induction of systematic resistance in plants requires close vicinity or physical contact between fungi and bacteria (Figure 1). But, volatile organic compounds producing bacteria can inhibit phytopathogenic fungi from a distance. The production of antifungal volatile compounds by bacteria has long been identified and these bacterial antagonists are used to protect crops from their fungal enemies.\[^{12}\] This approach is proved to be eco-friendly and alternative way to avoid pathogens.

**Volatile compounds mediated interactions between bacteria and plants**

Plant-associated microorganisms like bacteria generate an abundant of low molecular weight volatiles with the ability to behave as infochemicals. Such compounds have a very significant role in mediating interactions between plants and microbes.\[^{13-18}\] Studies researching the impacts of bacterial volatiles on crops have shown important promotion of plant growth or, in comparison, inhibition of weed plants when exposed to volatiles from various bacteria.\[^{16,17}\] In the experimental plant Arabidopsis thaliana, Burkholderia ambifaria secretes extremely bioactive volatiles that led to important increases in biomass.\[^{18}\] Bacterial VOCs mixtures in plants can also bring out a defense response.\[^{11}\] These defense responses help the plants to provide protection against pathogens. So, volatile compounds from microbial origin have capacity to mould the plants in different manners.

**Fungal volatile organic compounds**

A broad variety of volatile organic compounds (VOCs) are recorded to be produced by fungi. The predominant are alcohols, ketones, terpenes, esters and sulfur compounds.\[^{19,20}\] VOCs play various important and diverse roles for fungi in their natural environments including ecological interactions with different organisms. So that also called as “infochemicals”. Different strains of Trichoderma have been reported to produce volatile compounds that give the research community excellent interest in them. *Aspergillus*, *Penicillium*, *Alternaria*, *Cladosporium*, *Mucor* and Ulocladium are some of the most commonly found fungal genera that are produce profuse organic volatiles.\[^{21}\] In spite of some limitations related to the methodology and technology, scientists found and distinguished about 250 VOCs of fungal origin, most of which have distinctive odors. These are produced by fungi during primary and secondary metabolic activity.\[^{22}\] These compounds have the potential to be used in agriculture, industry and medicine. These are very significant for use as semiochemicals, mycofumigation, mycodesign and biocontrol. In agriculture, by decreasing the utilization of hazardous fungicides on crop plants, it can use a better environmentally sound pest management method. Fungal VOCs also have great potential to be used as biological control (biocontrol) agents to inhibit...
fungal pests. The fungal growth of a plant pathogenic strain of *Fusarium oxysporum* was inhibited by the volatile substances from wild-type antagonistic of *F. oxysporum*. Some bacterial strains were also used to prepare consortia with *F. oxysporum*.

**Volatile compounds mediated interactions between fungus and plants**

Soil-borne fungal VOCs can benefit agricultural crops by activating their disease defense system and prepare them to resist pathogenic attacks, as well as promoting development of neighboring plants. *Muscodor albus*, one of the endophytic fungi, produce volatile organic compounds which can be used for the biological suppression of soil-borne diseases. It can be used to control disease by mixing the endophytic fungi into soil. Fungal root pathogens, *Rhizoctonia solani* which causes damping-off disease in broccoli can be inhibited by using *M. albus* as biocontrol agent. It can also used to control root rot of bell pepper disease caused by *Phytophthora capsici*. Besides the deleterious effect, another desired effect may be the stimulation or enhancement of soil-borne biocontrol agents. Volatile compounds also have ability to increase the efficacy of biocontrol agent of phytopathogens when applied in combination. *Trichoderma atroviride*, a filamentous soil fungus emits organic compounds which stimulate the expression of primary biocontrol genes in *Pseudomonas fluorescens*. T. *viride* motivate growth in the plant model system *Arabidopsis thaliana* (45% greater fresh weight and 58% greater chlorophyll concentration after four weeks) by interacting through organic mediators compounds. In contrast to it, some truffle fungi inhibit the growth of plants like *Arabidopsis thaliana*. It may be indicative of an ability of mycorrhizal fungi to create dead zones, potentially removing the competitors of their hosts.

**Applications of microbial volatiles organic compounds**

In the past decades, applications and potential of microbial originated volatiles have been recognized in agricultural, medical and Industrial sectors. These ecofriendly agents can be utilized in the cost-effective plan or strategy to promote crop production in agricultural field (Figure 2). It may be possible by exploiting these compounds in several ways like plant growth promotion and inhibition of crop pathogens. Some VOCs are also widely reported to have antibiotic and immunosuppressant as well as phyto- and mycotoxic activities. It is very common that all types of microbes are used for the incorporation of flavor and aromas in the diverse foodstuffs like yoghurt, cheese, beer and wine. Analysis and profiling of microbial volatiles also have application in the isolation and identification of microbes mainly fungi in the field of taxonomic research.

**Biological control formulations**

Despite the fact that soil microflora including both fungi and bacteria are known to produce myriads of volatile organic compounds antagonistic behavior of these compounds to plant-pathogenic microbes is poorly understood and needs to be extended due to a different types of soil and conditions in world agriculture. Several fungi present major threats to food safety, such as rice blasting agents (*Magnaporthe grisea*), potato late blight (*Phytophthora infestans*), and wheat powdery mildew (*Blumeria graminis*), as well as destructive rust (*Puccinia* spp., *Uromyces* spp.) and cereal smut (*Ustilago* spp.). Microbial volatiles organic compounds, as natural chemicals, have potential as alternatives to toxic pesticides, fungicides and bactericides. There are scopes for genetic modifications to improve their efficacy and production up to desirable level. Inhibition of putative phytopathogenic fungi causing major crop diseases through bacterial volatiles could be exploited for biological control agent, keeping in view the hazards caused by chemicals/fungicides. Application of bacterial volatiles as biofungicide to control phytopathogenic fungi is an environmental friendly strategy and act as an innovative approach for reducing the environmental pollution posed by the chemical fungicides. So it can contribute to sustainable crop protection and pest management. Recent developments in the field endorse the emerging theory that microbial volatiles contain unexploited, environmentally friendly chemical commodities that could help to select efficient strategies for biocontrol and contribute to safer management of diseases in the agriculture. Their biological effects, decreased residues in the environment and agriculture, and ease of use in various agricultural systems make the use of VOCs a promising and sustainable approach to replacing conventional fungicides in plant pathogens control.
A variety of volatile organic compounds (VOCs) including medium-chain and highly branched compounds, have been reported to be produced by some fungi that have potential to be used as fuel. These types of compounds are collectively termed as myco-diesel. Greater compatibility of these microbial VOCs with current engine and fuel transport technologies makes them a more attractive option for biofuels than ethanol.[33-37] Out of these, a very common volatile compounds such as 3-methyl-1-butanol, offered a recent solution for biofuel production.[37-39] An endophytic fungus, *Gliocladium* species from *Enchytrae cordiformis* was reported to produce medium-chain-length branched hydrocarbons and other organic derivatives that could be utilized as potential alternative fuel sources.[40]

**Contamination Indicators (Electronic Nose Technology)**

In the present time, moisture associated bacterial and fungal growth over buildings is one of the most common causes of health problems. Eye and upper airway irritation are the most obvious health consequences due to the exposure of microbial volatiles.[5] They may be responsible for the musty, earthy, mushroom-like odour from the old buildings and fields. Traditionally, the amount of viable fungi from soil, settled dirt, surface and building materials have been used to measured fungal contamination in an area. This method has several drawbacks and disadvantages like it takes long time for analyses and has possibility to detect only viable airborne spores. In the present time, fungal contamination can be indicated by detecting the volatiles profile of microbes. This type of technology is known as electronic nose technology (E-nose). Electronic nose technology is a really interesting way to detect fungal growth in buildings easily and cost-effectively as fungi produce different profiles or signatures of volatile compounds.[41] With the help of this innovative technology, microbial growth in food products, buildings and potential causative agents for adverse health effects can be easily detected. The idea of using microbial volatiles as bio-contamination indicators was originally put forward by the food processing industry in the 1970s and proposed analyzing unpleasant-smelling as a realistic and rapid method for detecting undesirable or spoilage processes induced by micro-organisms during food storage or processing.[42-46] Diagnostics based on volatile organic compounds offer a lot of promise as the next generation of pathogen detection and infectious disease management tools.[47]

**Mycodiesel**

**Plant Growth Promotion**

In the agriculture, farmers and consumers continuously demand new innovative products and techniques that allow sustainable development and eco-friendly alternative to chemicals. Therefore, in the last decade, volatile organic compounds (VOCs) produced from microorganisms have emerged as a effective, efficient, and an environmental friendly approach. Since the initial reports documenting the safety and growth-promoting capability of bacterial VOCs on experimental plants[1,48] the great potential of these gaseous substances in crop improvement and defense has been evidenced by increasing numbers of studies[49,50] By regulating phytohormone synthesis or metabolic pathways, bacterial volatiles play an important role in stimulating plant growth. It is reported that *Bacillus subtilis*, a plant growth promoting rhizobacterium, produce bacterial volatile compounds which has significant role on hormone regulation and plant growth stimulation in tomato under experimental conditions.[51] Bacterial volatile compounds (BVCs) promote plant growth in two manners. It promotes plant growth above the ground level by modulating phytohormone signaling, promoting photosynthesis and sugar accumulation as food material. These compounds also upgrade mineral absorption below ground and modify architecture of the root system.[52]

**Semiochemicals**

Volatile can easily spread through the gas phase and within the biological system due to high vapor pressure and low molecular weight. They can therefore act as signals for the transmission of information within and between the species. Environmentalists have clarified the function of VOCs as semiochemicals that serve as attractants and deterrents to insects and other invertebrates. Fungal VOCs have been used in the agricultural sector as part of biological control strategies to prevent plant pathogens from growing.[22] Usually, microbial VOCs (mVOCs) are emitted in a multi-faceted and diverse bouquet, primarily from catabolic context, and contain a majority of low-complex, very lipophilic compounds. [10,17,15,33] Thus, microbial volatiles are therefore regarded as bona fide semiochemicals capable of evaporating into extracellular space, entering target species and partitioning into biological membranes or intracellular compartments. Pseudoflowers can be produced by fungi which imitate real flowers in sight and smell by producing volatile compounds used in pollinator attraction to facilitate pollen transfer.[64]
CONCLUSION

The current and future knowledge of volatile compounds may be useful for future researchers. By using bacterial enemies to protect crops against their fungal infections, this knowledge is entering real life. Microbes can also emit a variety of volatiles and it seems that microbial volatile substances can play a significant role in intra- and inter-kingdom contacts. When our knowledge of intra- and inter-organismal mVOC-based interactions slowly grows, it is important to investigate and elucidate in depth volatile perception, signal transduction and phenotypical reactions in the recipient species. They play a significant role in agro-industrial processes and food technology. A body of evidence shows that MVOCs are environmentally friendly and can be used as a cost-effective sustainable approach for agricultural innovations.

This review paper focuses on some strategies where microbial volatiles can play a significant role in intra- and inter-organismal mVOC-based interactions and inter-kingdom contacts. When our knowledge of volatile substances can play a significant role in intra-organismal mVOC-based interactions, it is important to investigate and elucidate in depth volatile perception, signal transduction and phenotypical reactions in the recipient species. They play a significant role in agro-industrial processes and food technology. A body of evidence shows that MVOCs are environmentally friendly and can be used as a cost-effective sustainable approach for agricultural innovations.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ABBREVIATIONS

MVOCs: Microbial Volatile Organic Compounds; 
VOCs: Volatile Organic Compounds; E-nose: Electronic nose; BVCs: Bacterial Volatile Compounds.

SUMMARY

The aim of present review was to discuss about the microbial volatile organic compounds which play a very crucial role in intra- and inter-kingdom interactions.

In the VOCs database, 600 microbes are already registered that produces 1,300 volatile compounds.

Microbial volatiles present an area of critical research to find out solutions for many unsolved issues for the benefit of human beings.

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