Review Article

# Microbial Volatile Organic Compounds: Applications and Future Prospects

**Vikas Kumar[1,*], Manoj Singh[1], Ashwanti Devi[1], Kavita Rani[2], Amit Kumar[1], Sunil Kumar[1], Pooja Sharma[1], Anil K Sharma[1]**

[1]Department of Biotechnology, Maharishi Markandeshwar (Deemed to be University), Mullana, Ambala, Haryana, INDIA.
[2]Animal Biochemistry Division, ICAR-National Dairy Research Institute, Karnal, Haryana, INDIA.

Submission Date: 07-10-2021; Revision Date: 16-11-2021; Accepted Date: 20-11-2021

## 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.

**Correspondence:**
***Vikas Kumar,***
Department of Biotechnology, Maharishi Markandeshwar (Deemed to be University), Mullana 133207, Ambala, Haryana, INDIA.
Phone no: +91-9671986855

Email: vmeashi@gmail.com

## 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

SCAN QR CODE TO VIEW ONLINE

www.ajbls.com

DOI: 10.5530/ajbls.2021.10.71

reported to be as most frequently mVOC producers. Similarly, fungi like *Aspergillus* sp., *Fusarium* sp., *Muscodor* 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 *Thielaviospis* 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.

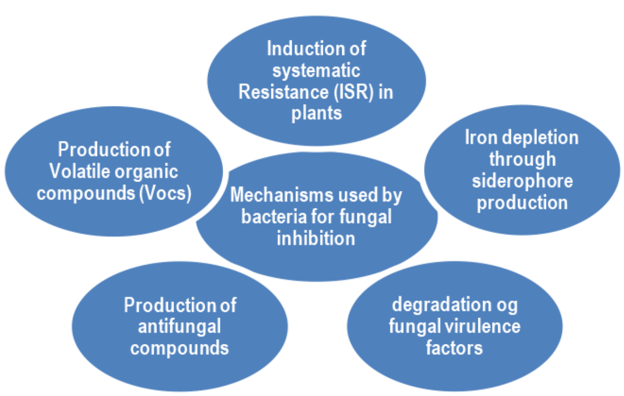


**Figure 1: Several mechanisms adopted by bacteria for the inhibition of fungi.**

### *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.[13-15] 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.[16,1,17] In the experimental plant *Arabidopsis thaliana*, *Burkholderia ambifaria* secreted extremely bioactive volatiles that led to important increases in biomass.[18] Bacterial VOCs mixtures in plants can also bring out a defense response.[1] 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, mycodiesel 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*.[23] 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.[24] 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.[25] 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*.[26] *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.[27] 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.[28,29]

## 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.[30]

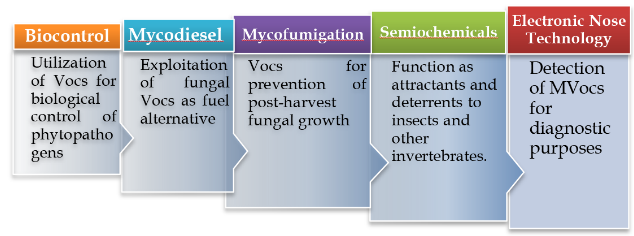


**Figure 2: Applications of microbial volatile organic compounds in different sectors.**

### *Biological control formulations*

Despite the fact that soil microflora including both fungi and bacteria are known to produce myriads of volatile organic compounds[31] antagonistic behavior of these compounds to plant-pathogenic microbes are 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 grisae*), 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.).[32] 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.[33] 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.[34]

### Mycodiesel

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.[35-37] Out of these, a very common volaltile compounds such as 3-methyl-1-butanol, offered a recent solution for biofuel production.[37-39] An endophytic fungus, *Gliocladium* species from *Eucryphia cordifolia* 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]

### 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

Volatiles 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.[10,17,15,53] 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.[54]

## 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 use as agents that improve plant growth, productivity and resistance to disease. So, microbial volatiles present an area of critical research to find out solutions for many unsolved issues for the benefit of human beings. This review paper focuses on some strategies where we can decipher volatile compounds to develop new innovations.

## ACKNOWLEDGEMENT

Authors acknowledge the support provided by Prof. Anil Kumar Sharma, Head of the Department of Biotechnology, Maharishi Markandeshwar (Deemed to be University) during the writeup of this manuscript.

## 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


## REFERENCES


1. Ryu CM, Farag MA, Hu CH, Reddy MS, Wei HX, Paré PW, *et al*. Bacterial volatiles promote growth in Arabidopsis. Proc Natl Acad Sci USA. 2003;100(8):4927-32. doi: 10.1073/pnas.0730845100, PMID 12684534.
2. Marie C, Gohlke B-O L, Toguem SMT, Preissner S, Piechulla B, Preissner R. mVOC 2.0: A database of microbial volatiles. Nucleic Acids Res. 2017;46:D1261–D1265. https://doi.org/10.1093/nar/gkx1016.
3. Quintana-Rodriguez E, Rivera-Macias LE, Adame-Alvarez RM, Torres JM, Heil M. Shared weapons in fungus-fungus and fungus–plant interactions? Volatile organic compounds of plant or fungal origin exert direct antifungal activity *in vitro*. Fungal Ecol. 2018;33:115-21. doi: 10.1016/j.funeco.2018.02.005.
4. Berry DR. Products of primary metabolic pathways. In: Berry DR, editor. Physiology of industrial fungi. Oxford: Blackwell Scientific Publications; 1988. p. 130-60.
5. Korpi A, Järnberg J, Pasanen AL. Microbial volatile organic compounds. Crit Rev Toxicol. 2009;39(2):139-93. doi: 10.1080/10408440802291497, PMID 19204852.
6. Abis L, Loubet B, Ciuraru R, Lafouge F, Houot S, Nowak V, *et al*. Reduced microbial diversity induces larger volatile organic compound emissions from soils [sci rep:6104]. Sci Rep. 2020;10(1):6104. doi: 10.1038/s41598-020-63091-8, PMID 32269288.
7. Garbeva P, Weisskopf L. Airborne medicine: Bacterial volatiles and their influence on plant health. New Phytol. 2020;226(1):32-43. doi: 10.1111/nph.16282, PMID 31651035.
8. Kai M, Effmert U, Berg G, Piechulla B. Volatiles of bacterial antagonists inhibit mycelial growth of the plant pathogen *Rhizoctonia solani*. Arch Microbiol. 2007;187(5):351-60. doi: 10.1007/s00203-006-0199-0, PMID 17180381.
9. Piechulla B, Lemfack MC, Kai M. Effects of discrete bioactive microbial volatiles on plants and fungi. Plant Cell Environ. 2017;40(10):2042-67. doi: 10.1111/pce.13011, PMID 28643880.
10. Schulz S, Dickschat JS. Bacterial volatiles: the smell of small organisms. Nat Prod Rep. 2007;24(4):814-42. doi: 10.1039/b507392h, PMID 17653361.
11. Voisard C, Keel C, Haas D, Dèfago G. Cyanide production by Pseudomonas fluorescens helps suppress black root rot of tobacco under gnotobiotic conditions. EMBO J. 1989;8(2):351-8. doi: 10.1002/j.1460-2075.1989.tb03384.x, PMID 16453871.
12. Weisskopf L. The potential of bacterial volatiles for crop protection against phytopathogenic fungi. In: Méndez-Vilas A, editor. Microbial pathogens and strategies for combating them: science, Journal of technology education. Spain: Formatex; 2013. p. 1352-63.
13. Kai M, Piechulla B. Plant growth promotion due to rhizobacterial volatiles – an effect of CO2? FEBS Lett. 2009;583(21):3473-7. doi: 10.1016/j.febslet.2009.09.053, PMID 19808036.
14. Wenke K, Kai M, Piechulla B. Below ground volatiles facilitate interactions between plant roots and soil organisms. Planta. 2010;231(3):499-506. doi: 10.1007/s00425-009-1076-2, PMID 20012987.
15. Peñuelas J, Asensio D, Tholl D, Wenke K, Rosenkranz M, Piechulla B, *et al*. Biogenic volatile emissions from the soil. Plant Cell Environ. 2014;37(8):1866-91. doi: 10.1111/pce.12340, PMID 24689847.
16. Han SH, Lee SJ, Moon JH, Park KH, Yang KY, Cho BH, *et al*. GacS-dependent production of 2R, 3R-butanediol by Pseudomonas chlororaphis O6 is a major determinant for eliciting systemic resistance against *Erwinia carotovora* but not against *Pseudomonas syringae* pv. tabaci in tobacco. Mol Plant Microbe Interact. 2006;19(8):924-30. doi: 10.1094/MPMI-19-0924, PMID 16903358.
17. Blom D, Fabbri C, Eberl L, Weisskopf L. Volatile-mediated killing of Arabidopsis thaliana by bacteria is mainly due to hydrogen cyanide. Appl Environ Microbiol. 2011b;77(3):1000-8. doi: 10.1128/AEM.01968-10, PMID 21115704.
18. Groenhagen U, Baumgartner R, Bailly A, Gardiner A, Eberl L, Schulz S, *et al*. Production of bioactive volatiles by different Burkholderia ambifaria strains. J Chem Ecol. 2013;39(7):892-906. doi: 10.1007/s10886-013-0315-y, PMID 23832658.
19. Fischer G, Müller T, Schwalbe R, Ostrowski R, Dott W. Exposure to airborne fungi, MVOC and mycotoxins in biowaste- handling facilities. Int J Hyg

Environ Health. 2000;203(2):97-104. doi: 10.1078/S1438-4639(04)70014-0, PMID 11109561.
20. Kiviranta H, Tuomainen A, Reiman M, Laitinen S, Liesivuori J, Nevalainen A. Qualitative identification of volatile metabolites from two fungi and three bacteria species cultivated on two media. Cent Eur J Public Health. 1998;6(4):296-9. PMID 9919382.
21. Claeson A. Volatile organic compounds from microorganisms—Identification and health effects [PhD thesis]. Sweden: Umeå University; 2006.
22. Morath SU, Hung R, Bennett JW. Fungal volatile organic compounds: A review with emphasis on their biotechnological potential. Fungal Biol Rev. 2012;26(2-3):73-83. doi: 10.1016/j.fbr.2012.07.001.
23. Minerdi D, Bossi S, Gullino ML, Garibaldi A. Volatile organic compounds: A potential direct long-distance mechanism for antagonistic action of *Fusarium oxysporum* strain MSA 35. Environ Microbiol. 2009;11(4):844-54. doi: 10.1111/j.1462-2920.2008.01805.x, PMID 19396945.
24. Mercier J, Manker DC. Biocontrol of soil-borne diseases and plant growth enhancement in greenhouse soilless mix by the volatile-producing fungus *Muscodor albus*. Crop Prot. 2005;24(4):355-62. doi: 10.1016/j.cropro.2004.09.004.
25. Wheatley RE. The consequences of volatile organic compound mediated bacterial and fungal interactions. Antonie Leeuwenhoek. 2002;81(1-4):357-64. doi: 10.1023/A:1020592802234, PMID 12448734.
26. Lutz MP, Wenger S, Maurhofer M, Défago G, Duffy B. Signaling between bacterial and fungal biocontrol agents in a strain mixture. FEMS Microbiol Ecol. 2004;48(3):447-55. doi: 10.1016/j.femsec.2004.03.002, PMID 19712313.
27. Hung R, Lee S, Bennett JW. Arabidopsis thaliana as a model system for testing the effect of Trichoderma volatile organic compounds. Fungal Ecol. 2013;6(1):19-26. doi: 10.1016/j.funeco.2012.09.005.
28. Splivallo R, Novero M, Bertea CM, Bossi S, Bonfante P. Truffle volatiles inhibit growth and induce an oxidative burst in *Arabidopsis thaliana*. New Phytol. 2007;175(3):417-24. doi: 10.1111/j.1469-8137.2007.02141.x, PMID 17635217.
29. Splivallo R, Ottonello S, Mello A, Karlovsky P. Truffle volatiles: from chemical ecology to aroma biosynthesis. New Phytol. 2011;189(3):688-99. doi: 10.1111/j.1469-8137.2010.03523.x, PMID 21287717.
30. Karlshøj K, Larsen TO. Differentiation of species from the *Penicillium roqueforti* group by volatile metabolite profiling. J Agric Food Chem. 2005;53(3):708-15. doi: 10.1021/jf0485887, PMID 15686424.
31. Leff JW, Fierer N. Volatile organic compound (VOC) emissions from soil and litter samples. Soil Biol Biochem. 2008;40(7):1629-36. doi: 10.1016/j.soilbio.2008.01.018.
32. Strange RN, Scott PR. Plant disease: A threat to global food security. Annu Rev Phytopathol. 2005;43:83-116. doi: 10.1146/annurev.phyto.43.113004.133839, PMID 16078878.
33. Bailly A, Weisskopf L. Mining the volatilomes of plant-associated microbiota for new biocontrol solutions. Front Microbiol. 2017;8:1638. doi: 10.3389/fmicb.2017.01638, PMID 28890716.
34. Tilocca B, Cao A, Migheli Q. Scent of a Killer: Microbial volatilome and its role in the biological control of plant pathogens. Front Microbiol. 2020;11:41. doi: 10.3389/fmicb.2020.00041, PMID 32117096.
35. Fortman JL, Chhabra S, Mukhopadhyay A, Chou H, Lee TS, Steen E, *et al*. Biofuel alternatives to ethanol: Pumping the microbial well. Trends Biotechnol. 2008;26(7):375-81. doi: 10.1016/j.tibtech.2008.03.008, PMID 18471913.
36. Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci U S A. 2006;103(30):11206-10. doi: 10.1073/pnas.0604600103, PMID 16837571.
37. Zhang K, Sawaya MR, Eisenberg DS, Liao JC. Expanding metabolism for biosynthesis of nonnatural alcohols. Proc Natl Acad Sci U S A. 2008;105(52):20653-8. doi: 10.1073/pnas.0807157106, PMID 19064911.
38. Atsumi S, Hanai T, Liao JC. Non-fermentative pathways for synthesis of branched-chain higher alcohols as biofuels. Nature. 2008;451(7174):86-9. doi: 10.1038/nature06450, PMID 18172501.
39. Connor MR, Cann AF, Liao JC. 3-methyl-1-butanol production in Escherichia coli: random mutagenesis and two-phase fermentation. Appl Microbiol Biotechnol. 2010;86(4):1155-64. doi: 10.1007/s00253-009-2401-1, PMID 20072783.
40. Griffin MA, Spakowicz DJ, Gianoulis TA, Strobel SA. Volatile organic compound production by organisms in the genus Ascocoryne and a re-evaluation of myco-diesel production by NRRL 50072. Microbiology (Reading). 2010;156(12):3814-29. doi: 10.1099/mic.0.041327-0, PMID 20705658.
41. Kuske M, Romain AC, Nicolas J. Microbial volatile organic compounds as indicators of fungi. Can an electronic nose detect fungi in indoor environments? Build Environ. 2005;40(6):824-31. doi: 10.1016/j.buildenv.2004.08.012.
42. Kamiński E, Libbey LM, Stawicki S, Wasowicz E. Identification of the predominant volatile compounds produced by *Aspergillus flavus*. Appl Microbiol. 1972;24(5):721-6. doi: 10.1128/am.24.5.721-726.1972, PMID 4629700.
43. Kaminski E, Stawicki S, Wasowicz E. Volatile flavor compounds produced by molds of *Aspergillus*, *Penicillium*, and Fungi imperfecti. Appl Microbiol. 1974;27(6):1001-4. doi: 10.1128/am.27.6.1001-1004.1974, PMID 16349989.
44. Börjesson T, Stöllman U, Schnürer J. Volatile metabolites produced by six fungal species compared with other indicators of fungal growth on cereal grains. Appl Environ Microbiol. 1992;58(8):2599-605. doi: 10.1128/aem.58.8.2599-2605.1992, PMID 1514807.
45. Borjesson T, Stollman U, Adamek P, Kaspersson A. Analysis of volatile compounds for detection of molds in stored cereals. Cereal Chem. 1989;66:300-4.
46. Wilkins CK, Scholl S. Volatile metabolites of some barley storage molds. Int J Food Microbiol. 1989;8(1):11-7. doi: 10.1016/0168-1605(89)90075-5, PMID 2641484.
47. Hong-Geller E, Adikari S. Volatile organic compound and metabolite signatures as pathogen identifiers and biomarkers of infectious disease. In: Rinken T, Kivirand K, editors. Available from: https://doi.org/10.5772/intechopen.72398. Biosensing technologies for the detection of pathogens-A prospective way for rapid analysis. United Kingdom: IntechOpen; 2018.
48. Ryu CM, Farag MA, Hu CH, Reddy MS, Kloepper JW, Paré PW. Bacterial volatiles induce systemic resistance in Arabidopsis. Plant Physiol. 2004;134(3):1017-26. doi: 10.1104/pp.103.026583, PMID 14976231.
49. Bailly A, Weisskopf L. The modulating effect of bacterial volatiles on plant growth: Current knowledge and future challenges. Plant Signal Behav. 2012;7(1):79-85. doi: 10.4161/psb.7.1.18418, PMID 22301973.
50. Kanchiswamy CN, Malnoy M, Maffei ME. Chemical diversity of microbial volatiles and their potential for plant growth and productivity. Front Plant Sci. 2015;6:151. doi: 10.3389/fpls.2015.00151, PMID 25821453.
51. Tahir HAS, Gu Q, Wu H, Raza W, Hanif A, Wu L, *et al*. Plant growth promotion by volatile organic compounds produced by *Bacillus subtilis* SYST2. Front Microbiol. 2017;8:171. doi: 10.3389/fmicb.2017.00171, PMID 28223976.
52. Sharifi R, Ryu CM. Revisiting bacterial volatile-mediated plant growth promotion: Lessons from the past and objectives for the future. Ann Bot. 2018;122(3):349-58. doi: 10.1093/aob/mcy108, PMID 29982345.
53. Schenkel D, Lemfack MC, Piechulla B, Splivallo R. A meta-analysis approach for assessing the diversity and specificity of belowground root and microbial volatiles. Front Plant Sci. 2015;6:707. doi: 10.3389/fpls.2015.00707, PMID 26442022.
54. Ngugi HK, Scherm H. Mimicry in plant-parasitic fungi. FEMS Microbiol Lett. 2006;257(2):171-6. doi: 10.1111/j.1574-6968.2006.00168.x, PMID 16553849.

**Cite this article:** Kumar V, Singh M, Devi A, Rani K, Kumar A, Kumar S, Sharma P, Sharma AK. Microbial Volatile Organic Compounds: Applications and Future Prospects.Asian J Biol Life Sci. 2021;10(3):533-8.