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Review

Reviews of emission of biogenic volatile organic compounds (BVOCs) in Asia

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ABSTRACT

Biogenic volatile organic compounds (BVOCs) in the atmosphere play important roles in the formation of ground-level ozone and secondary organic aerosol (SOA) in global scale and also in regional scale under some condition due to their large amount and relatively higher reactivity. In places with high plant cover in the tropics and in China where air pollution is serious, the effect of BVOCs on ozone and secondary organic aerosols is strong. The present research aims to provide a comprehensive review about the emission rate, emission inventory, research methods, the influencing factors of BVOCs emissions, as well as their impacts on atmospheric environment quality and human health in recent years in Asia based on the summary and analysis of literatures. It is suggested to use field direct measurement method to obtain the emission rate and model method to calculate the emission amount. Several recommendations are given for future investigation and policy development on BVOCs emission.

Introduction

The volatile non-methane hydrocarbons synthesized by different plant tissues, such as leaves, flowers, fruits and roots through secondary metabolic pathways, are known as biogenic volatile organic compounds (BVOCs) (Loreto and Schnitzler, 2010; Laothawornkitkul et al., 2009). Many vascular plants can discharge biogenic volatile organic compounds into the atmosphere. It is estimated that the total amount of BVOCs released in 2000 was about 1 Pg (10^{15} g), including isoprene (ISO, 53%), monoterpene (MTS, 16%) and other reactive VOCs (OVOCs, 31%), nearly 10 times higher than that of anthropogenic volatile organic compounds (AVOCs) (Guenther et al., 1995, 2012; Simpson et al., 1999). Among them, forest is the main source of BVOCs in the ecosystem.

BVOCs are important chemical messengers and play an important role in regulating the growth and reproduction of plants, resisting environmental stress, and preventing the harm of animals and insects. On the other hand, they have important impact on the redox state of atmospheric environment, tropospheric chemistry and global carbon cycle, due to their high reactivity (Klinger et al., 2002). Most of the BVOCs, such as isoprene and monoterpenes are active for the photochemical reactions in atmosphere. BVOCs make dominant contribution to global secondary organic aerosol (SOA), and thus affect global solar radiation. Compared with anthropogenic volatile organic compounds (AVOCs), atmospheric concentrations of BVOCs in polluted areas are relatively low, but BVOCs can make significant contribution to secondary oxidants due to their relatively higher high reactivity (Claeys et al., 2004; Joutsensaari et al., 2005).

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The components of BVOCs vary greatly in time and space. Therefore, only by accurately obtaining the emission rates and fluxes of BVOCs in various ecosystems at regional and global scales, it is possible to reasonably evaluate the temporal and spatial effects and interactions of BVOCs on regional or global tropospheric chemistry and photochemistry (such as ozone, SOA). Therefore, it is very important to accurately measure the emission rate and flux of BVOCs in typical plant ecosystems in different regions, and to study and determine the relationship between various environmental factors and the emission of BVOCs, so as to understand the internal regularity of the spatial-temporal change pattern of BVOCs.

After decades of development, scholars have carried out a lot of work in BVOCs sampling technology, analysis methods and model building, and made a significant breakthrough from the measurement of various BVOCs emissions to the calculation of regional emission amounts (Acton et al., 2016; Aydin et al., 2014; Misztal et al., 2011). In general, the emission characteristics and emissions amount of BVOCs in USA and parts of Europe are comprehensive and detailed, while the data in Asia are far from enough. In some regions of Asia, especially in China, the NO_x emission is still very high and the environmental ozone pollution is still serious. A review of known emission rate, the emission inventory, research methods of BVOCs in China is therefore needed to aid in formulating a mitigation policy.

1. BVOCs emission research technology

1.1. BVOCs emission observation technology

There are two main types of methods to study plant emission rate or flux of BVOCs: direct measurement methods, micrometeorological methods. Researchers can choose different research methods depending on the research purpose, study area scale and research environment.

1.1.1. Direct measurement methods

Direct measurement and analysis methods are used widely, including static closed sampling, dynamic headspace sampling and so on (Wang et al., 2002, 2003; Huang et al., 2011; Zhao et al., 2004). In both methods, the branches, leaves or the whole plant of a certain outdoor tree species are sampled, and then the sampling adsorption tube is brought back to the laboratory to determine the sample components and the content of each component using analytical instruments. Static closed sampling is to cover some branches and leaves of the tree species to be tested in a box or bag, measure the concentrations of the studied gases in the box/bag at a certain interval, and then calculate the gases emission rates of the covered surface based on the change of gas concentrations with time. Dynamic headspace sampling is currently used to measure BVOCs emission from living plants. Different from static closed sampling, the bag used in this method is open at both ends to maintain a natural air flow in the bag. The air is extracted by a sampling pump and introduced into the adsorption tube, during which BVOCs are attached to the adsorbent. The BVOCs absorbed in the tube are then desorbed by thermal desorption for gas chromatography-mass spectrometry analysis (GC–MS).

Both of the above methods are simple, easy to perform and can measure individual plant species. They are classic methods for measuring emission rate and emission flux, and are still widely used up to now. However, since these methods need to enclose the branches in a certain container, the influence of temperature changes cannot be ignored. Although the dynamic headspace method can partly solve this problem, it cannot completely eliminate the impact. In addition, to calculate the emission rate, the biomass of the covered plants is also required, which also cannot be obtained accurately. The emission rate of BVOCs from plant sources is greatly affected by temperature and light, so the data of emission rate measured at a few time points cannot represent the BVOCs emission characteristics of the plant. A large number of observation experiments are needed to obtain the laws of daily and seasonal changes. At the same time, the emission rate of the same species of plant varies greatly under the conditions of different tree ages and different growing places etc. Therefore, even if there is some emission rate data about one plant species, when in a different place from previous observation area, it is also necessary to carry out observations again to confirm the reliability of emission rate data.

1.1.2. Micrometeorological methods

Micrometeorological methods are to derive surface gas emission flux based on micrometeorological measurements. Information about the surface gas emission flux can be obtained by measuring the turbulence and concentration changes of trace gases in the near-surface layer (Gao et al., 2009). These methods require uniform distribution of upwind gas emission flux on the measured surfaces and measured points in a large scale. In recent years, many scholars have tried to measure the emission flux of BVOCs in a certain area by micrometeorological methods. According to different measuring parameters, micrometeorological methods can be divided into eddy covariance method, flux gradient method, Bowe ratio method and mass balance method. The advantage of the micrometeorological method is that the sampling process is out of the research system, the plants are completely under natural conditions without interference and the determination of emission rate is more accurately. Meanwhile, since these methods do not need to calculate emission flux by calculating emission rate, there is no need to know the biomass. Direct measurement methods will undoubtedly bring uncertainty and error during the measurement of emission rate and biomass, and these can be avoided by using micrometeorological methods, thus making up the shortcomings of direct measurement methods. But micrometeorological methods require extremely accurate sensors and their workloads are considerable, so these methods are expensive and require a lot of resources.

1.2. Models simulating BVOCs emission

At present, in the study of large-scale BVOCs emissions, model simulation methods are mainly used. A series of regional and global BVOCs emission estimation methods and models have been established worldwide, such as biogenic emission inventory system (BEIS) models (BEIS1, BEIS2, global biosphere emissions and interactions system (GloBEIS)), Guenther models (G9l, G93, G95, model of emissions of gases and aerosol from nature (MEGAN)). After years of improvement and development, these models have been widely used in global and regional BVOCs emission researches.

1.2.1. BEIS model

In 1991, Pierce (1991) established the first-generation biogenic emission inventory system (BEIS1) model based on observed or calculated data, including land use, leaf biomass, emission factors and meteorological parameters. The BEIS1 model is the first method to calculate BVOCs emissions. The model can calculate the BVOCs emission rate of a local species by inputting hourly temperature, relative humidity, wind speed, cloud coverage data and US county code. However, BEIS is only applicable to the simulation of BVOCs emission at the regional scale (for example, counties in the United States) with a relative low spatial resolution (about 16 km), and there are some uncertainties due to the limitation of some of the important data, such as land use type, leaf biomass and emission factor monitoring.

In 1998 (Pierce et al., 1998), based on BEIS1 and G95 and combined with the latest research results at that time, the second-generation biogenic emission inventory system (BEIS2) model was developed. BEIS2 used the latest land use data and emission rate data, and classified the vegetation from 3 types in BEIS1 to 76 types. The emission rate was corrected by temperatures and photosynthetically active radiation (PAR). By multiplying coefficients, the emission rate was standardized to standard emission rate at 30°C with a PAR of 1000 μmol/(m^2·sec). Compared with BEIS1 and G95, BEIS2 has been greatly improved in terms of land use data update, improvement of spatial resolution, and revision of environmental correction methods. However, its use of ambient temperature instead of leaf temperature and the uncertainty of canopy solar radiation estimation lead to a certain deviation in simulation results.

In the late 1990s, the US Environmental Protection Agency (EPA) and the National Center for Atmospheric Research (NCAR) jointly developed the global biosphere emissions and interactions system (GloBEIS). Since then, BEIS series have developed from a regional model to a global model. GloBEIS improved the G95 algorithm and made many improvements compared with the previous model: (1) introduced the networked high resolution (1 km) Biogenic Emissions Landuse Database-BELD3 (version3), covering North America, including 270 vegetation; (2) proposed the calculation method of average landscape discharge rate based on land use type; (3) considering the influence of leaf growth status on emissions, LAI data from satellite sources were used to simulate the composition of new and old mature leaves and the spatial distribution of emissions in the canopy; (4) starting to consider the consumption in the canopy, proposed the dissipation efficiency; (5) model modularization, including four modules: data preprocessing, canopy environment model simulating canopy environment and vegetation characteristics, emission algorithm, emission cost-effectiveness and format arrangement; (6) using the most advanced emission algorithm at that time; (7) introducing geostationary operational environmental satellite (GOES) satellite data to simulate solar radiation data; (8) the effects of drought and continuous high temperature can be simulated; (9) the energy balance model of leaves is established. In addition, GloBEIS has higher spatial resolution and obvious advantages in detail representation. However, it uses parameterized regional measurement data to simulate global emissions and the parameters such as emission rate and leaf biomass are strongly affected by factors like climate, soil type and altitude, therefore, the accuracy of simulation results is low.

1.2.2. Guenther series models

In 1991, Guenther measured the emission rate of isoprene from *Eucalyptus* by experiment, and found that the emission rate of isoprene from *Eucalyptus* was related to light and temperature (Guenther et al., 1991). He worked out a method G91 to calculate the plant isoprene emissions based on experimental data. This method is simple and will not be described here. In 1993, Guenther et al. (1993) developed isoprene and monoterpenes emission rate algorithm G93 based on G91 and the latest experimental data. Compared with the G91 model, the G93 model standardized the emission conditions of isoprene under various environmental conditions to temperature (T) of 303 K and PAR of 1000 μmol/(m^2·sec). In 1995, Guenther et al. (1995) developed a global emissions inventory activity, G95, based on the algorithms G91 and G93 and relevant data. G95 can calculate the global emissions inventory with a resolution of 0.5° × 0.5° by inputting the global ecosystem type, global vegetation index, precipitation, temperature and cloud cover grid data in the model. It is flexible and modular, easy to update data and improve algorithm, and easy to integrate with future versions. Due to the lack of measured data, researches focus on the emission of isoprene and monoterpenes and made only rough estimates of other VOCs, however, the contribution of these VOCs to the total VOCs cannot be ignored. Thus, the emission rate of other VOCs needs to be further measured and determined. Moreover, the parameters in the model (such as temperature, precipitation and cloud cover) are not accurate enough, and most of them are monthly average with large uncertainty.

In 2006, Guenther et al. (2006) developed a model of emissions of gases and aerosol from nature (MEGAN) based on G95 and numerous experimental data. Compared to previous models, MEGAN has a higher resolution (1 km × 1 km) and can meet the requirement of both regional and global scale simulation. To simulate regional or global BVOCs emission using MEGAN, the following parameters are necessary, such as leaf area index (LAI), plant function types (PFTs) and meteorological conditions (such as solar radiation transmission, atmospheric temperature, air humidity, wind speed, and soil moisture). LAI and PFTs are from satellite observations, ecosystem models outputs, ecosystem distribution maps, and vegetation inventories. MEGAN divides the world into different vegetation functional types and assigns different emission factors accordingly. It also simulates the light and temperature distribution of different canopy types. MEGAN can fully meet the requirements of regional and global chemical and transmission modeling, and more observational studies on the effects of physical (temperature and light) and chemical (CO_2 and ozone) environment on emissions are needed to further improve the model.

In recent years, satellite remote sensing technology, high-precision meteorological models and dynamic vegetation models have been widely used in BVOCs emission modeling. The BVOCs emission models are continuously being improved in algorithms and data, and the model versions are constantly being updated (BEIS3, G1oBEIS3.5 and MEGAN3.0). Based on the above algorithms, researchers have developed other BVOCs emission models suitable for regional or global simulation, such as the Taiwan biogenic emission inventory system (TBEIS) based on BEIS2, community climate system model based on G95, and European biogenic emission model (BEM) also based on G95. In general, although many climate models use off-line simulation results of emission models to study the climate and environmental effects of BVOCs, few climate models realize bidirectional online coupling in emission models. Table 1 shows the comparison of some BVOCs emission models.

2. Components of BVOCs

At present, the direct measurement methods are used to detect and analyze the volatile components of different tree species under natural conditions in many researches. The content of BVOC analysis mainly focuses on the differences from different organs, arbor, shrub and grass. Studies show that (Guenther et al., 2006) the volatile gases of general plants are mainly composed of isoprene, terpenes compounds such as monoterpenes and sesquiterpenes, carbonyl compounds, a series of alcohols, oxide and esters, etc., among them, isoprene content is the highest, followed by monoterpenes. For example, volatiles emitted by *Salix babylonica* include terpenes, esters, alkanes, alcohols, aldehydes and heterocyclic compounds (Mu et al., 2014); volatiles emitted by *Ulmus pumila* mainly include terpenes, alcohols, aldehydes, esters, ketones and alkanes (Zhang et al., 2014); volatiles emitted by *Pinus tabulaeformis* mainly include terpenes, alkanes, esters, ketones, alcohols and aldehydes (Huang et al., 2013). Statistically, there are about 30,000 compounds in BVOCs (Penuelas and Llusià, 2004). Guenther et al. (1995) classified BVOCs released by plants around the world into four categories according to their chemical structure, activity and impact on atmospheric chemical process, namely 44% isoprene, 11% monoterpene, 22.5% other active VOCs and 22.5% non-active VOCs. The BVOCs components of some common tree species in the literature were summarized, and listed in Table 2.

Table 1 – Biogenic volatile organic compounds (BVOCs) emission model comparison.

Models	Input variables	Output variables	Characteristics	Disadvantages	Scale
BEIS1 (Pierce, 1991)	Land use, leaf biomass, emission factor, meteorological data (temperature and humidity, wind speed, cloud cover), county code	Isoprene, α-pinene, other monoterpenes, etc.	(1) Based on leaf biomass emission factors; (2) Affected by temperature and light.	High uncertainty; small application range; low spatial resolution; only 3 vegetation types.	Regional
G95 (Guenther et al., 1995)	Grid ecosystem type, global vegetation index, meteorological data (precipitation, temperature, cloud cover)	Isoprene, monoterpenes, and other VOCs	(1) Based on the ecosystem emission factor; (2) Only isoprene is related to light; (3) All outputs are affected by temperature.	Focus on isoprene and monoterpenes, and the parameters used is monthly average with low accuracy.	Global
BEIS2 (Pierce et al., 1998)	Meteorological conditions at the top of canopy per hour (direct and scattered light flux density, temperature and humidity, wind speed, etc.)	Isoprene, monoterpenes, and other VOCs	(1) Introduces a land use database with high spatial resolution; (2) Vegetation classifications is more refined, reaching 76 tree species; (3) The environmental parameter correction method is revised; (4) Only isoprene is related to light; (5) All outputs are affected by temperature.	Replace leaf temperature with ambient temperature; lack of robust canopy models to simulate solar radiation distribution.	Regional
GloBEIS (Guenther et al., 1999)	Land use, leaf area index, meteorological data (PAR, temperature and humidity, wind speed, cloud cover, etc.)	Isoprene, monoterpenes, and other VOCs	(1) It is the global mode of BEIS model; (2) Mainly simulates isoprene emission; (3) Considers the influence of leaf growth state on emission and dissipation efficiency; (4) Only monoterpenes are not related to light, other VOCs are fully affected by light; (5) All outputs are affected by temperature.	The parameter values are rough and cannot represent different situations in all time periods.	Global
MEGAN (Guenther et al., 2006)	Leaf area index, vegetation function type, meteorological data (PAR, temperature and humidity, soil humidity, wind speed, etc.)	Isoprene, monoterpenes, and other VOCs	(1) It can meet both regional and global scale simulation needs; (2) It divides different vegetation function types globally; (3) Considers the influence of leaf age of vegetation and soil humidity; (4) Puts forward the calculation method of dissipation efficiency; (5) All outputs are affected by temperature and light.	It should be further improved in the effects of physical (such as temperature and light) and chemical (such as CO_2 and O_3) environments on emissions.	Global/Regional
BEM (Poupkou et al., 2010)	Land use, meteorological data, leaf biomass, emission factors	Isoprene, monoterpenes, and other VOCs	(1) The model is based on G95, simple and practical; (2) Emission factors based on land use type; (3) Only isoprene is related to light; (4) All outputs are affected by temperature.	The algorithm is out of date, the monthly average values of emission factors and leaf biomass are rough and only applicable to Europe.	European

BEIS1: the first-generation biogenic emission inventory system; G95: Guenther model in 1995; BEIS2: the second-generation biogenic emission inventory system; GloBEIS: the global biosphere emissions and interactions system; PAR: photosynthetically active radiation; MEGAN: model of emissions of gases and aerosol from nature; BEM: European biogenic emission model.

Table 2 – BVOCs components of common arbor species.

Tree species	Evergreen arbors		Deciduous arbors					
	Pinus tabulaeformis	*Platycladus orientalis*	*Populus tomentosa*	*Betula platyphylla*	*Quercus variabilis*	*Robinia pseudoacacia*	*Salix babylonica*	*Ulmus pumila*
Relative content from high to low	α-Pinene	α-Pinene	Isoprene	Sabinene	Isoprene	Isoprene	Isoprene	α-Phellandrene
	β-Pinene	4-Thujene	Ocimene	Limonene	α-Pinene	α-Pinene	Limonene	Limonene
	Limonene	Limonene	Limonene	α-Pinene	β-Pinene	Myrcene	α-Pinene	Camphene
	Myrcene	Myrcene	α-Pinene	Pinus palustris mill terpene	Limonene	Ocimene	β-Pinene	α-Pinene
	Camphene	2-Thujene	β-Pinene	Caryophyllene			3-Carene	α-Ocimene
	Tricyclene	3-Carene	3-Carene				Camphene	
		α-Phellandrene						

3. Factors affecting emission rate of BVOCs

3.1. Plant internal factors

(1) Tree species: Tree species difference is the primary factor determining the emission of BVOCs. It plays a decisive role in the BVOCs components and the emission rate. The release rate, composition and characteristics of BVOCs are closely related to the group of plants, that is, there are great differences among different genera. The research of Owen et al. (2002) demonstrated that, at the subordinate level, most of the genera of *Maackia, Quercus, Ficus, Populus* and *Salix* have the ability to release isoprene, and most of them are strong releasers. However, *Acer, Betula, Pieca, Pinus* and other genera were the major emitters of terpene compounds. At the family level, most species and genera of the *Arecaceae* and *Gramineae* are isoprene releasers, while the *Betulaceae* and *Pinaceae* species release terpenes. The release rate of different species of the same genus also varies greatly. Benjamin and Winer (1998) tested 26 species of *Quercus*, and the results showed that the emission rates could vary by up to 22 times.

(2) Tree age: Tree age also has a certain impact on BVOCs emission. Some studies showed that younger trees emitted more volatiles than older ones. Street et al. (1997) found that the emission rate of volatiles in branches and leaves of *Pinus pinea* saplings was 2–3 times higher than that of mature ones under the same condition. And other studies showed that mature trees had higher BVOCs emission rate. Kim et al. (2005) found that the BVOCs emission rates of mature *Cryptomeria japonica* and *Pinus koraiensis* were higher than those of saplings, but the components were similar.

(3) Plant development stage: Plant development stage is also an influence factor on BVOCs components from plants and their content. The emission rates of volatiles are significantly higher in the bud stage and flowering stage than that in the leaf growth stage, and the components vary greatly in different stages. Kuzma and Fall (1993) found that mature leaves of velvet bean emit more isoprene than young leaves. This may be mainly due to the different activities of organic-related regulatory enzymes in plants. Mozaffar et al. (2017) measure the BVOC emissions of maize (*Zea mays L*), which is the most cultivated crop species in the world, at all the leaf developmental stages. They found that BVOC emission rates varied strongly among the different leaf developmental stages, and senescent leaves showed a larger diversity of emitted compounds than leaves at earlier stages.

3.2. Environmental factors

(1) Humidity: The change of humidity has a great influence on the BVOCs emission of plants, and this change has a great difference among different tree species. The BVOCs emission rate of some tree species increases with the increase of environmental (atmosphere and soil) humidity, while some are not sensitive to the change of environmental humidity, or even decreases with the increase of humidity. Caser et al. (2019) investigated the performance and metabolic profile of *Salvia dolomitica Codd* in response to two drought treatments (moderate or severe) relative to well-watered control plants, and found that both drought stress conditions led to modulate the expression of some genes involved in biogenic volatile organic compound, in particular induced an increase in sesquiterpene production. Saunier et al. (2017) found that under drought conditions, due to plant stomata closure, all BVOCs emitted by *Quercus pubescens* in spring and summer will be reduced by about 40%-50%, but there is no impact in autumn. Lupke et al. (2016) also reached the same conclusion through the research about three *Scots pine*. Under summer drought stress, the release rate, net photosynthetic rate and transpiration rate of isoprene all decreased, and recovered significantly after rehumidification. Janson (1993) researched the *Pinus sylvestris* and *Picea abies*, and the results showed that the increase of environmental humidity could not only accelerate the emission of BVOCs, but also change the BVOCs components emitted by trees. Ning et al. (2013) studied the emission patterns of major BVOCs from two typical arbors in Yunnan, and found that relative humidity has a significant positive correlation with the emission of α-pinene and a significant negative correlation with the emission of isoprene of these two species, and the correlation with isoprene was stronger than that with α-pinene.

(2) Temperature: Temperature is another important factor affecting the BVOCs emission of plants. The emission profiles of both isoprene and monoterpenes are related to temperature. In general, BVOCs synthesis and emission rates gradually increase with the increase of temperature. The main reason is that the activity of synthetase is affected by temperature. This directly leads to the obvious seasonal, monthly and daily variation in BVOCs emissions. But the emission rate declines when the temperature is higher than a certain degree. Ren et al. (2010) treated the potted *Eupatorium coelestinum* infested with aphis gossypii and the control ones at different temperatures and analyzed the components of leaf volatiles and their relative content. The results showed that the relative content of volatiles in damaged plants significantly increased with the increase of temperature at 15 to 30°C, and the emission rate was temperature dependent, however, the emission rate decreased obviously when the temperature exceeded 30°C. The main reason may be that higher temperature reduces the activity of synthetase. Li et al. (2019a) conducted a long-term climate warming simulation on Arctic plants, and found that the increase of temperature led to a tripling of

monoterpene emissions. Guidolotti et al. (2019) measured the emission of BVOCs from *Eucalyptus robusta* branches exposed to the increasing temperature, and found that the emission of isoprene increased and photosynthesis decreased with the increase of temperature from 30 to 45°C. Kivimäenpää et al. (2016) studies on the effect of high temperature on *Scots pine* trees have shown that the total emissions of monoterpene, sesquiterpene and some active compounds have increased by two to four times. Bamberger et al. (2017) found that net photosynthesis and stomatal conductance of plants decreased sharply under high temperature exposure, and isoprene emission of *Robinia pseudoacacia* increased by 6 to 8 times during high temperature treatment.

(3) Light: Light has an effect on plant photosynthesis rate, transpiration rate and stomatal conductance. Guenther et al. (1993) explained that leaf temperature and light could control the production of isoprene by affecting the precursor of isoprene, γ-dimethylallyl pyrophosphate (DMAPP) and isoprene synthase. Meeningen et al. (2017) conducted light gradient experiments on three common European tree species, and found that isoprene, cyprinene, α-pinene and others all showed high light response. In the afternoon, the temperature dropped and the emission of volatiles decreased, which was consistent with the normal metabolism of plants.

3.3. Stress factors

The stress factors include damage, carbon dioxide concentration, ozone concentration. (1) Damage: BVOCs emission rate is significantly affected by interference (disturbance and stress) and damage. Animals, insects, herbivores feeding and human disturbance can stimulate BVOCs emission (Ye et al., 2018; Faiola et al., 2019). (2) CO_2 concentration: At present, the research results on the effect of CO_2 on BVOCs are different. Some studies have found that high concentration of carbon dioxide can promote BVOCs methods (Jasoni et al., 2004), but some studies have also revealed that high concentration of carbon dioxide fumigation can inhibit BVOCs emissions (Rosenstiel et al., 2003; Loreto and Sharkey, 1990; Possell et al., 2005; Michael et al., 2004), even some studies have found that the impact of carbon dioxide concentration on BVOCs emissions is not obvious (Rapparini et al., 2004; Constable et al., 1999). (3) Ozone concentration: Considering the important influence of BVOCs on atmospheric photochemical process and the complex interaction between ozone and BVOCs, many international researchers begin to pay attention to the response of BVOCs to ozone stress. Compared with plants growing under natural environment, ozone stress can stimulate (Li et al., 2009; Calfapietra et al., 2008), inhibit (Cojocariu et al., 2005; Acton et al., 2018; Feng and Yuan, 2018) or not affect (Vuorinen et al., 2005) the release of BVOCs. These varied responses mainly depend on the type of BVOCs, ozone exposure concentration, ozone exposure time, vegetation type and even different growth stages of plant leaves.

Furthermore, there are few studies on BVOCs emission patterns under the combined effect of biotic and abiotic stresses, future research should strengthen the multi-factor interactive studies, which will provide valuable theoretical support to air pollution control.

4. BVOCs emission inventory in different regional scales

4.1. Researches on BVOCs emission rate

In recent years, many scholars have studied the emission rate of BVOCs in certain tree species in their countries, and the general conclusion is that isoprene is mainly emitted by broad-leaf trees, while monoterpenes are mainly emitted by coniferous species. Aydin et al. (2014) studied the BVOCs emission rate of 31 tree species with 98% coverage in Turkey, and found that *Abies fabri, Quercus, Populus* davidiana, and *Robinia pseudoacacia* have higher isoprene emission rates; *Pinus, Corylus avellana* and *Castanea mollissima* have higher monoterpenes emission rates; and emission rate of sesquiterpene is generally low. Okumura et al. (2018) studied the emission rates and rules of 14 bamboo species in Japan, and found that most bamboo species are high-isoprene emission species. For countries with large planting area of Japanese *Phyllostachys pubescens*, the impact of *Phyllostachys pubescens* forest on the increase of atmospheric ozone concentration and atmospheric oxide cannot be ignored (Matsunaga et al., 2017). Acton et al. (2016) studied the BVOCs emission fluxes of *Carpinus turczaninowii* and *Quercus* mixed forest in northern Italy, and the results showed that *Carpinus turczaninowii, Corylus avellana* and *Acer campestre* have higher monoterpenes emission; and *Quercus* have higher isoprene emission.

As we know that trees absorb carbon from the atmosphere through photosynthesis, the tropical forests are estimated to absorb up to 1.3 Pg of carbon per year (Lewis et al., 2009). Some of the assimilated carbon is released back into the atmosphere in the form of reactive volatile organic compounds, such as isoprene and monoterpenes. Especially in the tropics, which are considered to account for half of the world's VOC emissions (Karl et al., 2004). Sahu et al. (2015, 2016) pointed out that in an urban site in India, isoprene, as one of the primary VOCs, the average mixing ratios was 1.1 ± 0.47 ppbV, coming from biogenic and anthropogenic sources. And he also (Sahu et al., 2017) researched the sources and characteristics of volatile organic compounds (VOCs) in a metropolitan city of India during winter to summer transition period by using proton transfer reaction time-of-flight mass spectrometer (PTR-TOF-MS) instrument. The results showed that the contribution of biological and secondary sources to OVOCs and isoprene increased by 10%-15% from winter to summer, providing an important reference for the role of biological emissions in air quality in tropical urban areas. Jones et al. (2011) used gas chromatography flame-ionization detector (GC-FID) to observe isoprene, α-pinene, camphene, 1-3-carene, γ-terpinene and limonene, as well as oxygenated VOCs such as methacrolein above a tropical rainforest in Malaysian Borneo. Among them, isoprene was the single largest volatile carbon source, while monoterpenes were found to contribute a comparatively smaller, but still significant fraction. Yadav et al. (2019) analyzed a wide variety of atmospheric non-methane volatile organic compounds (NMVOCs) first time in an urban atmosphere Sahu et al. (2016) of western India by using a GC-FID technique. The results showed that the mixing ratio of isoprene was highest of 1.6 ± 0.3 ppbV in April and lowest of 0.5 ± 0.3 ppbV in August. The elevated values of isoprene in the pre-monsoon season indicate significant emissions from biogenic sources. Chaliyakunnel et al. (2019) used a high resolution nested chemical transport model (GEOS-Chem) simulation for the Indian subcontinent to carry out the atmospheric inversion focusing on VOCs emissions, and found that modeled biogenic VOCs emissions to be overestimated by about 30%-60% for most locations and seasons, and derive that the best biogenic flux in 2009 of the subcontinent wide was estimated to be 16 Tg C/year. Biogenic emissions were still the largest VOCs source over the Indian subcontinent.

As for the emission rate, Varshney and Singh (2003) measured isoprene emission rates from 40 tropical Indian tree species for the first time by using a dynamic flow through enclosure chamber technique, and found that the species with the maximum isoprene emission rate was *Dalbergia sissoo Linn*, about 81.5 μg/(g·hr). Malik et al. (2018) examined 49 representative plant species of the Achanakmar-Amarkantak Biosphere Reserve forest of Central India for emission of a number of biogenic volatile organic compounds (BVOCs). The emission rates of different plant species were ranged from negligible to 80.6 ± 0.82 μg/(g·hr). Forty-seven plant species were found to emit isoprene and monoterpenes. Alpha-pinene (α-pinene) was found as the most dominant monoterpene with about 41.40% of the total monoterpene emission. The emission rates of this study were considerable different compared to previous studies even for the same species. Aydin et al. (2014) investigated the normalized biogenic volatile organic compound (BVOCs) emission rates for thirty-one tree species that cover the 98% of national forested areas in Turkey. Sixty-five BVOCs classified in five major groups (isoprene, monoterpenes, sesquiterpenes, oxygenated sesquiterpenes, and other oxygenated compounds) were analyzed. Then found that isoprene was mostly emitted by broad-leaved trees while coniferous species mainly emitted monoterpenes. The highest normalized total BVOCs emission rate of 27.1 μg/(g·hr) was observed for oxygenated compounds were the third most prominent BVOCs group and sesquiterpenes had slightly lower contributions. Langford et al. (2010) made the above-canopy fluxes of isoprene, monoterpenes and oxygenated volatile organic compounds from a South-East Asian tropical rainforest in Malaysia by virtual disjunct eddy covariance. They found that the dominant non-methane hydrocarbon emitted by the forest was isoprene, which accounted for 80% (as carbon) of reactive carbon fluxes measured, while the total monoterpene emissions only accounted for 18%. The fluxes of other VOCs including the oxygenated VOCs, methanol, acetaldehyde and acetone, accounted for less than 2% of the total reactive carbon flux. Misztal et al. (2011) measured the reactive biogenic volatile organic compounds (BVOCs) from oil palms by using proton transfer reaction-mass spectrometry (PTR-MS) in Malaysian Borneo, and found that at midday, the net isoprene flux constituted the largest part of all emitted, about 84%. Even that small amounts monoterpene were detected, oil palm is not a significant monoterpene emitter. Besides, they thought that the largest sources of BVOCs were floral emissions form oil palms, which are much higher than from a rainforest.

The emission rates of different tree species in foreign literatures are summarized in Table 3.

4.2. BVOCs emission amount in China

The research on BVOCs started in 1990s in China. After decades of research and development, some preliminary results have been achieved. At present, the BVOCs emission rate and emission are mostly based on direct measurement and Guenther models. The emissions are classified in to isoprene, monoterpenes and other VOCs. Based on the systematic observation data available in China, the emission rate of common tree species is in Table 4. The measured BVOCs emission rates are standardized and then applied to various models to calculate the regional BVOCs emission flux based on remote sensing images and forestry survey data. For example, Liu et al. (2018) estimated the emission of BVOCs over the Yangtze River Delta (YRD) region for year 2014, based on the interpretation of remote sensing image and moderate resolution imaging spectroradiometer (MODIS) data using the model of emissions of gases and aerosols from nature (MEGAN). And evaluate the influence of BVOCs emission on ozone formation. The biogenic emissions were estimated to be 18.86 × 10^5 ton/year over the YRD region for year 2014. Tables 5 and 6 show the national and regional total annual emission of BVOCs from natural sources in China, respectively. It should be noted that, there are only a few studies on standard emission factors of BVOCs in China, and the values observed by different scholars vary significantly. Therefore, the observation of emission rate needs to be carried out in depth and systematically.

Table 3 – BVOCs emission rate of different tree species.

Tree species	Isoprene (μg/(g·hr))	Monoterpenes (μg/(g·hr))	Countries	Tree species	Isoprene (nmol/(m^2·sec))	Monoterpenes	Countries	Tree species	Isoprene (μg/(g·hr))	Monoterpenes (μg/(g·hr))	Countries
Dalbergia sissoo	81.5 ± 17.78	–		*Phyllostachys heterocycla*	51.1 ± 7.7	–		*Nordmann fir*	2.26 ± 1.40	0.32 ± 0.21	
Ficus religiosa	76.5 ± 15.0	–		*Bambusa oldhamii*	63.9 ± 8.7	–		*Oriental spruce*	2.37 ± 1.79	3.69 ± 1.69	
Ficus infectoria	53.5 ± 2.04	1.9 ± 0.07	India (Malik et al., 2018; Varshney and Singh, 2003)	*Semiarundinaria fastuosa*	46.6 ± 3.9	–	Japan (Okumura et al., 2018)	*Sessile oak*	9.63 ± 7.83	0.013 ± 0.004	Turkey (Aydin et al., 2014)
Ficus glomerata	47.6 ± 6.80	–		*Phyllostachys bambusoides*	48.0 ± 11.8	–		*Eastern cottonwood*	4.72 ± 5.26	0.067 ± 0.044	
Eucalyptus globulus	49.9 ± 1.81	5.5 ± 0.23		*Phyllostachys aurea*	57.4 ± 11.0	–		*European aspen*	22.40 ± 11.2	0.22 ± 0.18	
Madhuca longifolia	64.8 ± 2.64	–		*Bambusa multiplex*	43.0 ± 6.6	–		*Black locust*	12.40 ± 11.10	0.071 ±0.029	
Syzygium cuminii	61.6 ± 1.80	4.4 ± 0.35		*Semiarundinaria yashadake*	40.4 ± 0.9	–		*River red gum*	5.14 ± 4.04	0.18 ± 0.18	
Peltaforum pterocarpum	48.4 ± 0.24	–		*Sinobambusa tootsik*	33.9 ± 7.5	–		*Sweet chestnut*	0.38 ± 0.50	14.20 ± 7.5	
Pterocarpus marsupium	44.7 ± 0.47	4.1 ± 0.16						*Orieantal plane*	27.0 ± 25.3	0.025 ± 0.006	
Bauhinia variegata	48.9 ± 2.60	–									

- refers to not detected.
Conditions: PAR = 1000 μmol/(m^2·sec), temperature (T) = 303 K.

Table 4 – Isoprene and monoterpenes emission rates of common tree species in some regions of China.

	Isoprene (μg/(g·hr))	Monoterpene (μg/(g·hr))	Regions
Cyclobalanopsis glauca	278.9	3.5	South China (Wang et al., 2002; Huang et al., 2011; Zhao et al., 2004)
Populus tomentosa	271.62	–	
Nelumbo nucifera	246.92	–	
Quercus glandulifera	222.17	–	
Caryotamitis	147. 96	–	
Salix babylonica	132.91	–	
Phyllostachys pubescens	116 0.04±23 0.35	–	
Broussonetia papyrifera	97.48	–	
Pleioblastus amarus	86.03	–	
Liqnidambar formosana	74.22	–	
Albizzia Jutibrissin	70.18	–	
Trachycarpus fortunei	60.38	–	
Salix chaenomeloides	58.81	–	
Mahonia fortunei	50.41	–	
Pragmites commanis	47.12	–	
Quercus fabri	43.12–211.12	–	
Lespedeza bicolor	40.33	–	
Dalbergia hupeana	34.12	–	
Adenanthera pavonina	33.45	–	
Bambusa multiplex	20–103	–	
Eucalyptus citrodora	17. 10	2.90	
Elaeocarpus apiculatus	13.48	–	
Camellia sinensis	13.39	–	
Ficus hispida	12.1±2.3	2.5±0.7	
Syzygium cumini	9.66	13.46	
Ficus benjamina	9.4	–	
Glochidion puberum	9.16	–	
Musa basjoo	8.28	–	
Typha orient	6.41	–	
Ficus altissima	6.28	–	
Eucalyptus robusta	5.6	0.13	
Indocalamus latifolius	4.87	–	
Bambusa vulgaris	2.7±0.6	11.9±0.7	
Koelreuteria bipinnata	2.1	6.33	
Duabanga grandiflora	0.8±0.3	3.1±0.7	
Pinus massoniana	0.7	1	
Litchi chinensis	–	15.32	
Avicennia marina	–	12.69	
Carmona microphylla	–	10.64	
Platanus orientalis	139±42	0.3±0.1	Beijing (Zhao et al., 2004; Wang et al., 2003)
Populus tomentosa	105.8±16.1	0.2±0.1	
Salix babylonica	70.2±9.3	3.7±2.6	
Sophora japonica	52.5±17.5	1.9±1.0	
Quercus	32.1±14.8	7.8±1.6	
Robinia pseudoacacia	37.3±2.1	2.3	
Quercus Mongolica	9.3	0.2	
Ilex chinensis	4.9±1.4	6.7±2.3	
Pinus tabuliformis Platycladus orientalis	0.4±0.1 0.07	19.0±4.5 2.2 ±0.4	
Malus pumila Mill	0.8±0.1	278±180	
Oryza sativa	0.7±0.17	15.8±9.2	
Lespedeza bicolor	0.33	0.1	
Prunus persica	0.2±0.1	6.6±0.1	
Ginkgo biloba L	<0.01	0.2±0.1	
Pyurs spp	0.4±0.1	1.4±0.5	
Triticum aestivum	<0.1	1.9±0.3	
Zea mays	–	0.35	
	Isoprene (mg/(m^2·hr))	Monoterpene (mg/(m^2·hr))	Regions
Grasslands	707	–	Inner Mongolia (Bai et al., 2003)
Tropical rubber plantation	0.9–1.1	–	Yunnan (Bai and Baker, 2004)
Tropical forest	0.25–0.75	–	Yunnan (Bai et al., 2004)
Broadleaf forest	–	0.242	Changbai Mountain (Bai et al., 2012)

- refers to not detected.
Conditions: PAR = 1000 μmol/(m^2·sec), temperature (T) = 303 K.

Table 5 – Total annual emission of BVOCs in China (g C/year).

Isoprene	Monoterpenes	Other VOCs	Total	Literature
1.5×10^{13}	4.3×10^{12}	9.1×10^{12}	2.8×10^{13}	Guenther et al., 1995
6.7×10^{12}	1.8×10^{12}	3.9×10^{12}	1.2×10^{13}	Wang et al., 2008
4.1×10^{12}	3.5×10^{12}	1.3×10^{13}	2.1×10^{13}	Klinger et al., 2002
7.5×10^{12}	2.2×10^{12}	3.1×10^{12}	1.3×10^{13}	Chi and Xie, 2011
5.7×10^{12}	1.3×10^{12}	1.5×10^{12}	8.6×10^{12}	Zhang and Xie, 2009
1.0×10^{13}	5.5×10^{12}	4.3×10^{12}	2.0×10^{13}	Song et al., 2012

Table 6 – Regional total annual emission of BVOCs in China (g C/year).

Regions	Isoprene	Monoterpenes	OVOCs	Total	Literature
Beijing	1.4×10^{10}	0.78×10^{10}	2.63×10^{10}	4.8×10^{10}	Kilnger et al., 2002
Tianjin	0.69×10^{9}	2.9×10^{9}	4.1×10^{9}	7.7×10^{9}	Gao et al., 2016
Hangzhou	6.8×10^{10}	4.9×10^{9}	5.4×10^{9}	7.8×10^{10}	Chang et al., 2012
Hong Kong	2.6×10^{9}	3.4×10^{9}	2.6×10^{9}	8.6×10^{9}	Tsui et al., 2009
Taiwan	8.0×10^{10}	6.5×10^{10}	6.9×10^{10}	21.4×10^{10}	Chang et al., 2005
Pearl River Delta	6.4×10^{10}	8.9×10^{10}	6.9×10^{10}	22.1×10^{10}	Zheng et al., 2009
Yangtze River delta	7.04×10^{11}	3.03×10^{11}	8.79×10^{11}	18.8×10^{11}	Liu et al., 2018
Eastern China	5.1×10^{12}	3.6×10^{12}	2.7×10^{12}	11.4×10^{12}	Song et al., 2012

5. Effects of BVOCs on ambient air quality and human health

5.1. *Effects of BVOCs on ambient air quality*

5.1.1. *Effects of BVOCs on ozone formation*

In recent years, ozone has become the second only to particulate matter as another atmospheric pollutant, and has even become the major pollutant in many areas. Ozone is harmful to the ecological environment and human health. It will not only result in premature decay and shedding of plant leaves, but also affect human lung function and health. As the main component of VOCs in atmosphere, BVOCs are one of the main contributors to troposphere ozone generation. In urban areas, BVOCs released into the atmosphere are far less than anthropogenic volatile organic compounds (AVOCs) discharged by human beings, but the reaction of BVOCs are faster due to the higher activity of them, especially isoprene, the main component of BVOCs, whose OH reaction rate constant ranks first among the main VOCs, making a great contribution to the generation and accumulation of ozone. Early studies have shown that a series of complex photochemical reactions caused by VOCs and NO_x, non-methane hydrocarbons (i.e. volatile organic compounds, ozone precursors) increase the concentration of ozone in the troposphere by about 17% (Houweling et al., 1998), and increase the concentration of ozone near the ground by 50%-60%, resulting in an increase of ozone in the marine atmosphere by about 40% (Poisson et al., 2000). In Beijing area (Shao et al., 2005), the olefin, which accounts for only 15% of the VOCs mixture in the atmosphere, provides about 75% of the chemical active substances in the atmosphere. Mo et al. (2018) employed a mass balance technique-box model to calculate the biogenic isoprene emissions based on the ground-level measurements between October 2009 and September 2010 in Beijing, and they found that the isoprene emissions contributed half (49.5%) of the total ozone formation potential (OFP). Sahu (2012) pointed out that in the photochemistry of tropical troposphere, VOCs play a key role due to high abundance of water vapor (H_2O) and intense solar radiation flux. In the Atlanta area of the United States, the quality of atmospheric environment did not improve after the control of anthropogenic pollution emissions, because of ozone pollution caused by large amounts of isoprene released by plants (Chameides et al., 1988). Zou et al. (2019) using an online gas chromatography-flame ionization detector (GC-FID) system to investigate the effect of isoprene on the ozone peak profile, and found that isoprene ranked first with regard to ozone formation potential (OFP) and propylene-equivalent mixing ratio among 56 measured non-methane hydrocarbons (NMHCs). Li et al. (2019b) applied the regional chemistry and transport model to analyze summertime ozone observations over the contiguous United States, and found that ozone peak time is sensitive to isoprene emissions and increasing isoprene emissions leads to earlier peak time. Simon et al. (2019) conducted a box model study for a selected region in Germany and indicated that higher ozone levels with higher isoprene concentration, especially in non-saturated atmospheres. Nishimura et al. (2015) studied the relationship between BVOCs emission and ozone generation in 10 areas around Osaka and found that BVOC emissions have a significant contribution to ozone concentration. The sum of the maximum generated ozone concentration in each area was up to 10.3 ppbV, and the contribution rate was up to 15.9%. Watson et al. (2006) studied the effect of isoprene on trace gas components in urban troposphere using a two-box atmospheric chemical model, and found that isoprene could reduce the concentration of hydroxyl radicals and nitrogen oxides in summer and increase the concentration of atmospheric ozone.

5.1.2. *Effects of BVOCs on secondary organic aerosols formation*

At present, BVOCs is considered to be one of the most important factors contributing to the formation and growth of secondary organic aerosol (SOA) (Hallquist et al., 2009). For example, isoprene alone contributes about 50% of SOA in the United States (Liao et al., 2007). However, before the 21st century, the academia generally believed that BVOCs had no contribution to the formation of SOA. For example, Pandis et al. (1991) conducted simulation experiments by introducing natural hydrocarbon organic compounds into smoke boxes, and found no formation of SOA. Until the beginning of the 21st century, the contribution of BVOCs to the formation of SOA was not recognized. Ruppert and Becker (2000) found that isoprene has its own secondary cycle and interaction mechanism through smoke box experiment, and 2-methyl-4-butanol was produced through two-step oxidation process. Subsequently, Claeys (2004) found and identified two optical isomers of 2-methyl-4-butanol that retained the structure of isoprene parent nucleus through sampling in the amazon rainforest, and verified the experimental results of Ruppert and Becker (2000). Studies in the last decade (Wang et al., 2008) have shown that the reaction of isoprene with ·OH is more important, and the reaction rate is significantly higher than the oxidation reaction with ozone and NO_3·, which is the main source of SOA formation. Zhang et al. (2018) suggest that SOA from monoterpene oxidation accounts for approximately half of summertime in Centreville, AL (Alabama, USA), a forested area in the southeastern United States. The saturated vapor pressures of products generated in BVOCs reaction are low, so secondary organic aerosols (SOAs) can be formed through further oxidation, nucleation, condensation and other processes (Xiong et al., 2013). SOAs are the main sources of $PM_{2.5}$ in the ambient air. In an article published by Nature UK in 2014, it was revealed that SOAs account for 27% of $PM_{2.5}$ mass concentration on average (Huang et al., 2014). Geng et al. (2011) studied the reaction of isoprene and OH radicals to generate SOAs using a smoke box simulation device, and obtained the amount of SOAs generated and its median particle size increased the increase of isoprene reaction amount. After the gas phase materials kept stable, the SOAs yield ranged of 5.6% to 11.7%, and the particle size ranged from 22 to 165 nm. Kleindienst et al. (2007) analyzed the content of secondary organics in the atmospheric particulate matter samples of Research Triangle Park in the United States, and found that the secondary organics formed by isoprene, α-pinene, toluene and β-syringene contributed a lot to the total organics. For BVOCs, different volatiles have different fractional aerosol coefficient (FAC) values. The FAC values of methyl cyclohexane, *n*-undecane, *n*-decane, methyl-benzene, ethyl-benzene, *o*-xylene, isoprene, monoterpenes were 2.7%, 2.5%, 2%, 5.4%, 5.4%, 5%, 2%, and 30%, respectively. It can be seen that the SOA formation potential of monoterpenes is the largest in terpenes.

5.2. *Effects of BVOCs on human health*

5.2.1. *BVOCs components beneficial to human health*

Studies show that the allelopathy of other organisms on human in environment such as forest and green space mainly comes from the volatile components of plants. All of these components have effects on human physiology and psychology through stimulation such as olfaction. Guo et al. (2010) studied *Rhus typhina* using natural sedimentation and found that volatile organic compounds emitted by it could effectively inhibit bacteria in the ambient. Hu (2007) studied the inhibitory effects of BVOCs in the leaves of eight common green plants (*Cinnamomum camphora, Podocarpus macrophyllus, Nerium indicum, Buxus megistophylla, Viburnum odoratissinum, Photinia serrulata, Sabina chinensis* and *Cedrus deodara*) on *Escherichia coli* and *Staphylococcus aureus*, and found that BVOCs emitted by the leaves of eight plants had a good bacteriostatic effect on the tested strains. In addition to the antibacterial and bacteriostatic effects, the beneficial volatile components can also exert two effects through breathing: (1) eliminating fatigue, promoting sleep, making the human body in a relaxed state; (2) refreshing, making the human body in a moderate state of tension awake, and improving work efficiency. Terpenes have strong physiological effects, and can stimulate autonomic nerves, stabilize temperament, promote endocrine, regulate sensory system and concentrate spirit. They also have effects such as analgesic, antibacterial, antihistamine, anti-inflammatory, anti-rheumatic and anti-tumor, promote bile secretion, diuretic, expectoration, lowering blood pressure, detoxification and anti-diarrhea. Japanese scholars have used the sum of the relative contents of monoterpenes and sesquiterpenes as an indicator to measure the health effects of plants. Among them, terpenes such as α-pinene, caryophyllene, *d*-limonene, phellandrene, myrcene and cedarene have effects of anti-cancer, bacteriostatic, insect repellent and insect killing. Carvone has a defensive activity. Zheng et al. (1992) found in the test tissue of mice that carvone can induce the production of detoxifying glutathione transferase in vivo. The 1,8-eucalyptus oil can increase blood flow in the human brain. Linalool can reduce myocardial oxygen consumption and improve the symptoms of hypertension patients. Decanal and ethyl acetate can make human feel happy in the natural state. And nonanal and most organic acids have strong inhibitory and killing effect on common contaminated bacteria in food.

5.2.2. *Harmful effect of BVOCs to human health*

Some BVOCs components have adverse effects on human body. For example, 3-camphene is an insect inducer that has no obvious inhibitory effect on insects. When inhaled at high concentrations, it can cause bronchoconstriction in animals, aggravate skin allergy reaction and even cause lung diseases. Dichloromethane and trichloromethane in halohydrocarbons account for a relatively high proportion of emissions in the whole year and are harmful to human central nervous system and respiratory system. Benzene and toluene in benzene series can cause adverse reactions in humans, such as headache, inattention and nausea. Other BVOCs components that may cause damage to human health need to be further studied.

6. Conclusions and prospects

This paper summarizes the research methods, components, influencing factors of emission rate, the impact of BVOCs on the environment, atmosphere, plants and human health, the emission rate and emissions of the main plants in China. The main conclusions and suggestions are as follows:

(1) The research results of BVOCs are quite sufficient in the United States and parts of Europe, scattered in China with incomplete data of emission rate. It is necessary to establish BVOCs observation network in the Pearl River Delta, Yangtze River Delta, Beijing-Tianjin-Hebei region with serious air pollution in China, to obtain the emission characteristics of BVOCs, and calculate the emissions, so as to facilitate in-depth study of its impact on SOA and ozone.

(2) The knowledge of BVOCs components is mainly focused on isoprene, monoterpene and other components, but there are few studies on the identification and emission intensity of other hydrocarbons and oxygen-containing volatile organic compounds. Although in general, isoprene and monoterpene account for about 70% of the total BVOCs emissions, the contribution of other active VOCs to ozone and SOA should not be ignored. It is suggested to pay attention to the emission characteristics, the chemical and physical properties in the atmosphere of other active VOCs during observation.

(3) The research methods of BVOCs of plant emission are field observation and model method. Field observation can be divided into direct measurement method and micrometeorological method. These two methods are both widely used. However, in order to make the data comparable, it is necessary to unify the observation methods. It is suggested to use field direct measurement method to obtain the emission rate and model method to calculate the emission amount.

(4) BVOCs emission measurement data of grassland, crops and other vegetation types are still lacking, and other VOCs of these vegetation types accounts for a large proportion of the total emissions in some areas, so we should increase the research on such vegetation in the future to make the estimation results of BVOCs more accurate.

(5) Under the external pressure stress (insects, CO_2, etc.) and the combined impacts of several influencing factors (such as ozone and drought, CO_2 and drought, etc.), the research on BVOCs emission is less, and the research on BVOCs response of plants under the influence of environment

and climate interaction needs to be strengthened. The enhancement of the study of BVOCs in some unstudied regions, such as tropical Asia and modeling of BVOCs are also suggested.

Declaration of competing interest

None.

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