Are we conscious of isoprene emissions from our poplar plantations?

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The growing energy demand and increasing pollution due to conventional energy sources prompted the concept of bioenergy plantations, which are considered as carbon neutral. The area under bioenergy plantations is increasing rapidly to meet economical and ecological societal needs. Poplar is one of the most important sources of green energy amongst all species. It is widely cultivated as a bioenergy crop due to its fast growth, short rotation and carbon neutrality. However, one of the major aspects that we must consider is that it is a strong emitter of isoprene which can alter ozone flux in the atmosphere. Owing to its extremely reactive nature, isoprene may substantially influence the tropospheric composition by affecting its oxidative capacity with serious impact on air health, global warming, ecological functions and thus human life. We should assess isoprene emissions from existing poplar plantations and the expected increase in isoprene load with future expansion of poplar plantations in India, to know their long-term effect on atmospheric chemistry and climate change. This will help in deciding whether we should further promote poplar plantations, or look for suitable alternative non-/low-emitting species for bioenergy plantations.

Keywords: Bioenergy plantations, global warming, isoprene, ozone, poplar.

INCREASING pollution, deficit resources of fossil fuels and issues of energy security paved the way for the exploration of green energy sources. Use of woody biomass is increasing in India and all over the world. Amongst all green energy sources, poplar has emerged as the most potential source of bioenergy. Poplar, being a fast-growing and short-rotation crop, is suitable and highly productive for energy plantations. It is being extensively used in short-rotation bioenergy plantations for the production of cellulose worldwide. Such energy plantations of poplar are common in India and China[1,2]. Poplar as a source of bioenergy is a renewable substitute to fossil fuels[3]. The green sources of energy are carbon neutral and possess carbon sequestration potential. Therefore, the attraction of bioenergy plantations is not limited to economic interests alone, but these energy sources also have tremendous potential to mitigate climate change and global warming[4]. However, one facet of the bioenergy plantations has not been given due attention which certainly impacts their environment-friendly status. This aspect is the release of BVOC (biogenic volatile organic compounds) by vegetation, particularly the chosen bioenergy trees. Vegetation-originated emission of VOCs has been estimated to be ten times higher than those released by anthropogenic sources on the global basis[5]. Isoprenoid is one of the most abundant and significant groups of BVOCs. Isoprene, a chemical constituent of the isoprenoid group, represents about 50% of the global BVOCs emission. It produces a diversity of compounds on reacting with OH and NO_x through a chain of reactions. These compounds are carbon monoxide, ozone, organic acids, nitrates, peroxyacetyl nitrate and aerosols[6]. Most of the tree species planted in the bioenergy plantation (poplar, willow, eucalyptus and oil palm) across the world are strong emitters of isoprene. Green sources of bioenergy are considered as carbon neutral, but isoprene emission from bioenergy trees may have a greater impact than CO_2 on atmospheric composition. Poplar plantations are expanding rapidly for production of biomass, which would enhance tropospheric ozone by increased isoprene emission, detrimental to ecosystem and human health.

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International and national status of poplar

The poplar cover under plantations was estimated to be 31.4 million ha in 2016 across the world[7]. Different proportions of global area under poplar plantations serve different purposes, such as 58% area is managed for multifarious uses, 30% for procurement of wood, 9% for environmental health and management, and rest 3% for meeting the energy needs in terms of fuelwood. Canada recorded the highest area under poplar (69% of the global poplar area) followed by China (27%). France has 0.2 million ha under poplar, whereas USA, Turkey, Spain and Iran each have 0.1 million ha poplar plantations. In agroforestry systems, poplar and willow together constitute 6.3 million ha area, of which maximum is occupied by poplar (95%). Mixed plantation of poplar and willow contribute to 4%, whereas only 1% area is under willows[7].

India has 32.57 m ha area under forest plantations, which constitutes 17% of the total plantation area in the world. The country boasts of having the second largest plantation area in the world, followed by China. Poplar and eucalyptus are the major species in the forest plantations in India along with other species such as acacia, silver oak and rubber wood[8]. The National Poplar Commission, quoting the Forest Survey of India (FSI), has reported 317,800 ha area under poplar in the country (includes area 270,000 ha under *Populus deltoides* in agrforestry plantations)[9].

What is isoprene?

The simplest form of isoprenoid is isoprene, which is chemically 2-methyl-1,3-butadiene. Most of the trees grown in bioenergy plantations like poplar and willow are strong emitters of isoprene. The share of woody plants in total global isoprene emission to the atmosphere is 75%. Isoprene is one of the most abundant VOCs emitted by biogenic sources. Approximately 0.5–0.6 Pg C per annum is released as isoprene on the global basis, constituting half of the total BVOCs, one third of non-methane hydrocarbon release[5,10] and is nearly similar to methane flux to the atmosphere[11]. Biosynthesis of isoprene takes place in chloroplasts through the methylerythritol 4-phosphate (MEP) pathway, where dimethylallyl diphosphate (DMADP) changes to isoprene with the help of an enzyme known as isoprene synthase. Depending on the concentration of nitrous oxide, it can alter ozone fluxes (increase/decrease) in the atmosphere by oxidation[12]. Many researchers have recently supported the fact that VOC release from vegetation may significantly alter troposphere composition by the formation of ozone and secondary air pollutants[13]. The chemical compounds of the isoprenoids group, especially isoprene, feed the NO–NO_2–O_3 cycle, thus resulting in the formation or degradation of ozone in the troposphere[14]. Geng *et al.*[15] observed that the BVOC release from prominent forest types located to the south of Shanghai, China, enhanced ozone production (6–8 ppb h^{-1}) in the city, primarily due to the carbonyl formation as a result of constant isoprene oxidation in the forest air. The substantial formation of ozone due to isoprene (12–14%) occurs when the VOC/NO_x ratio lies between 4 and 12, according to studies conducted in Rio de Janeiro[16]. On the basis of output from MEGAN (Model of Emissions of Gases and Aerosols from Nature), Pike *et al.*[17] showed that isoprene emission peak in the Northern Hemisphere in July corresponds to increase in ozone owing to the simultaneous release of isoprene and NO_x from biogenic and anthropogenic sources respectively. Isoprene scavenges the OH radicals and alters the atmospheric composition by affecting its oxidative capacity, and thus the lifespan of atmospheric methane, condensation, nucleation or formation of secondary organic aerosols (SOAs)[18]. Claeys *et al.*[19] provided the first field evidence for the contribution of isoprene to ambient organic aerosol formation through oxidation in the Amazonian rainforest. They showed the presence of 2-methyltetrols compounds in aerosols having the same carbon skeleton as isoprene. Further studies strongly suggested that isoprene oxidation results in the production of methyltetrols, thus indicating that isoprene is an important precursor of SOAs. A growing body of literature subsequently indicated that oxidation of isoprene significantly influences SOA production in the troposphere[20–23]. Even if the production is small (say 1%), isoprene can substantially enhance the total atmospheric POM (particulate organic matter) to a greater extent (e.g. 6 Tg yr^{-1}) due to large global emission and its high reactivity. Pike *et al.*[17] suggested that isoprene may cause 22.5% increase in the lifespan of tropospheric methane by acting as a scavenger for OH radicals. Thus isoprene emission can seriously impact atmospheric pollution, climate change and global warming.

BVOC emission in poplar

All species of poplar studied till date are isoprene emitters. They emit isoprene in response to biotic (infestation by microorganisms and herbivores) and abiotic (heat, drought, oxidative stress, etc.) factors. Usually emission of BVOCs varies in their mixing ratios depending upon inducing stimulus and emitting species (Table 1)[24–26].

Functions of isoprene in plants

Production of isoprene is expensive for the plants[27]. The utilization of carbon for biosynthesis of isoprene under stress conditions favours the theory that isoprene plays a protective role under environmental stresses. It had been reported that isoprene plays an important role in the protection mechanism of plants against heat and ozone damage[28,29]. At high temperatures, synthesis of isoprene in the leaves gets elevated indicating its role against high-temperature episodes. This may be due to the fact that isoprene has low heat capacity compared to water[27]. The role of isoprene is not limited to protection against heat, but extends to the recovery of plants post heat episodes. However, the defence mechanism of plants against heat stress through isoprene emission is still not clearly understood. The most popular theory about the protection

Table 1. Emission of BVOCs (biogenic volatile organic compounds) in response to stimuli in poplar

Stress factor	BVOCs emitted	Reference
Forest tent caterpillars and moth larvae	A mixture of various monoterpenes and sesquiterpenes (β-ocimene, linalool, α-farnesene, (E)-4,8-dimethyl-1,3,7-nonatriene (DMNT), germacrene D and caryophyllene)	24
Weevil and poplar leaf beetle	Monoterpenes and homoterpenes (mainly β-ocimene, DMNT and linalool)	24, 25
Ozone stress	Monoterpenes (α- and β-pinene), homo and sesquiterpenes (ocimenes, DMNT, TMTT, α-farnesene, farnesol)	24, 26
Pathogenic fungus (*Pollacia radiosa*)	Monoterpenes, ocimene DMNT and α-farnesene	26

mechanism of isoprene is that it stabilizes the thylakoid membrane by interacting with the non-polar components of the membrane due to its hydrophobic nature, thus making them resistant to denaturation[27]. Research conducted in the case of transgenic poplar (non-isoprene emitters) clearly showed the function of isoprene in the protection mechanism against heat stress by net CO_2 assimilation and photosynthetic electron transport[30,31]. Many researchers also reported that the antioxidant property of isoprene may possibly be attributed to its potential of quenching reactive oxygen species (ROS) generated under oxidative stress (induced by ozone, salinity, drought and also sunflecks)[32,33]. According to Vickers *et al.*[33], the antioxidant characteristic of isoprene is due to its double bond, an attribute of all higher compounds of the isoprenoid group which show antioxidant nature. Isoprene synthesis performs a regulatory function in the MEP (methyl-D-erythritol-4-phosphate) pathway, which is primarily responsible for the production of important isoprenoids in plants. During oxidative stress caused by drought, biosynthesis of isoprene limits the build-up of DMADP by biochemical feedback down regulation of the MEP pathway utilizing the excessive reducing power[34]. Recent work has also shown the direct and indirect roles of isoprene in the protection mechanism against herbivore infestation. Laothawornkitkul *et al.*[35] reported that isoprene emission discourages feeding of *Manduca sexta* caterpillars in transgenic tobacco (*Nicotiana tabacum* cv. Samsun). It protects the plant from generalist pests[36,37]; thus alien species which lack specialist parasites may get benefit being emitters[35,38].

Discussion and conclusion

There is expected increase in area under bioenergy plantation globally through afforestation on marginal land and apportioned agricultural lands to fulfil the demand for energy. Wiedinmyer *et al.*[39] simulated the worldwide changes in isoprene release due to anticipated land-cover changes in future through model-based projections. They estimated 889 Tg yr^{-1} of isoprene emission on the global basis using future temperature and land-use variables for predictions. Land-use changes due to anthropogenic factors such as population pressure, conversion of natural forests to plantations and modernization can enhance isoprene load, consequently increasing tropospheric ozone and photochemical air pollutants at the regional level. With promotion of bioenergy plantations and short rotation crops worldwide, these effects will be serious, particularly at a regional scale[40]. For example, large-scale conversion of land in China for raising tree plantations (e.g. eucalyptus and rubber trees) for commercial use had increased isoprene loads to a great extent[41]. Fowler *et al.*[42] reported three times higher biosynthesis of isoprene due to expansion of oil palm plantation on 27 M ha land than native crops in Southeast Asia, causing 11% increase in surface ozone. Ashworth *et al.*[43,44] predicted that expansion of 72 Mha area under poplar to fulfil the anticipated requirement of biomass as a non-conventional source of energy in the European Union, will lead to 39% increase in isoprene emissions. Similarly, O_2/O_3 ratios are anticipated to be high up to 2.26 ppb due to increased isoprene load following the expansion of short-rotation crops, mainly poplar in the temperate Northern Hemisphere (Eurasia, North America, and China)[43,45]. Results from past simulation studies suggested that higher rate of isoprene emission due to increase in area under poplar-based bioenergy plantations would substantially alter ozone level in the atmosphere, threatening ecosystem processes and human life. In India also, the area under bioenergy plantations is expected to increase at a large scale to fulfil the huge demands of industries. Pulpwood industries in India promoted bioenergy plantations through farm forestry under several schemes to fullfil the requirement of raw material. Area under bioenergy plantations reached nearly 343,000 ha by 2005 in a period of 16 years as a result of serious efforts made by the paper industries. At present, the target of paper industries is to expand plantations in an area of 65,000 ha per annum. However, to fulfill the additional need of 3 million tonnes per annum of pulpwood, 50,000 ha more area of bioenergy plantations is required at the prevailing productivity range. Therefore, the target is to plant 115,000 ha under poplar and eucalyptus every year to meet the demand of pulpwood[46]. However we lack information on isoprene estimation through such massive plantation drives in the country. Isoprene emissions due to poplar plantation in

India should be assessed, and the impact of isoprene load on air pollution and global warming must be analysed. Future planning of expanding area under bioenergy plantations through poplar should be based on prediction of isoprene emissions by simulation studies, and its impact on regional air health, atmospheric chemistry and global warming.

Solutions/recommendations

- Regional studies should be conducted to determine NO_x concentration in a particular area, as isoprene will increase or decrease ozone flux depending on nitrous oxide concentration of that area.
- Poplar germplasm should be screened for isoprene emission to identify low-emitting lines. Research should be carried out on developing low isoprene-emitting transgenic poplars through genetic manipulation.
- Other plant species suitable for bioenergy plantations, e.g. *Melia dubia* should be screened for isoprene emissions.
- Native species should be preferred for bioenergy planation as it was found that their isoprene biosynthesis/emission rate is lower than co-occurring alien species[36].
- Local species should be given priority in comparison to hybrids as tree genera characterized by extensive speciation and hybridization were observed to emit isoprene more frequently than their phylogenetically nearest non-speciose genera[47].

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