

Photonic Sensor–Based Quantification of Harmful Gas Uptake Efficiency in Roadside Air-Purifying Plant

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Abstract: Urban roadside areas experience high concentrations of nitrogen oxides (NO_x), sulphur dioxide (SO₂), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM), all of which negatively affect human health and environmental quality. Certain plant species are known to naturally absorb, metabolize, and reduce these pollutants, but accurate, real-time quantification of their uptake efficiency remains limited due to a lack of precise and non-invasive monitoring tools. This study proposes a photonic sensor–based system to measure pollutant concentrations before and after interaction with selected roadside air-purifying plants. Using optical absorption and fibre-optic sensing techniques, the system detects wavelength-specific signatures of NO₂, SO₂, and VOCs, enabling continuous, high-sensitivity, and in-situ monitoring of pollutant reduction.

A spatial network of photonic sensors will be installed around targeted plants to generate real-time pollutant concentration gradients, from which plant-specific gas uptake rates will be calculated. Machine learning models will further analyze the data to identify diurnal variations, environmental influences, and species-wise differences in pollutant removal capacity. The study aims to identify the most efficient roadside plant species for air purification and develop a scalable, non-destructive framework for evaluating phytoremediation performance. Overall, the system supports smart, plant-integrated air quality monitoring and offers new insights for sustainable urban green-belt planning.

Keywords: Photonic sensors, Fibre-optic gas sensing, Air quality monitoring, Phytoremediation, Roadside plants, Gas uptake efficiency, NO_x and VOC detection, Optical spectroscopy

1. Introduction

Air pollution is no longer an abstract environmental issue; it is a daily experience for people living in urban areas. Traffic-dominated roads are among the most polluted spaces in cities, where emissions are released at ground level and human exposure is immediate. Gaseous pollutants such as NO_x, CO, SO₂, O₃, and VOCs are strongly associated with respiratory and cardiovascular diseases, reduced lung function, and premature mortality (WHO, 2021). In many developing and rapidly urbanizing countries, including India, roadside air pollution often exceeds national and international air quality standards.

To reduce pollution exposure, cities increasingly rely on green infrastructure such as roadside trees, hedges, and shrubs. Vegetation is appealing because it offers multiple benefits at once: aesthetic improvement, noise reduction, thermal comfort, carbon sequestration, and air pollution mitigation. Numerous studies have shown that plants can reduce local air pollutant concentrations through direct uptake and surface deposition (Nowak et al., 2006; Escobedo et al., 2011). Despite this, the effectiveness of roadside vegetation is frequently assumed rather than measured.

One major limitation is the lack of suitable measurement techniques. Conventional air quality monitoring stations are designed to represent city-wide or regional conditions and cannot resolve the fine-scale variations that occur within and around plant canopies. Chamber-based plant experiments provide valuable physiological insights but often fail to represent real roadside conditions. As a result, there is a clear need for monitoring tools that are sensitive, fast, and capable of operating under natural field conditions.

Photonic sensors provide a promising solution to this challenge. By using light to detect gases, these sensors enable real-time, continuous, and non-invasive measurements of pollutant concentrations. When deployed near roadside vegetation, photonic sensors allow researchers to directly observe how plants interact with polluted air. This chapter explores how such sensors can be used to quantify harmful gas uptake efficiency and how the resulting information can guide sustainable urban planning.

2. Roadside Air Pollution: Sources and Human Exposure

Roadside air pollution primarily originates from vehicular emissions, including exhaust gases from combustion engines and evaporative losses from fuels. Nitrogen oxides and carbon monoxide are emitted directly during combustion, while VOCs arise from incomplete

combustion and fuel evaporation. These primary pollutants undergo photochemical reactions in the presence of sunlight, leading to the formation of secondary pollutants such as ozone and secondary organic compounds (Seinfeld & Pandis, 2016).

Pollution levels near roads are highly variable and depend on traffic volume, vehicle type, driving patterns, road geometry, and meteorological conditions. Concentrations can change within minutes, creating short-term exposure peaks that are not captured by fixed monitoring stations. People who spend long periods near roads such as traffic police, street vendors, and residents are therefore at particularly high risk (Karagulian et al., 2015).

Understanding how roadside vegetation alters these highly dynamic pollution patterns requires sensing approaches that can operate at comparable spatial and temporal scales. Photonic sensors are well suited to this task because they can provide high-resolution measurements without disturbing the environment.

3. Plant-Based Removal of Gaseous Pollutants

Plants continuously exchange gases with the atmosphere as part of their normal physiological functioning. The most important pathway for gaseous pollutant uptake is through stomata, which open to allow carbon dioxide to enter the leaf during photosynthesis. Pollutants such as NO_2 and SO_2 can enter leaves via the same pathway and dissolve in the aqueous phase of leaf tissues, where they may be detoxified or assimilated into plant metabolism (Wellburn, 1994).

In addition to stomatal uptake, non-stomatal processes play a crucial role in pollutant removal. Reactive gases, particularly ozone, can be destroyed on leaf surfaces through chemical reactions with waxes and other surface compounds. Leaf morphology, surface roughness, and the presence of trichomes influence the efficiency of this process (Burkhardt, 2010). Microorganisms living on leaf surfaces can further contribute to pollutant degradation.

The effectiveness of pollutant uptake varies widely among plant species and is strongly influenced by environmental conditions such as light, temperature, humidity, and soil moisture. For example, during hot and dry conditions, stomata close to conserve water, reducing pollutant uptake. These biological factors must be considered when evaluating the air-purifying performance of roadside plants.

4. Fundamentals of Photonic Gas Sensing

Photonic gas sensors are based on the interaction between light and gaseous molecules. Each gas has unique optical properties that determine how it absorbs, scatters, or alters light at specific wavelengths. By analyzing these interactions, photonic sensors can identify and quantify individual gases with high sensitivity.

Common photonic sensing techniques include absorption spectroscopy, surface plasmon resonance (SPR), and fiber-optic sensing. Absorption-based sensors rely on the Beer–Lambert law, which relates light absorption to gas concentration. SPR sensors detect changes in refractive index at metal surfaces caused by gas adsorption and are known for their exceptional sensitivity (Homola, 2008). Fiber-optic sensors guide light through optical fibers, allowing measurements in environments where electrical sensors may fail.

These technologies offer several advantages for roadside applications, including fast response times, minimal drift, and the ability to operate continuously. Importantly, they can be deployed close to plant canopies without interfering with plant physiology.

5. Integrating Photonic Sensors with Roadside Vegetation

In practical applications, photonic sensors are strategically positioned around roadside vegetation to capture changes in pollutant concentrations as air moves through plant canopies. A common approach involves placing sensors upwind and downwind of vegetation belts, allowing the estimation of pollutant removal efficiency. More detailed studies may include vertical profiling within the canopy to capture spatial gradients.

Field deployment presents challenges such as temperature fluctuations, humidity interference, dust accumulation, and vibrations caused by traffic. Regular calibration and data correction procedures are essential to maintain accuracy. Despite these challenges, field studies have demonstrated that photonic sensors can reliably operate in roadside environments and generate valuable datasets for analysis.

6. Quantifying Gas Uptake Efficiency

Gas uptake efficiency refers to the ability of plants to reduce pollutant concentrations under given environmental conditions. Using photonic sensor data, uptake efficiency can be expressed as a percentage reduction, deposition velocity, or pollutant flux per unit leaf area.

These metrics provide a more meaningful assessment of plant performance than simple concentration measurements.

To interpret sensor data, concentration measurements are combined with meteorological parameters, airflow estimates, and plant characteristics. Empirical models are often used for initial assessments, while mechanistic models describe gas diffusion and deposition processes in greater detail. Recent studies have also explored machine learning approaches to analyse large sensor datasets and predict pollutant removal under varying conditions (Zhao et al., 2020).

7. Evidence from Field Studies

Field studies using photonic sensors have provided important insights into the air-purifying performance of roadside vegetation. For example, optical NO₂ sensors have been used to compare different urban tree species, revealing that species with higher stomatal conductance and rougher leaf surfaces tend to show greater pollutant uptake (Pugh et al., 2012). Fiber-optic sensors have also been applied to study VOC removal by ornamental shrubs planted along urban corridors.

These studies demonstrate that not all green infrastructure is equally effective. Species selection, planting density, and maintenance practices all influence pollutant removal outcomes. Sensor-based evidence therefore plays a critical role in guiding urban greening strategies.

8. Limitations and Research Challenges

Although photonic sensor-based approaches offer clear advantages, they also face limitations. Cross-sensitivity to humidity or interfering gases can affect measurement accuracy. Biological variability among plants and seasonal changes introduce additional uncertainty. Long-term monitoring and standardized methodologies are required to address these challenges and improve comparability across studies.

9. Future Directions and Smart Cities

The integration of photonic sensors with Internet of Things (IoT) platforms represents a major opportunity for urban air quality management. Real-time data from roadside vegetation can be transmitted to central systems, supporting dynamic decision-making in smart cities.

Advances in nanophotonic, low-power electronics, and artificial intelligence are expected to further enhance sensor performance and data interpretation.

10. Conclusions

Quantifying the air-purifying performance of roadside vegetation is essential for realistic and effective urban air quality management. Photonic sensors provide a powerful and human-centred approach to observing how plants interact with harmful gases in real-world conditions. By combining optical sensing with plant science, this approach moves beyond assumptions and provides measurable evidence to support greener and healthier cities.

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