Abstract

Due to the increasing burden of air pollution and the growing impact of bioaerosols on human health and the environment, there is a need to develop accurate, real-time monitoring methods for ambient particulate matter (PM) and airborne biological particles. Conventional monitoring techniques often fail to provide rapid, label-free, high-resolution analysis of particles, especially for distinguishing inorganic particulates from biologically significant aerosols such as pollen. This thesis offers an in-depth examination of novel optical and spectroscopic methods for the detection, visualization, and analysis of particulate matter and bioaerosols. Initially, bright-field imaging sensors are evaluated as a simple, cost-effective method for ambient particulate matter monitoring, which provides particle detection and size assessment through direct optical imaging. However, their limitations in terms of contrast and specificity require the implementation of more advanced label-free imaging techniques. Further, quantitative phase imaging (QPI) has been used for label-free imaging of ambient pollen grains. It is a powerful technique that provides high-resolution, label-free measurement of optical path-length fluctuations, facilitating comprehensive morphological and structural examination of airborne pollen grains. Ambient pollen grains of different shapes and sizes have been identified, and a pollen calendar has been prepared. The ability to perform non-invasive, high-throughput measurements makes QPI particularly suitable for continuous environmental monitoring applications. Furthermore, LED-based evanescent-field (LED-EFI) imaging is explored for its ability to enhance surface sensitivity, thereby improving contrast and enabling accurate morphological characterization of pollen without staining. LED-EFI offers a practical, cost-effective alternative to laser-based systems. The use of LEDs enables uniform illumination, reduced speckle artifacts, and greater system stability, making the technique more suitable for portable and field-deployable applications. Different sizes, shapes, and surface morphologies, including intine, exine, and apertures, are identified. To enhance classification accuracy and differentiate between various aerosol types, a multispectral microscopy system has been developed. This system uses multiple illumination wavelengths to capture particles' spectral responses, effectively creating a unique spectral fingerprint for each aerosol type. By integrating both spatial and spectral information, the system improves the ability to distinguish between inorganic particulate matter and biologically relevant aerosols. Following the imaging-based characterization of particle morphology, structure, and fluorescence properties, the thesis employs Surface-Enhanced Raman Spectroscopy (SERS) as a complementary molecular analysis technique to obtain the chemical fingerprints of the collected particulate matter and bioaerosols. By exploiting the enhanced Raman scattering generated on nanostructured metallic substrates, SERS enables highly sensitive detection of trace chemical constituents and biological markers within individual particles. This sequential integration of optical imaging and SERS combines morphological, structural, fluorescence, and molecular information which provides comprehensive and label-free characterization of airborne particles. The developed methodologies demonstrate significant potential for real-time environmental monitoring while addressing challenges associated with sensitivity, specificity, and particle identification. Furthermore, the thesis outlines future directions toward compact multimodal sensing platforms that integrate multiple optical and spectroscopic techniques into a single portable system. The incorporation of artificial intelligence and machine learning for automated data analysis, feature extraction, and classification is expected to further enhance identification accuracy and enable real-time decision-making for environmental monitoring and public health applications.