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Recent Advances in Multiparameter 2D Chemical Imaging of Environmental Samples with Optical Sensors (Optodes)

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Summary:
We review recent advancements in multiparameter chemical imaging with optodes. Our focus is on the latest developments in 2D optical chemical imaging using dual-emission and grid-based optodes. These novel sensor designs allow for the simultaneous mapping of essential environmental parameters, including oxygen, temperature, and pH. Applications in soil and marine sediments demonstrate the robustness, accuracy, and versatility of these sensors. Our findings emphasize the potential of multiparameter optodes for detailed analysis of biogeochemical processes in complex environments.

Keywords: optical sensors, imaging, multiparameter measurements, 2D visualization, chemical gradients

Background, Motivation, and Objective

Understanding chemical gradients and heterogeneities is crucial for monitoring and interpreting processes in natural and engineered environments. Optical sensors (optodes) have significantly advanced environmental monitoring by enabling non-invasive, real-time visualization of chemical gradients in two dimensions (2D) [1]. Recent research has focused on integrating multiple sensing functionalities into single sensing platforms, enabling comprehensive multiparameter imaging (e.g., O_2, temperature, pH).

Despite substantial progress, challenges remain regarding sensor calibration, integration, and practical implementation. Multiparameter imaging is essential for revealing interactions within environmental samples such as sediments, soils, and aquatic ecosystems.

The objective of this research is to address the existing challenges by introducing recent developments in polymer-based optode designs. Here, we summarize recent progress, outline remaining challenges, and illustrate the applicability of multiparameter 2D optical chemical imaging for improved understanding of complex environmental processes.

Description of the New Method

We present recent advances in multiparameter optical chemical imaging by developing and optimizing novel optode designs based on two approaches:

(i) Advanced dual-emission luminescent optodes [2]. This approach utilizes newly synthesized luminescent indicator dyes exhibiting dual-emission properties, combining thermally activated delayed fluorescence (TADF) and phosphorescence signals. Such optodes enable precise and reliable two-dimensional imaging of oxygen (O_2) and temperature distributions.

(ii) Grid-based optode arrays [3]. Building upon previously demonstrated sensor array concepts, we have developed innovative grid optode designs. These sensors consist of a regular array of sensing spots, each containing a defined chemical composition printed onto a transparent substrate. The layout resembles a checkerboard pattern where each spot functions as a discrete chemical sensor, enabling 2D mapping through spatially resolved optical readout. This approach facilitates the simultaneous mapping of various chemical parameters with high spatial resolution.

Results

Our results demonstrate successful applications of multiparameter optodes in 2D imaging of environmental samples. We highlight examples, including:

(i) Simultaneous imaging of O_2 and temperature distributions in heterogeneous soil.

We successfully visualized two-dimensional oxygen and temperature gradients in soil containing a water pipe system, which mimicked underground heat exchange conditions (see Fig. 1).

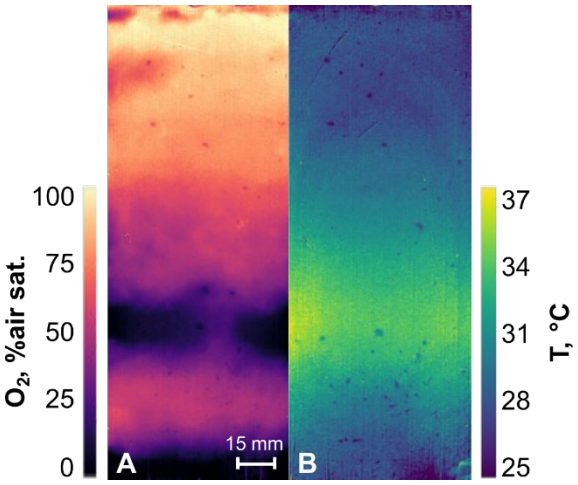

Fig. 1. 2D visualization of oxygen concentration (A) and thermal imaging (B) of heat transfer in soil with a heated water pipe [2].

The dual-emission mechanism significantly simplifies calibration, enhances measurement accuracy, and provides robust performance for rapid multiparameter imaging with minimal cross-interference.

(ii) Grid-based optode arrays for O_2 and pH mapping in marine sediments.

The developed grid optodes effectively mapped spatially resolved O_2 and pH gradients simultaneously within sulfidic marine sediments (see Fig. 2). These measurements provided detailed insights into sediment biogeochemical processes, highlighting the strengths of grid-based approaches for precise, spatially discrete multiparameter imaging in complex marine systems.

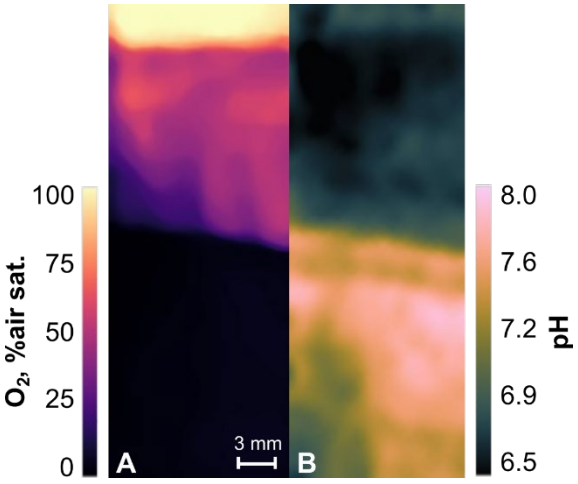

Fig. 2. (A) Oxygen concentration and (B) pH distribution image measured in sulfidic sediment using grid optodes [3].

Conclusions

Our results demonstrate the versatility and strong potential of multiparameter optical sensors for environmental applications. These recent developments significantly expand the analytical capabilities of optodes and pave the way for their broader use in monitoring, particularly for studying dynamic biogeochemical processes in heterogeneous samples.

References

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