

A miniaturized portable device for continuous sensing of environmental contaminants

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Summary:

This paper presents a compact, low-cost, and low-power device for multiplexed in situ detection of environmental contaminants in seawater. The system integrates microfluidics, electronics, and amperometric biosensors to perform up to eight simultaneous measurements. A novel pulsed-flow method ensures uniform fluid distribution across sensor chambers while reducing energy consumption. The device demonstrates good reproducibility (CV ~7%) and comparable performance to commercial potentiostats. Its portable design enables autonomous operation for real-time environmental monitoring. The platform shows strong potential for scalable and field-deployable biosensing applications.

Keywords: Lab-on-a-chip, time multiplexing, electrochemical sensors, environmental measurements

Introduction

In the last decade, the environmental, economic, and societal importance of marine ecosystems—particularly in Europe—has increased, with sectors such as aquaculture and fisheries strongly impacted by water quality [1]. Chemical contamination of coastal waters poses significant risks to ecosystems and public health, creating a need for early-warning systems capable of providing reliable, real-time data. Conventional analytical techniques, such as chromatography coupled with mass spectro-metry, offer high sensitivity but are limited by cost, complexity, and lack of in situ applicability [2].

To address these limitations, electrochemical biosensors, especially immunosensors, have emerged as promising alternatives due to their miniaturization, low power consumption, and suitability for field deployment [3]. Combined with microfluidic technologies, they enable automated handling, improved accuracy, and continuous monitoring. In this context, this work presents a validated, compact, low-cost, and low-power device for simultaneous detection of multiple contaminants in seawater. The proposed platform integrates microfluidics, electronics, and amperometric biosensors into a multiplexed system. A key contribution is the introduction of a pulsed-flow method that ensures uniform fluid distribution across multiple sensing chambers while significantly reducing energy consumption,

paving the way for scalable and autonomous environmental monitoring solutions.

Description of the System

The proposed device is a compact, portable platform designed for in situ and real-time monitoring of environmental contaminants in seawater. It integrates three main subsystems: a microfluidic module, an electronic control system, and an electrochemical sensing unit (Fig. 1). The module is responsible for handling and distributing the liquid samples and reagents through a network of channels, valves, and a peristaltic micro-pump. It includes two main manifolds: a mixing manifold, where the sample and antibodies are combined, and a sensing manifold, which distributes the processed fluid into eight independent microchambers. Each chamber hosts an electrochemical biosensor, enabling simultaneous multiplexed measurements. The electronic system is divided into two custom-designed systems (PCBs): The Sensor Unit (SU) and the Central Unit (CU). The SU is based on a 32-bit microcontroller and includes the analog front-end, implementing a miniaturized potentiostat for amperometric measurements, along with signal conditioning and data acquisition. The CU, also based on a microcontroller, manages the overall operation of the system, including fluidic control (microvalves and micropump), synchronization, power management, and communication with the user interface.

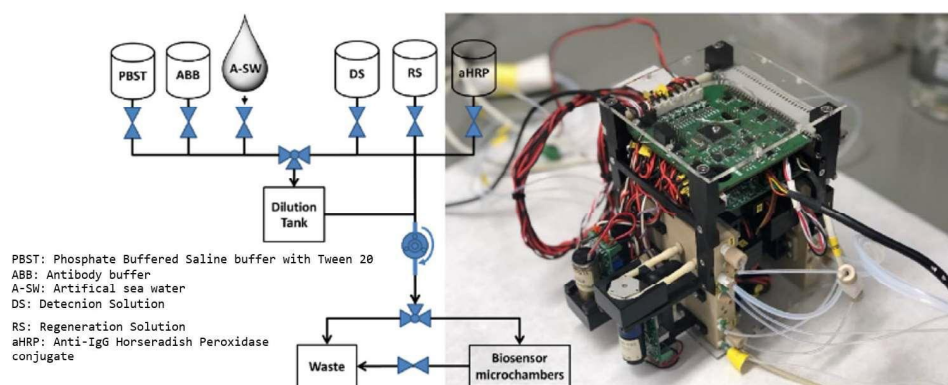


Fig. 1. On the left, the microfluidic schematic of the microfluidic system. On the right, the final device

The measurement method combines amperometric immunosensing with a pulsed-flow technique, where controlled fluid pulses are sequentially delivered to each microchamber instead of continuous flow. This ensures uniform reagent distribution while reducing energy consumption. The analyte interacts with immobilized biomolecules, generating an electrochemical current signal [4-5]. This approach enables reproducible parallel detection across multiple channels with low power consumption and efficient reagent use.

Results

The platform was validated by detecting the marine contaminant Irgarol 1051® as a model analyte. Measurements were performed using an amperometric immunosensing approach [4,5], where the analyte competes with an immobilized antigen (4e-BSA) for binding to a specific antibody (As87). Detection relies on an enzymatic reaction with HRP-labeled secondary antibody, generating an electrochemical current signal in the presence of TMB/H₂O₂ [5], proportional to the analyte concentration. Signal acquisition was performed simultaneously across eight channels using the pulsed-flow multiplexing method, ensuring uniform reagent delivery and consistent conditions. The chronoamperometric response reached a stable regime after an initial transient, with periodic variations due to pulsing. Final signals were extracted from the steady-state region, achieving reproducible results with a coefficient of variation of ~7% across channels. Calibration experiments were conducted by measuring different concentrations of Irgarol 1051®, allowing the construction of dose-response curves for each sensing channel (Fig. 2). The system achieved a mean IC₅₀ of approximately 16 nM and a limit of detection in the sub-nanomolar range.

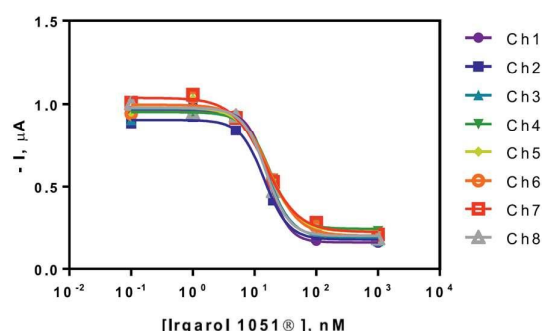


Fig. 2. Calibration curves obtained for the detection of Irgarol 1051® in the eight individual chambers.

The measurements presented in Fig. 2 illustrate the system performance, showing the calibration curves obtained simultaneously across the eight sensors. The consistency between channels demonstrates the robustness of the microfluidic distribution and the reliability of the electronic acquisition system. Overall, the results validate the proposed platform as a suitable solution for low-cost, low-power, and multiplexed in situ environmental monitoring.

Acknowledgments

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