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Smart Wastewater Surveillance of Viral Antibodies via Real-Time Optical Fiber Sensing

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Summary:

We present a remote, real-time wastewater monitoring system using a fiber-optic biosensor combined with machine learning to detect SARS-CoV-2-specific antibodies in untreated wastewater. The system is autonomous, requires no sample transport or preparation, and shows strong classification accuracy even in a complex matrix. The solution supports the early detection of epidemic outbreaks and aligns with current European directives on urban wastewater surveillance

Keywords: wastewater monitoring, SARS-CoV-2, fiber-optic sensor, machine learning, biosensing

1. Background, Motivation and Objective

Wastewater-based epidemiology (WBE) has emerged as a critical tool for public health monitoring. It enables early detection of viral outbreaks, including COVID-19, by assessing markers shed by both symptomatic and asymptomatic individuals. During the pandemic, WBE was utilized across EU member states to track SARS-CoV-2 activity [1]. As of April 2024, the revised Urban Wastewater Treatment Directive mandates real-time surveillance of public health markers—including SARS-CoV-2, influenza, and antimicrobial resistance—in municipal sewage systems [2].

However, conventional WBE depends on point sampling and laboratory analysis, typically involving time-consuming RT-qPCR methods [3]. These limitations inhibit continuous and automated monitoring. Our objective is to overcome these challenges by implementing a remote, label-free sensor system based on a biofunctionalized fiber-optic probe and supported by AI-driven signal classification. The system can detect SARS-CoV-2 IgG antibodies directly in raw sewage without sample preparation or transport, operating autonomously and in real time.

2. Description of the New Method or System

The core sensing element is a standard telecommunication-grade optical fiber with a microsphere tip, biofunctionalized to specifically bind SARS-CoV-2 antibodies. The functional layer was prepared using silanization, biotin-streptavidin coupling, and immobilization of spike S1 protein conjugates [4]. This sensor is capable of operating at 1310 nm, a wavelength compatible with current optical infrastructure.

Samples of untreated wastewater were collected and spiked with known concentrations of IgG (10^{-6} to 10^{-1} mg/mL). The probe was immersed in the samples, and signal variations were monitored using an optical spectrum analyzer. Key features were extracted from the resulting interferograms to create a numerical representation of each measurement.

157 signals were collected and processed. Machine learning models were trained to distinguish “positive” samples (IgG $\geq 10^{-4}$ mg/mL) from “negative” ones. Feature vectors were generated using three engineered parameters—peak

prominence variance, maximum peak width, and peak width standard deviation—and evaluated across a suite of algorithms for classification performance.

3. Results

The fiber-optic sensor system showed a strong, concentration-dependent response to IgG antibodies spiked into real, untreated wastewater. The design allowed signal modulation to be detected directly from the probe immersed in wastewater, without any need for sample filtration, concentration, or chemical labeling. The operational mechanism relies on the refractive index shift and light absorption changes caused by specific antigen-antibody interactions occurring at the surface of the microsphere sensor head.

When exposed to increasing IgG concentrations (10^{-6}-10^{-1} mg/mL), the reflected optical power recorded by the sensor exhibited a consistent and quantifiable decrease. In the lower concentration rangethe sensor response was linear, with a characteristic sigmoidal shape appearing at higher concentrations due to surface saturation. This response confirms the sensor's high sensitivity and specificity to the SARS-CoV-2 antibody-antigen binding reaction. The fast interaction kinetics, attributed to the biofunctionalized microsphere's high surface activity, supported real-time signal acquisition every 2 seconds with no signal lag.

Given the optical complexity of wastewater as a biological matrix—containing suspended solids, organic matter, and potential chemical interferents—signal interpretation based on raw optical intensity was insufficient. Traditional thresholding methods resulted in a low classification accuracy of only 38.9%. This performance was hampered by the signal variability caused by matrix noise, lighting fluctuations, and refractive interferences unrelated to specific binding.

To address this limitation, a machine learning pipeline was implemented. From collected interferogram, three engineered features were extracted: peak prominence variance, maximum peak width height, and standard deviation of peak widths. It was chosen based on their relevance to the expected spectral modulation during antigen-antibody interactions and their robustness to background interference. The dataset, was split into "positive" and "negative" classes using a 10^{-4} mg/mL IgG concentration threshold.

Multiple classification algorithms were trained and evaluated. The best-performing model, the KNeighborsClassifier, achieved an overall accuracy of 94.23%, a balanced accuracy of 92.97%, and an F1 score of 94.19%. These metrics reflect the model's ability to both correctly identify true positives and avoid false classifications. Compared to other models tested—such as ExtraTrees, GaussianNB, and LGBM—KNeighbors offered the best balance of accuracy, sensitivity, and computation time.

Additional validation of the sensor system was performed through repeatability testing. The probe was subjected to multiple cycles of antibody exposure and rinsing. The sensor response remained consistent across repeated measurements, with no evidence of hysteresis or sensor drift. No degradation of the biofunctionalized surface was observed.

The sensing system required no auxiliary reagents, labelling compounds, or pre-filtration steps, allowing real-time deployment directly in wastewater inflow channels. The ability to detect target biomolecules autonomously and continuously in situ makes this approach fundamentally different from conventional SARS-CoV-2 wastewater surveillance methods based on RT-qPCR.

In comparison to electrochemical sensors and surface-enhanced Raman scattering (SERS)-based approaches, which rely on pre-processed samples or high-cost instruments [5–7], the fiber-optic sensor system described here uniquely combines simplicity, scalability, and compatibility with existing optical fiber networks. This positions the system as a viable candidate for future implementation in smart urban infrastructure, enabling real-time health surveillance at the scale of cities, campuses, airports, and high-density public spaces.

4. References

[1] Singer AC et al., *A world of wastewater-based epidemiology*, Nat Water 2023;1:408–15.
[2] European Parliament, *New EU rules to improve urban wastewater treatment*, 2024.
[3] Ahmed W et al., *First confirmed detection of SARS-CoV-2 in untreated wastewater in Australia*, Sci Total Environ 2020;728:138764.
[4] Szczerska M et al., *The SARS-CoV-2 specific IgG antibodies biophotonic sensor*, J Biophotonics 2023;16(1):e202200172.
[5] Kumar MS et al., *Electrochemical sensing of SARS-CoV-2 amplicons with PCB electrodes*, Sens Actuators B 2021;343:130169.
[6] Sen P et al., *Detecting SARS-CoV-2 in wastewater using electrochemical aptamer sensors*, ACS Sens 2023;8:1558–67.
[7] Tian C et al., *SERS-based aptasensor for rapid detection of SARS-CoV-2 viral particles*, Sens Actuators B 2022;371:132445.