Portable Electrochemical Sensors with Engineered Interfaces and Data-Driven Waveform Analysis for Field-Ready Detection

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Acknowledgement

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Disclosure / Conflict of Interest

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Required for MHSRS / CE review — update this slide to match the submitted COI form.

Presenter: Zhe Wang, Ph.D., Oakland University

Relevant financial relationships: Oakland University

Grant support: NSF, NIJ and NIH

Investigational use disclosure: Portable electrochemical VOC sensing concepts and prototype data are research-stage and not presented as cleared clinical diagnostic products.

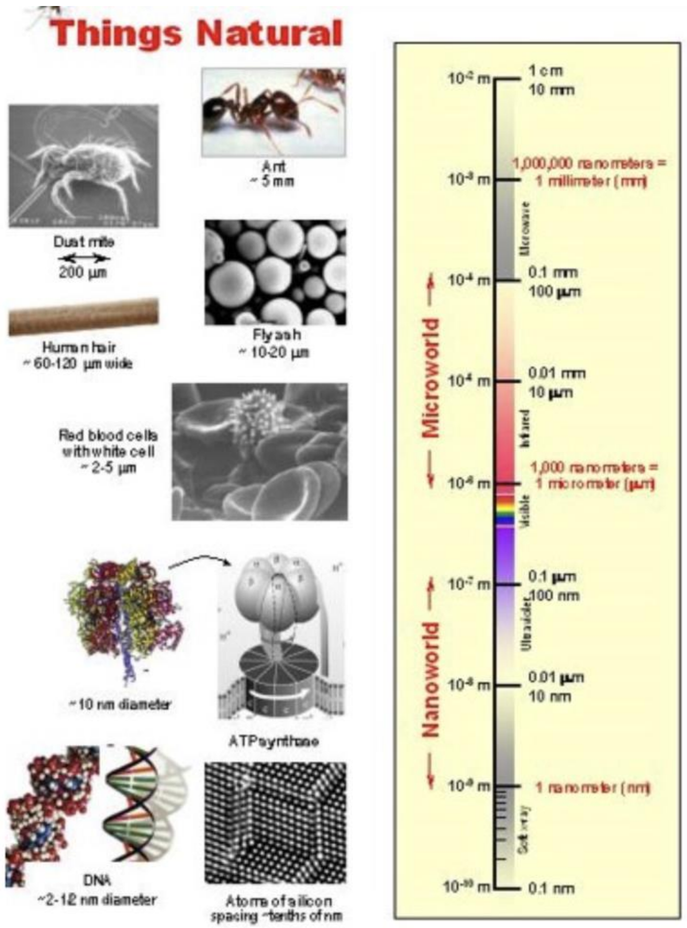
Educational & evidence-based

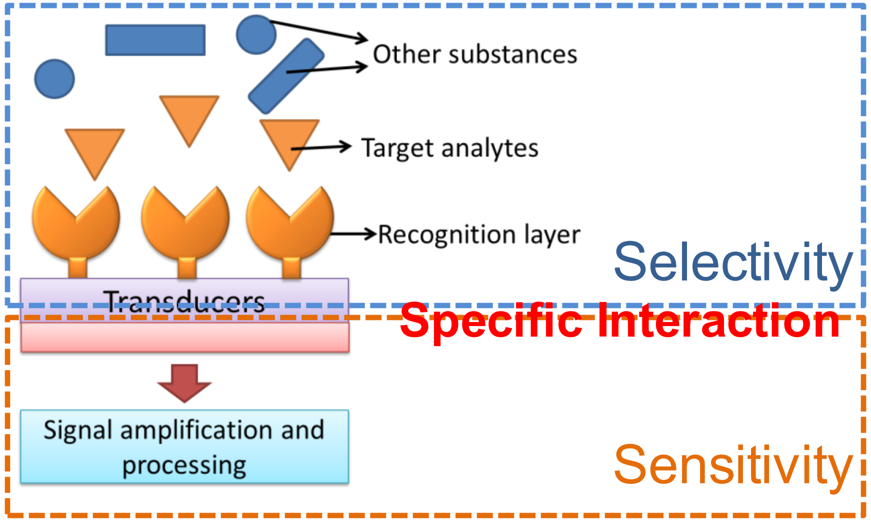
No product/device logos

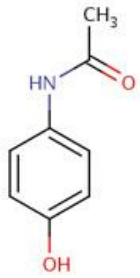
Generic method names

Balanced current landscape

Analytes for Biosensor and Sensor Design

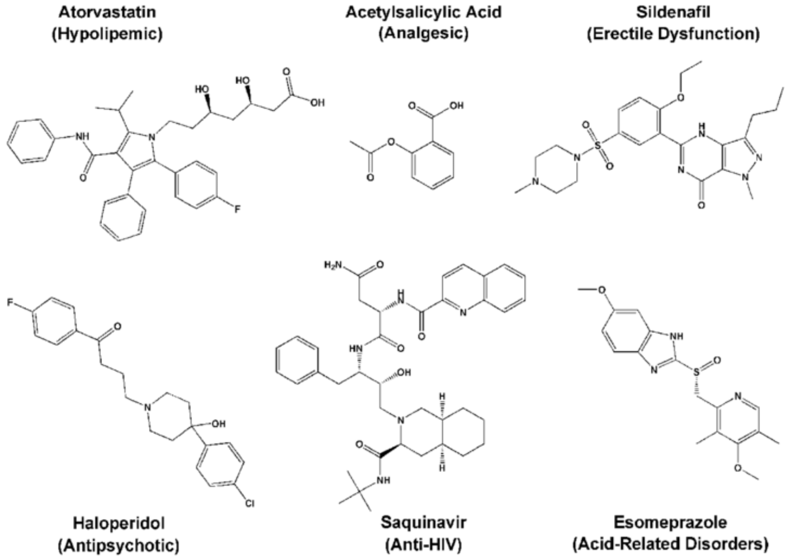






Biomarkers

- Cancer Cell
- Protein (Antibody-Antigen)
- Enzyme
- DNA
- Micro-RNA (miRNA)
- **Therapeutic Drug**
- Certain small organic compounds



https://electricalposts.com/introduction-to-nanotechnology/

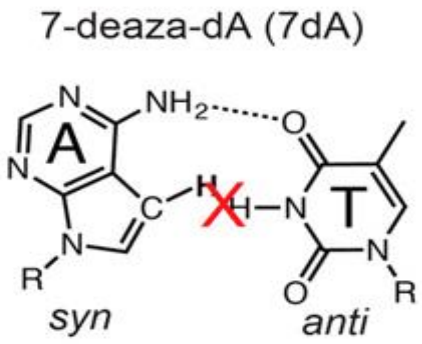
Small Molecule Detection

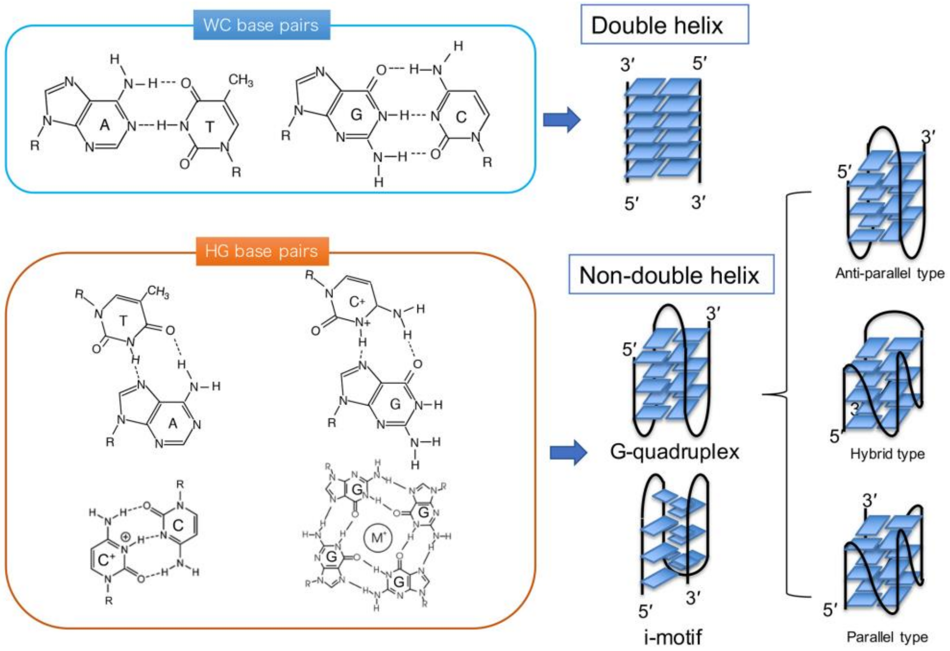
Watson–Crick versus Hoogsteen Base Pairs

Chemical Strategy to Encode and Express Genetic Information in Life

Protein−DNA complexes under solution conditions

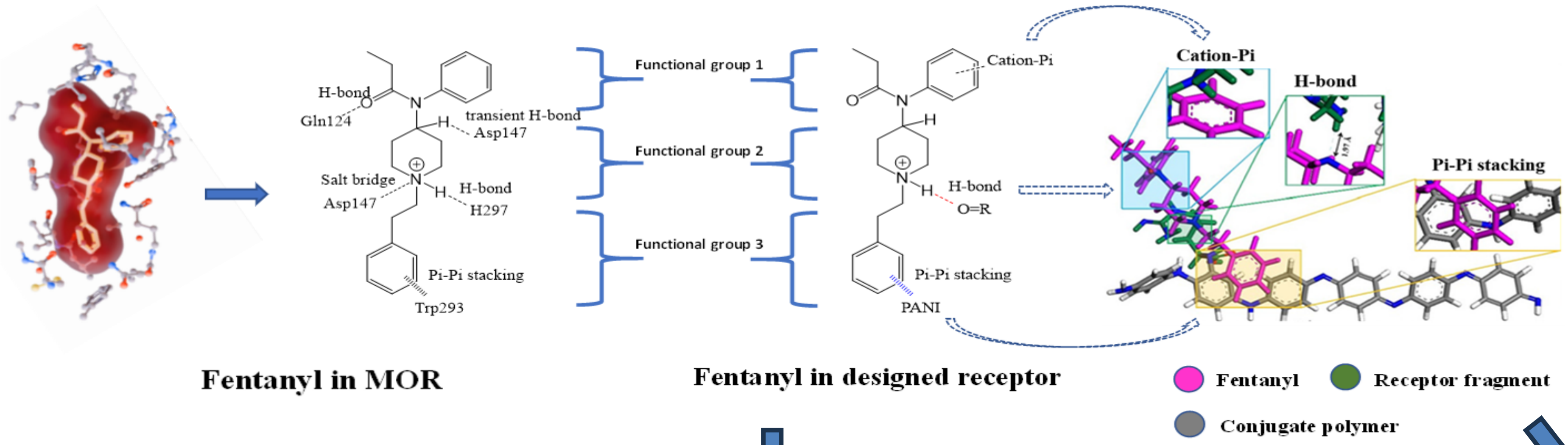
Shape recognition

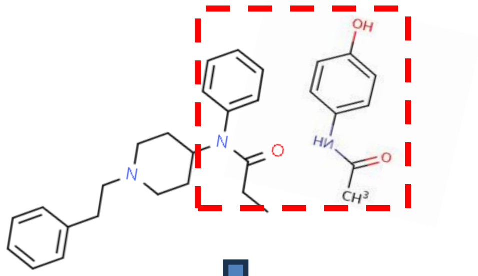


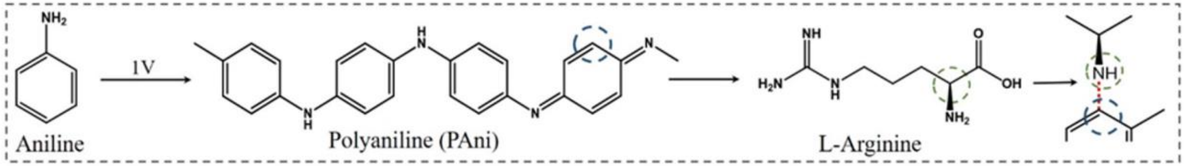


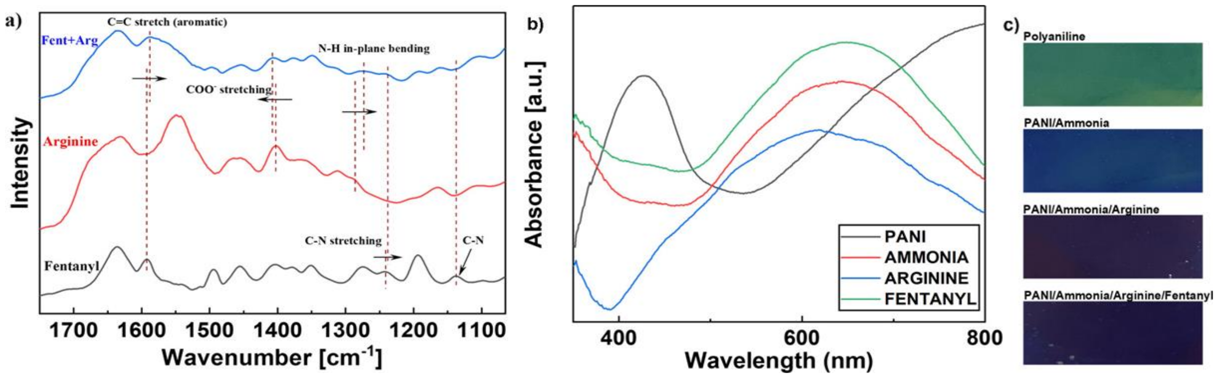
Nat Commun 2021 12, 984 *Acc. Chem. Res.* 2021, 54, 9, 2110

Fentanyl Receptor Design
(low EC activity and low concentration)









Cell 2022, *185* (23), 4361-4375.e19, *Nature Communications 12(1) (2021) 984*, *Anal. Chem. 2022, 94, 26, 9242–9251*

Impedance Optimization

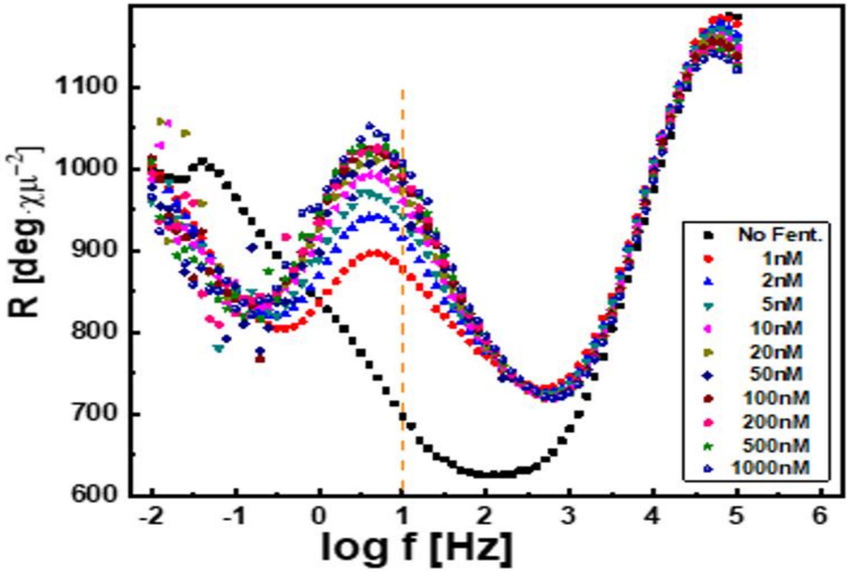
$$Z = \frac{1}{\omega C} = \frac{V_0 \cdot \sin \omega t}{I_0 \cdot \sin\ (\omega t + \ \Phi)}$$

Langmuir adsorption model

$$\Delta\varphi = \frac{qK_L C^{1-x}}{1 + K_L C^{1-x}}$$

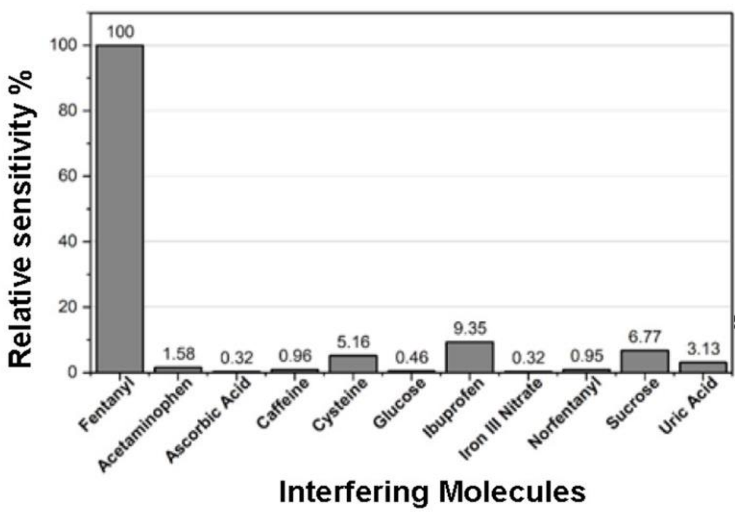
$$\frac{1}{\Delta\varphi} = \frac{1}{q} + \frac{1}{qK_L C^{1-x}}$$

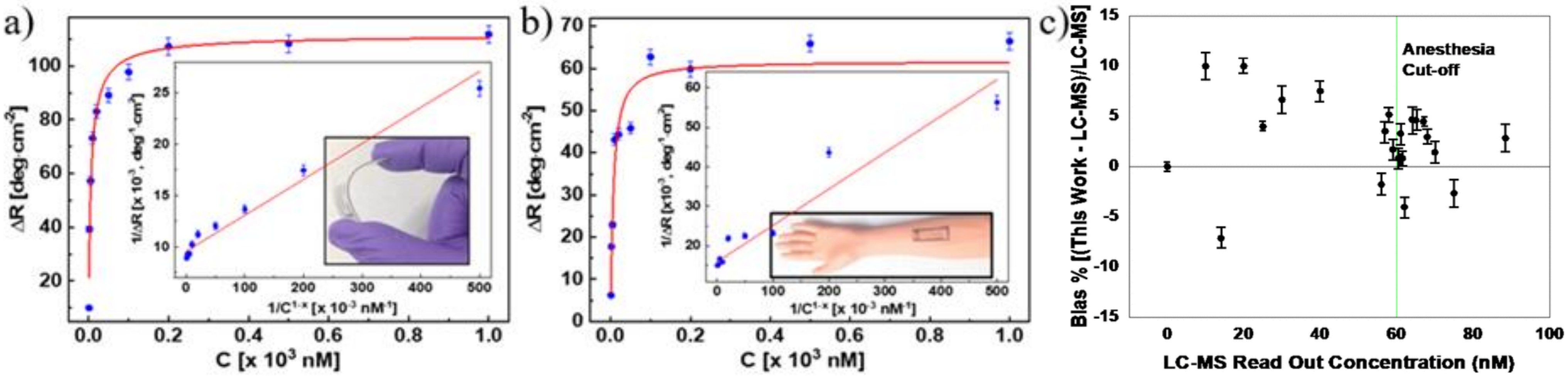
$\Delta\varphi$ is the difference in phase angle between sensor and fentanyl interaction,
q is the max monolayer coverage capacity ($ng.deg^{-1}$),
K_L is Langmuir isotherm constant (nM^{-1}),
C is the concentration of fentanyl (nM) and
x varies from 0 to 1.



Langmuir	PBS	HS	AT	AS
q	307.61	593.37	196.91	56.44
kl	92.60	136.72	535.37	58.79
x	0.4035	0.0405	0.0895	0.2945

POC Test





(**a**) flexible strip for the human serum and (**b**) attachable patch for artificial sweat on artificial arm. [Inset: Linear Langmuir behavior of the sensor with its digital images showing its flexibility (a) and transparency on artificial arm (b)]. (**c**) Statistical clinical human blood strip test compared to LC-MS. The scatter plot displays how detection results are distributed in negative and positive groups and each point is the mean of the triplicate measurements.

Anal. Chem. 2022, 94, 26, 9242–9251, Electro. Acta. 2026, 547, 20,147872.

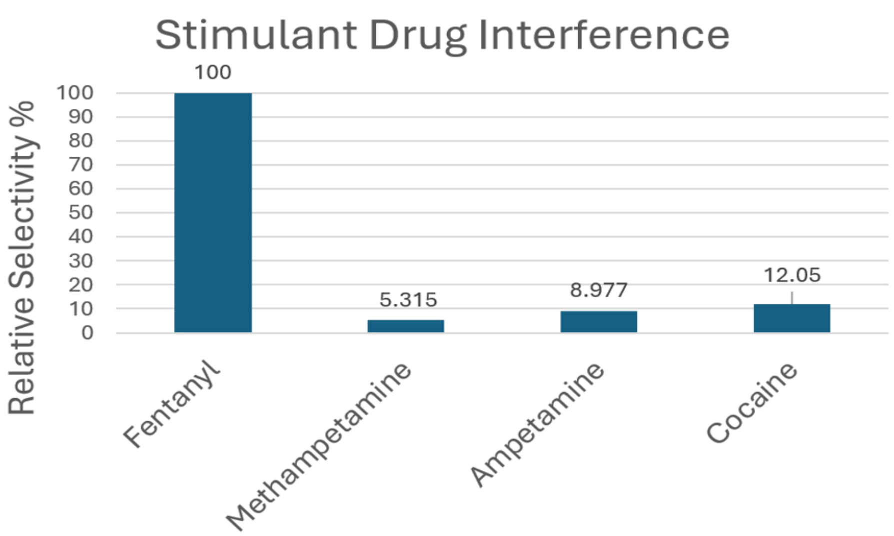
In Field Application

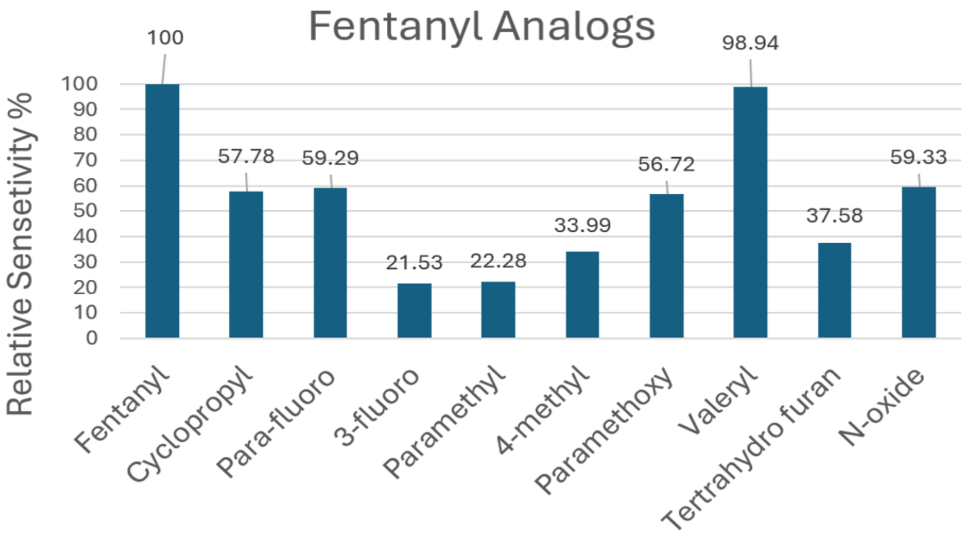
Current Challenges
Lack of Effective Fentanyl Tests
Handling the substances
Mixed with Other Substances/Sold as Other Drugs
High Cost of Current Solutions
Trafficking Adaptability
The rise of online marketplaces Legal loopholes and differing laws across regions. :

Sensor

- Portable
- Low cost
- Contactless detection
- High performances

Cloud AI





Unpublished results

Portable Breath VOC Solution: Spectroscopy vs. Electrochemistry

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Complementary tools: identify molecular biomarkers, then translate them into portable field signatures.

Spectroscopy / MS-based methods

Reference-grade chemical identification

- Optical spectra: FTIR, cavity ring-down spectroscopy, laser absorption
- Mass spectrometry: PTR-MS / SIFT-MS for real-time VOCs; GC–MS or GC×GC–MS for separation + identification
- Strength: molecular assignment, calibration, biomarker discovery and validation
- Limits: bulky instrumentation, cost, sampling standardization, humidity and preconcentration needs

Electrochemical methods

Portable transduction of chemical fingerprints

- Amperometry, voltammetry and EIS at functionalized electrodes or ionic-liquid interfaces
- Single-target sensors or sensor arrays decode redox, adsorption, transport and double-layer features
- Strength: compact, low power, rapid and compatible with field/point-of-care workflows
- Limits:

Cross-reactivity,

Drift,

Requires engineered interfaces + waveform analytics

What are we looking for?

1. **Active enough to response many VOCs**
2. **Stable**
3. **Could be quantified**

Bajo-Fernández et al., Front. Mol. Biosci. 2024; Li et al., Microsyst. Nanoeng. 2023; Jia et al., Metabolomics 2024; Heng et al., IEEE Rev. Biomed. Eng. 2025.

Superoxide

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Radical anion produced by the one electron reduction reaction of oxygen (ORR)

$$O_2 + e \rightarrow O_2^{\bullet -}$$

1. Activity

- Reactive toward both organic and inorganic compounds – may act as an oxidant, reductant, nucleophile or base
- Capable of degrading VOCs into benign compounds
- Inflicts oxidative DNA damage on cells
- O_2^- does not pose significant health risks – not released into the air

No.	Chemical	MF	No.	Chemical	MF
1	Carbon monoxide	CO	16	Naphthalene	$C_{10}H_8$
2	Nitrogen Oxides	NO, NO_2	17	Ethylene	C_2H_4
3	Ammonia	NH_3	18	Pinene (α-)	C_8H_{19}
4	Methane	CH_4	19	Formaldehyde	CH_2O
5	Ethane	C_2H_6	20	Acetaldehyde	C_2H_4O
6	Butane	C_4H_{10}	21	Methyl Alcohol	CH_4O
7	Pentane	C_5H_{12}	22	Methyl Ethyl Ketone	C_3H_8O
8	Hexane	C_6H_{14}	23	Methylene Chloride	CH_2Cl_2
9	Cyclohexane	C_6H_{12}	24	Trichloroethane (1,1,1-)	$C_2H_3Cl_3$
10	Benzene	C_6H_6	25	Trichloroethane (1,1,2-)	$C_2H_3Cl_3$
11	Toluene	C_7H_8	26	Carbon Tetrachloride	CCl_4
12	Xylene (o-,m-,p-)	C_8H_{10}	27	Tetrachloroethylene	C_2Cl_4
13	Trimethylbenzene, 1,2,4-	C_9H_{12}	28	Hexafluoroethane	C_2F_6
14	Ethylbenzene	C_8H_{10}	29	FC-12B	$CClBrF_2$
15	Styrene	C_8H_8	30	CFC-113	$C_2Cl_3F_3$

Superoxide in Ionic Liquids

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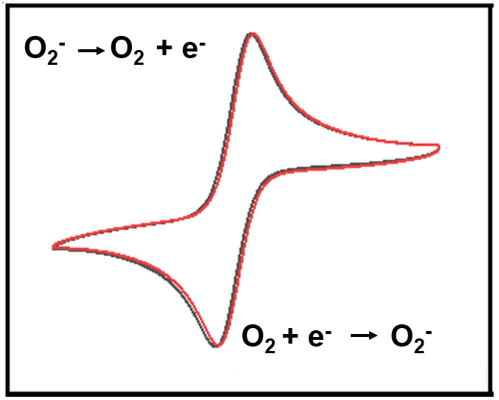


Interface Reaction:

♦Electrode reaction

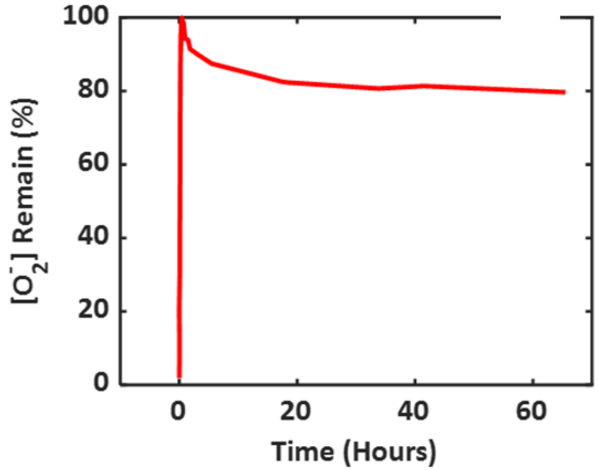
$O_2 + e \rightarrow O_2^{\bullet -}$

E= -1.2 V vs. Pt

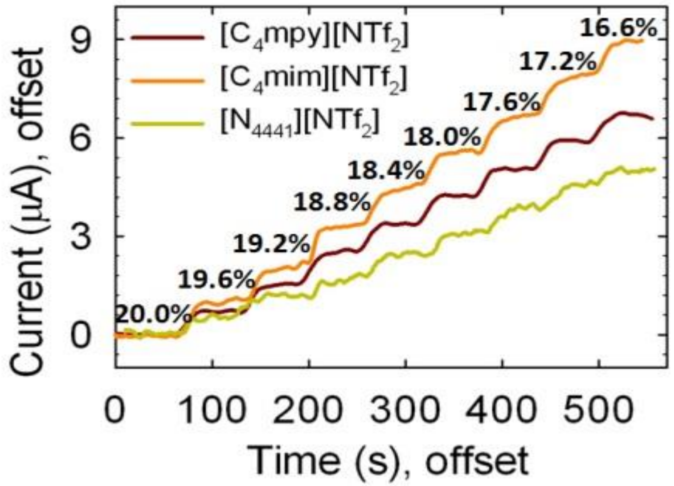
♦Mass transport

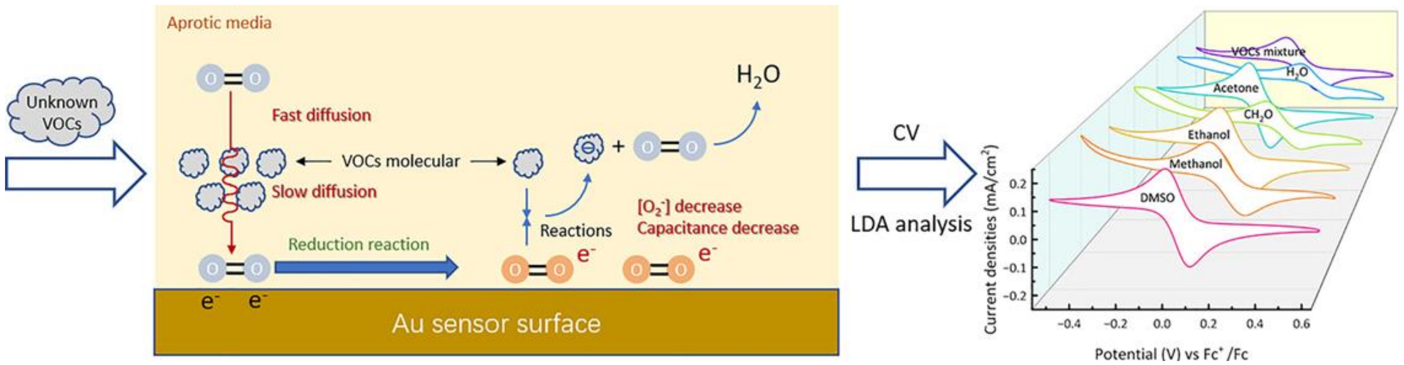
Stability

O_2^- can be stabilized by ionic liquids (ILs)

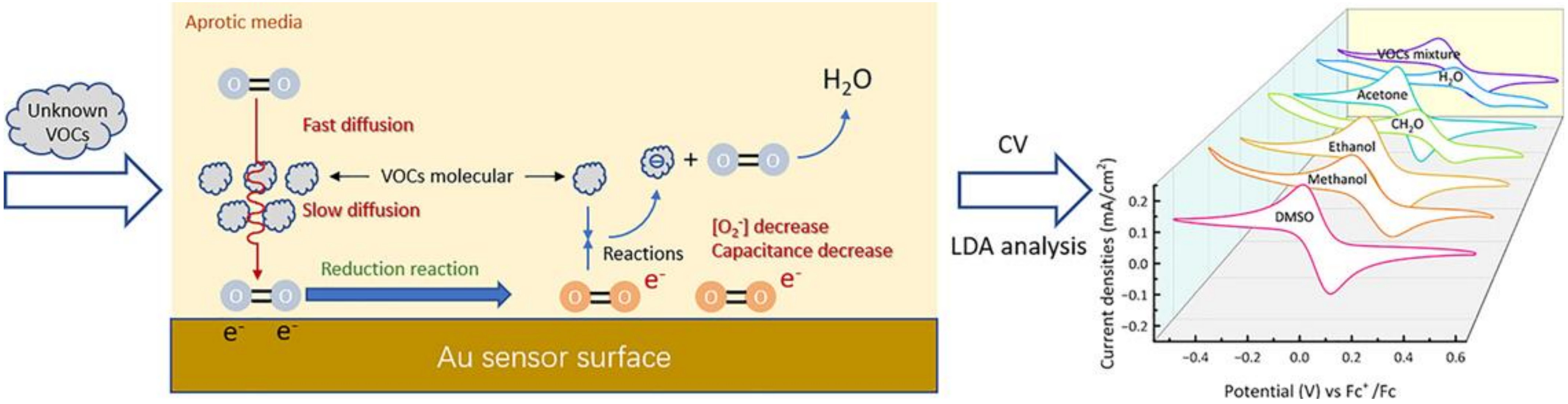


Quantifications



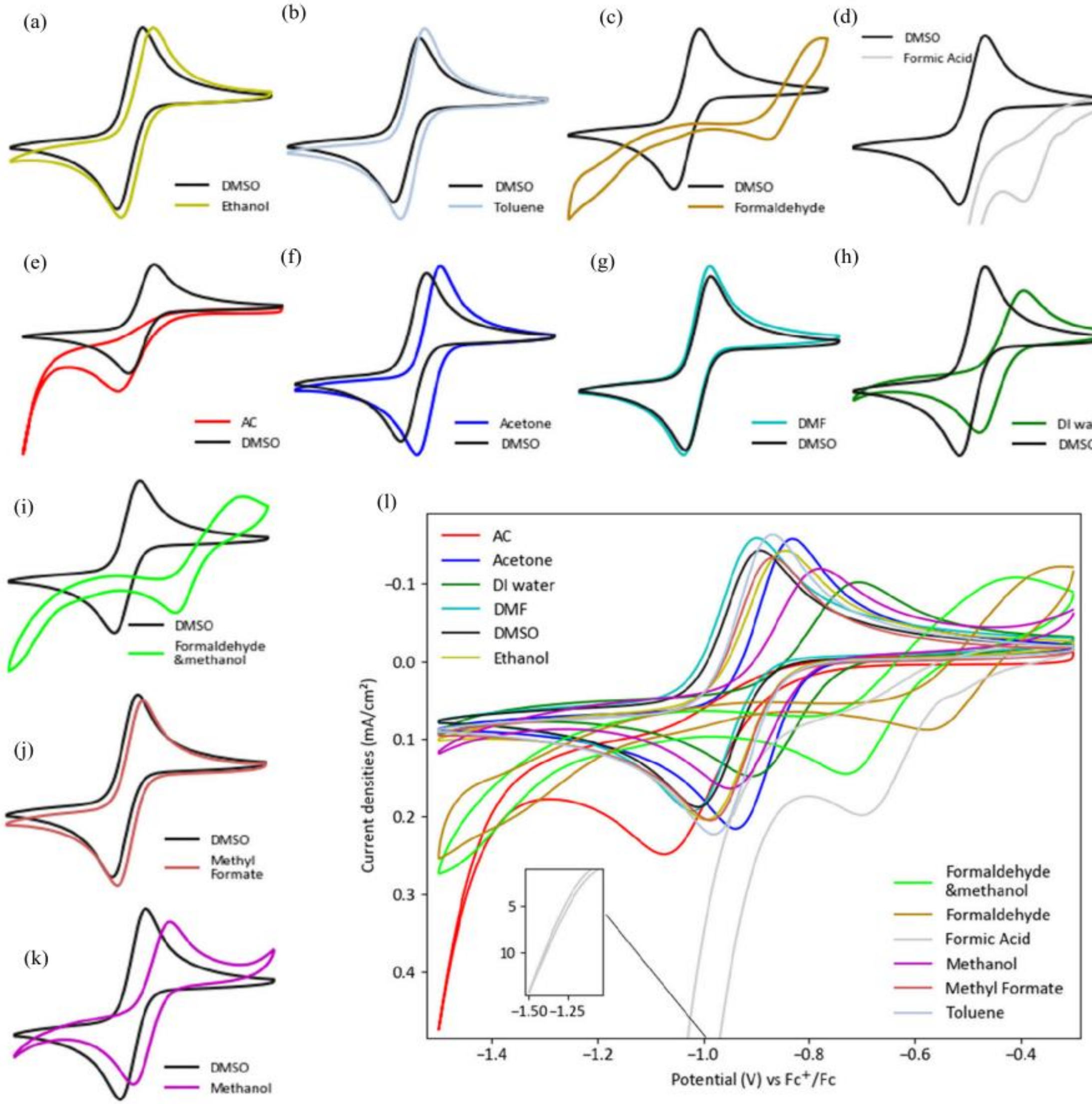


Hypothesis

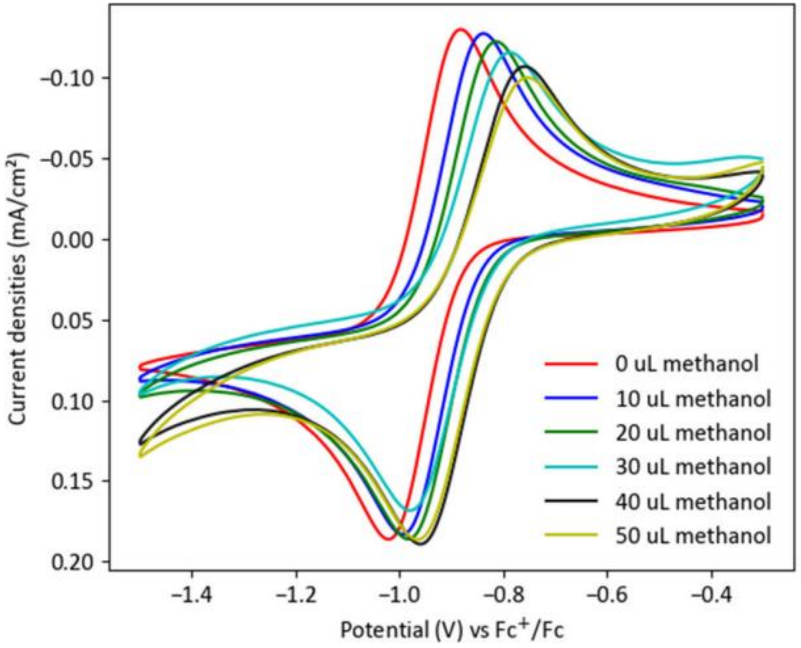


Unknown VOCs
Aprotic media
Fast diffusion
VOCs molecular
Slow diffusion
Reduction reaction
Reactions
[O2-] decrease
Capacitance decrease
Au sensor surface
CV
LDA analysis
VOCs mixture
Acetone
Ethanol
Methanol
DMSO
Current densities (mA/cm2)
Potential (V) vs Fc+/Fc

CV Spectrum with VOC in Ionic Liquids



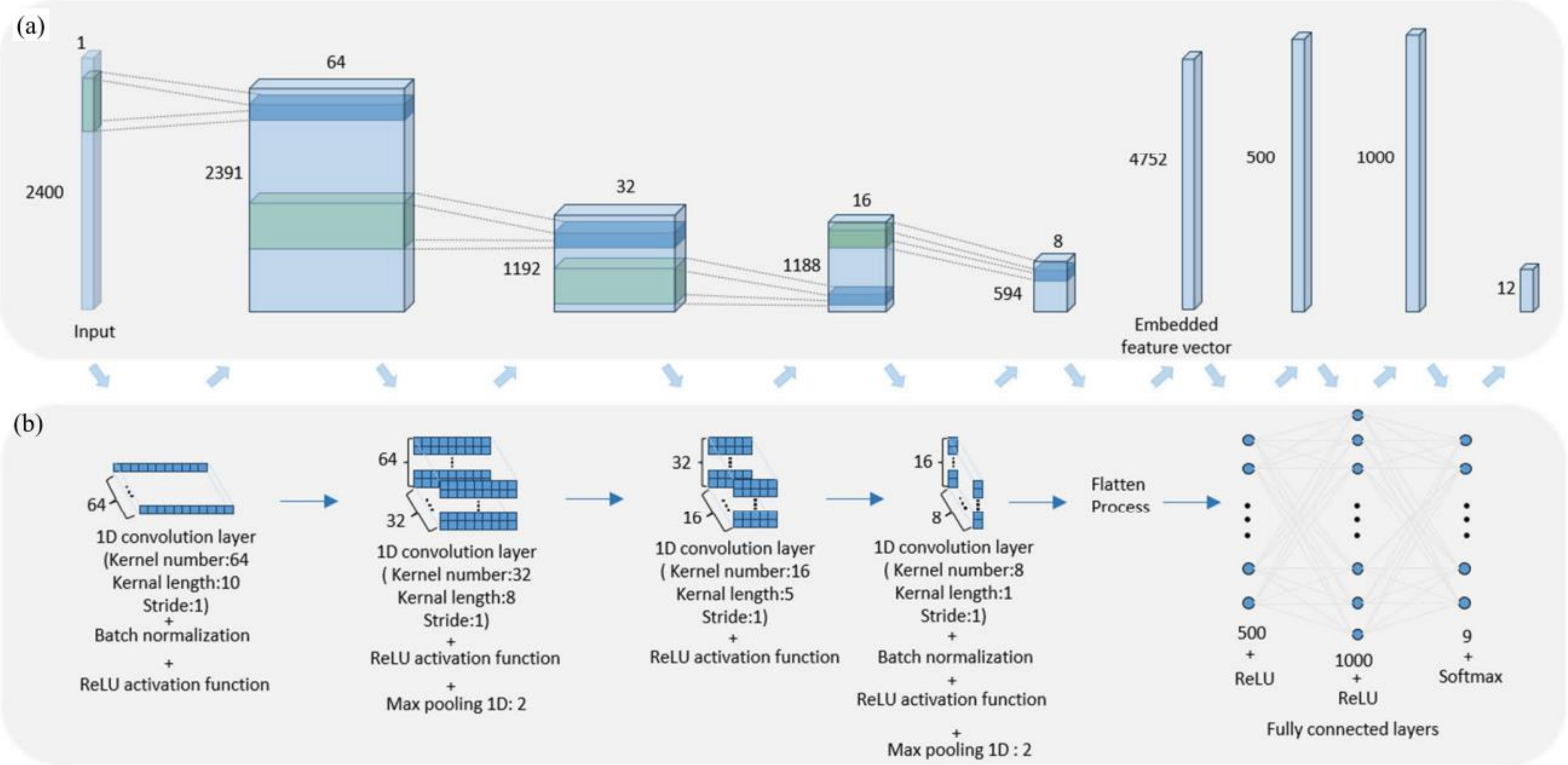
$$O_2^{-} + AH \rightleftharpoons O_2 + AH^{-} \underset{k_{-1}}{\xrightarrow{k_2}} H_2O + A^{-}$$



ACS Sensors. 2023, 8, 9, 3389–339.

IEEE SENSORS JOURNAL, 2024, 24, 9, 15011-15022.

Data Flow and Architecture of 1D- Convolutional Neural Network (CNN)



Superoxide-VOC Sensing

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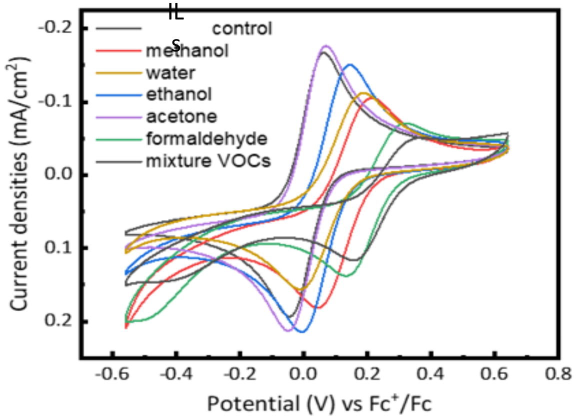
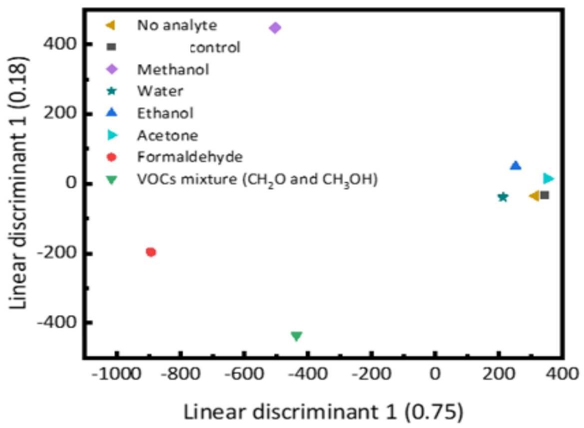
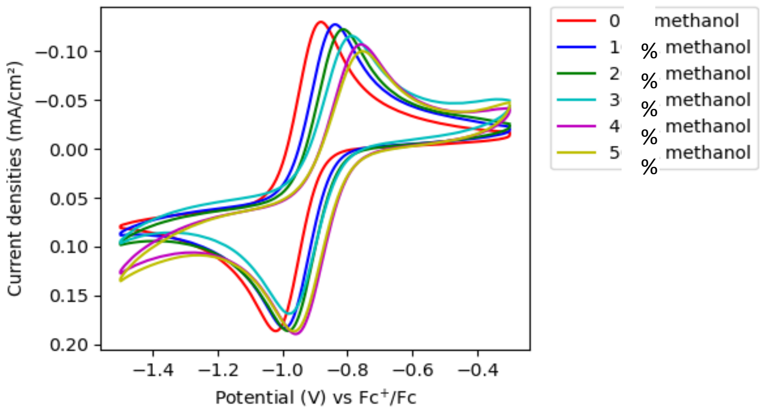
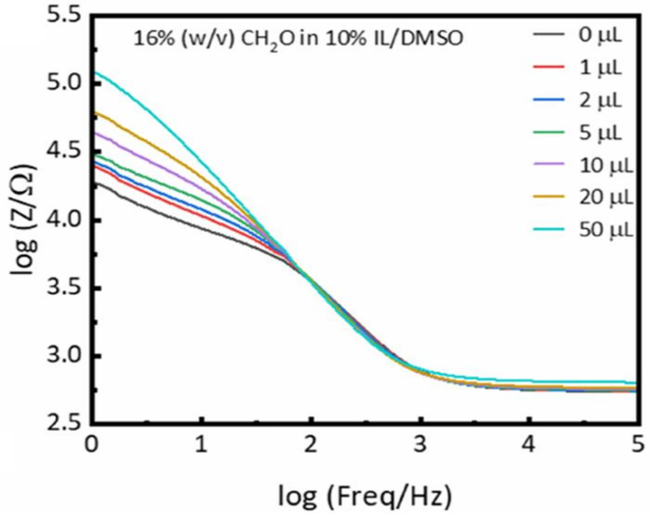


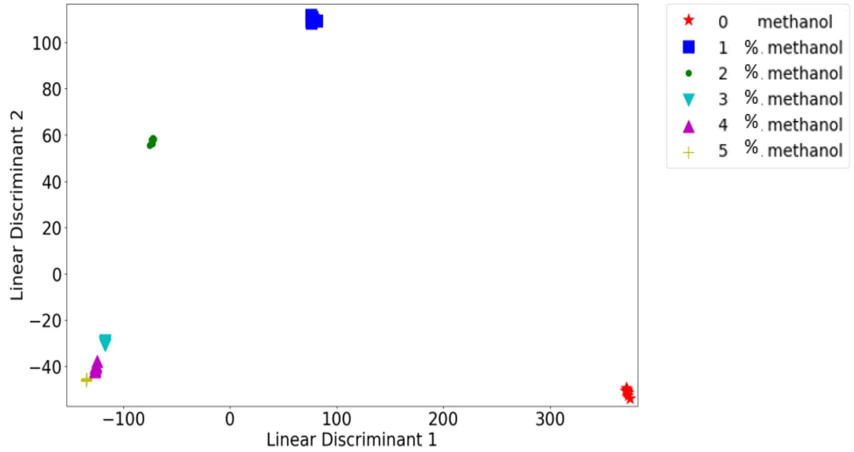


Selectivity

Sensitivity





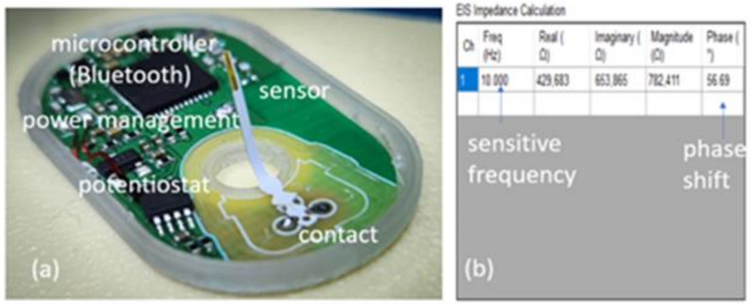


ACS Sensors. 2023, 8, 9, 3389–339.

IEEE SENSORS JOURNAL. 2024. 24. 9. 15011-15022.

On-going Work

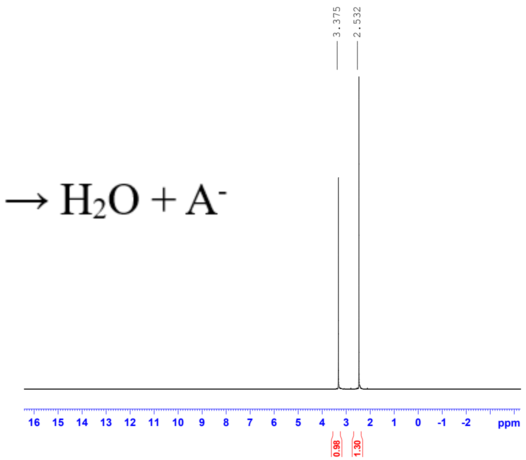
1. Prototype of VOC detection device



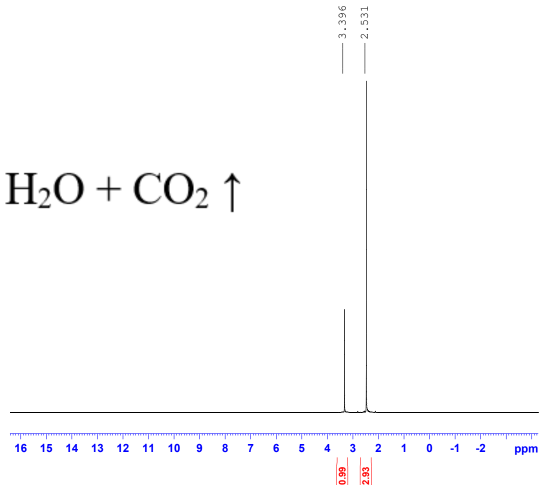
2. Chemical Warfare Agents (CWA)-(HD/CG/GB/VX) and Pharmaceutical-Based Agents

3. Disinfection

$$O_2^- + AH \rightleftharpoons O_2 + AH^- \rightarrow H_2O + A^-$$



$$O_2^- + CH_2O \rightarrow H_2O + CO_2 \uparrow$$



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Thank you!
Any Questions?