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Nano
UniTe LAB

(Bio)Sensors And Electroanalytical Devices Integrating Laser-Induced Nanostructured Films

D. Compagnone

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I.N.B.B.
Consorzio Interuniversitario

XV Convegno Nazionale

"Nuove strategie di ricerca integrata su Salute, Alimentazione e Ambiente

10-11 luglio 2025

NanoUnite Lab Main research line

UNIVERSITÀ DEGLI STUDI DI TERAMO UNITE

NANOSTRUCTURED SENSING SURFACES MANUFACTURING and INTEGRATION IN SUSTAINABLE LAB-MADE SENSORS AND ANALYTICAL DEVICES

Nano UniTe LAB

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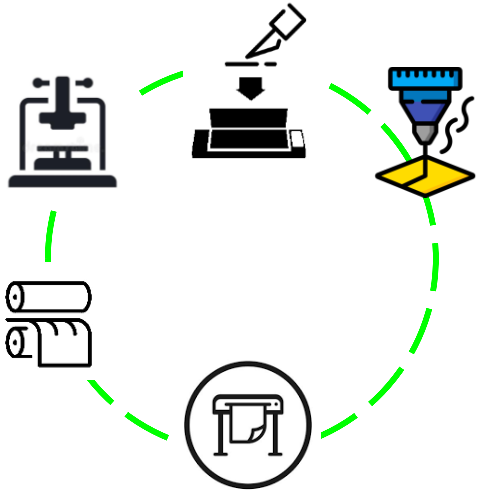
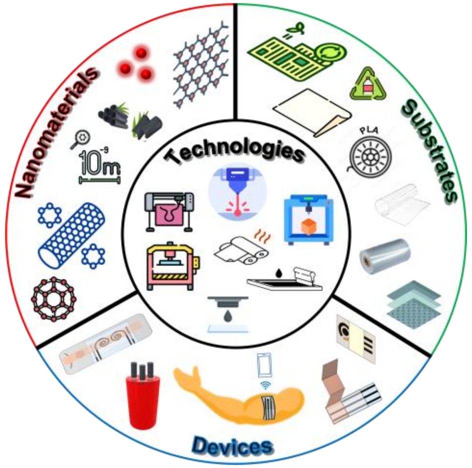
DEPARTMENT OF BIOSCIENCE AND AGRO-FOOD AND ENVIRONMENTAL TECHNOLOGY



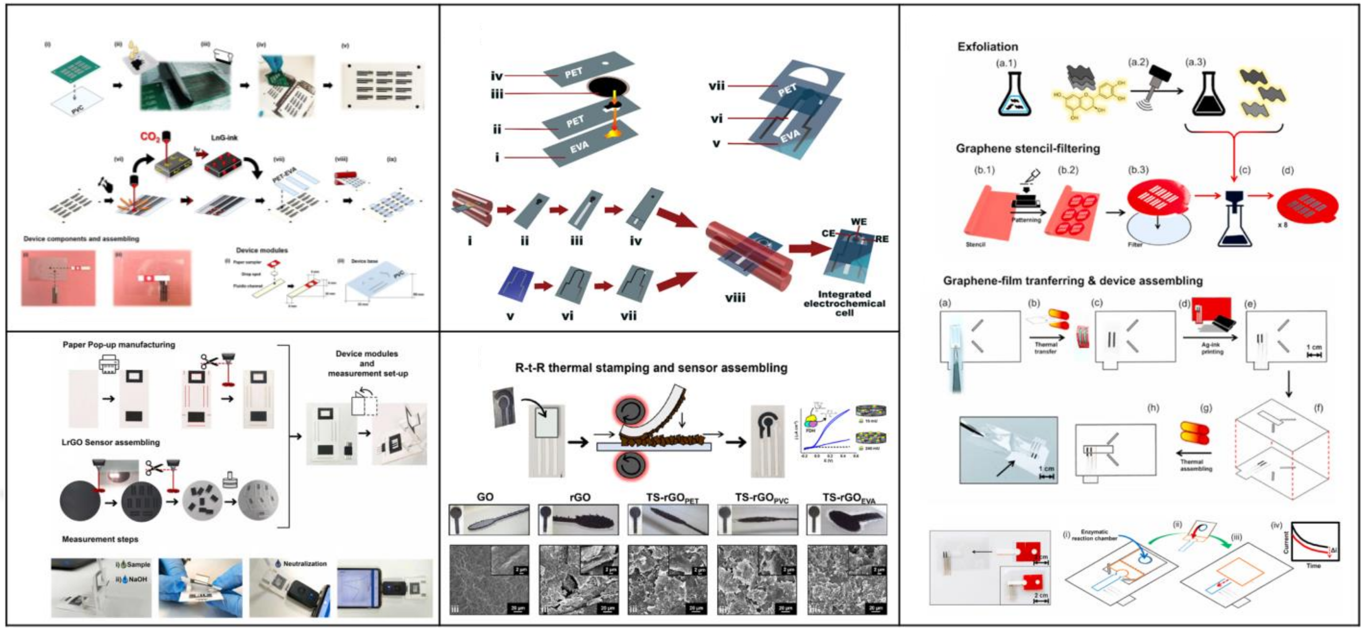


Aim

Formation of film constituted exclusively of NMs
Flexible/Paper analytical devices assembling

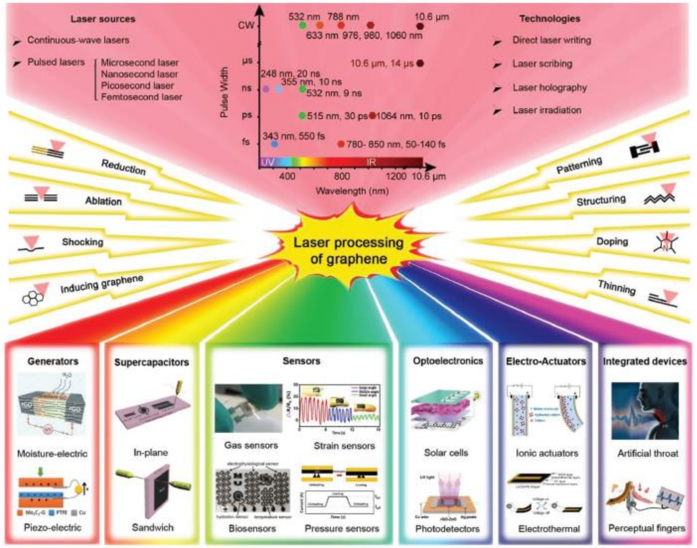
Strategy

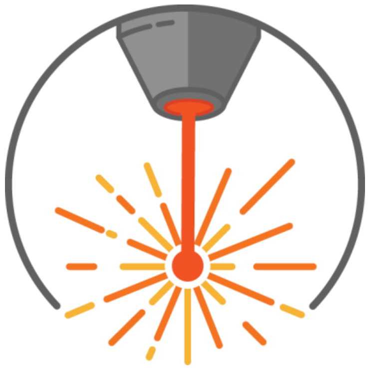
CO_2 Laser-Plotter patterning/engraving
Xurographic Manufacturing

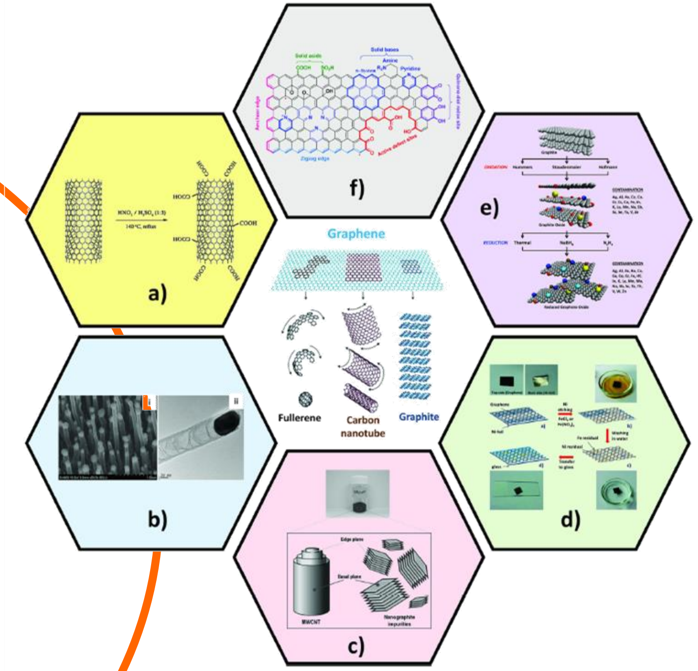


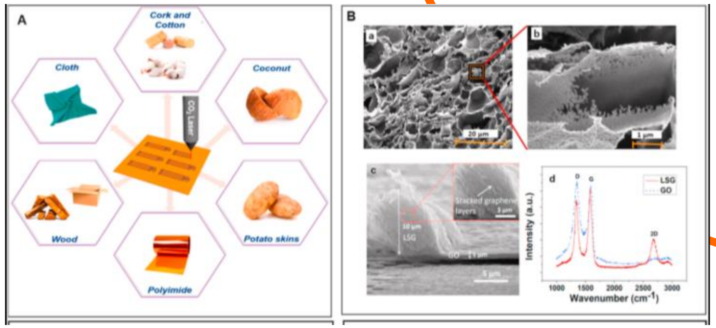
Silveri et al. (2025). **TrAC Trends in Analytical Chemistry**, 118175.

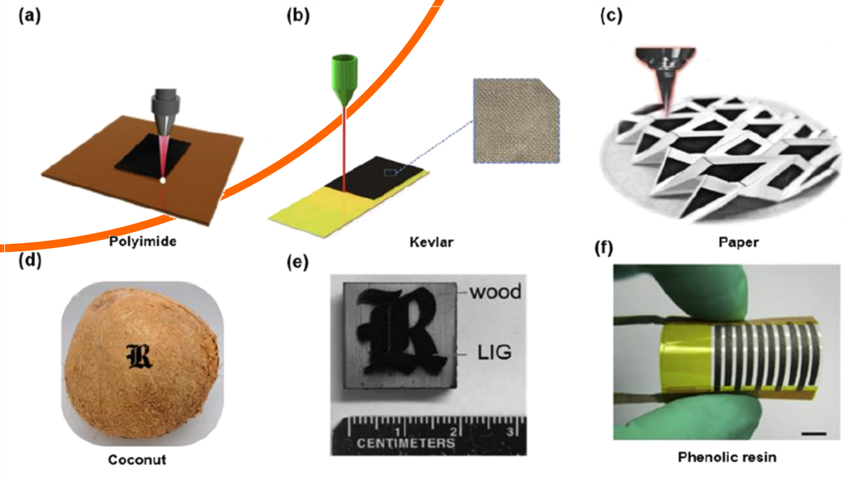
CO_2 laser-plotter for conductive nanostructured films formation







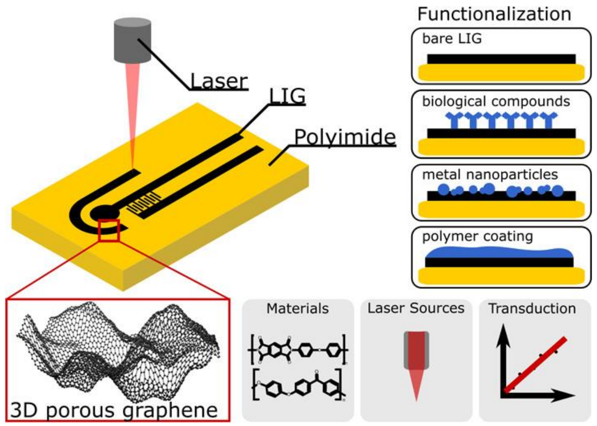


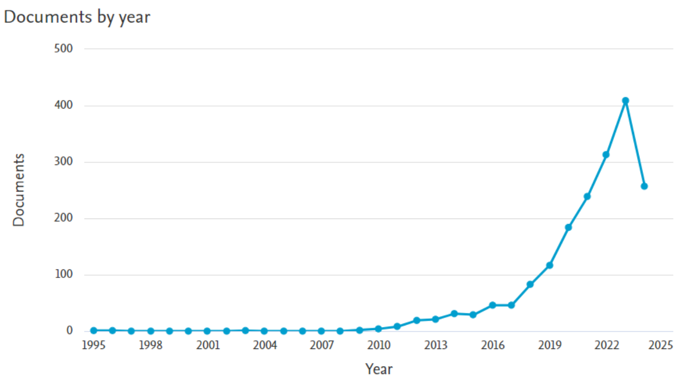


You et al. (2020). Advanced Materials, 32(15), 1901981.
Lahcen et al. (2020). Biosensors and Bioelectronics, 168, 112565
Wang et al. (2022). Biosensors, 12(2), 55.
Simsek, M., & Wongkaew, N. (2021). Analytical and Bioanalytical Chemistry, 413(24), 6079-6099.

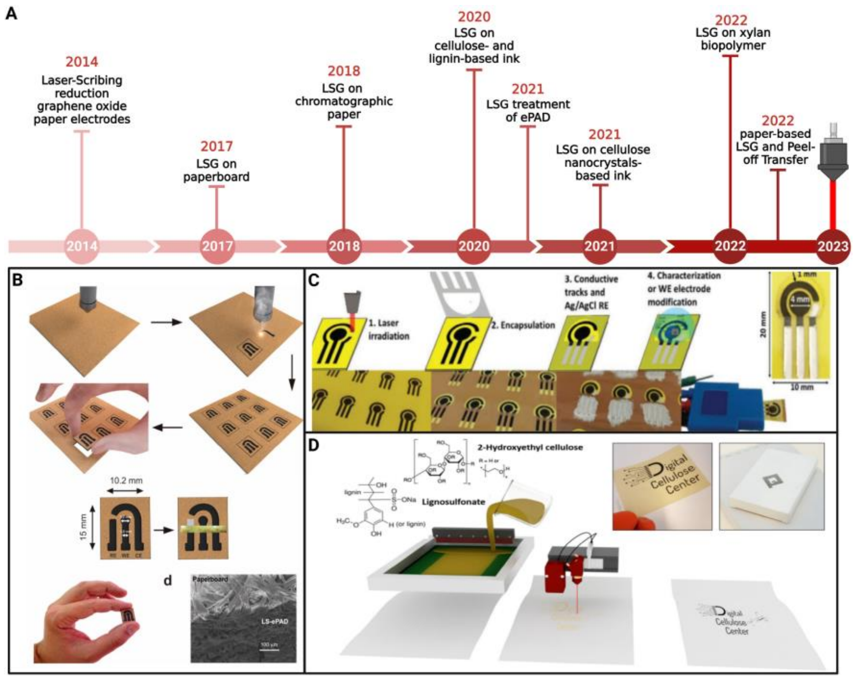
State of the Art

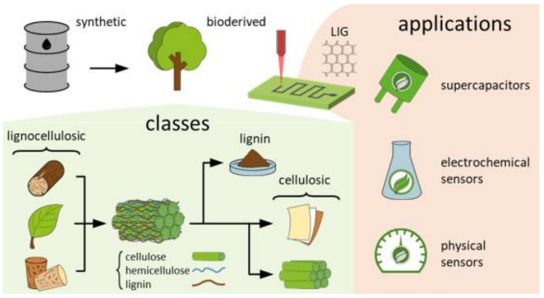
Laser-induced graphene (LIG)

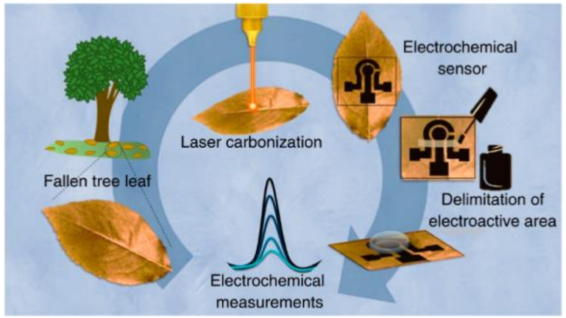


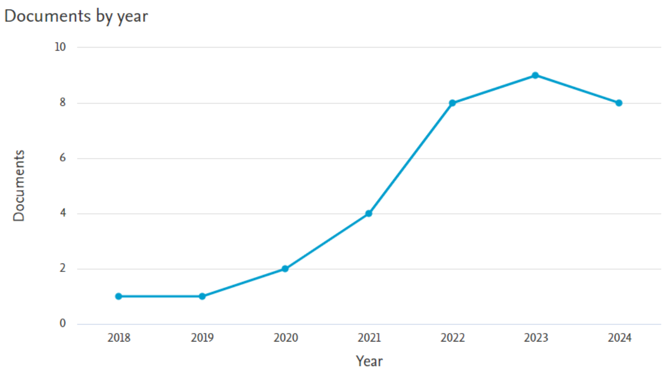


CO_2 laser towards sustainability









Vivaldi et al. (2021). ACS Applied Materials & Interfaces, 13(26), 30245-30260.
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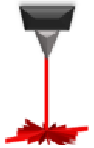
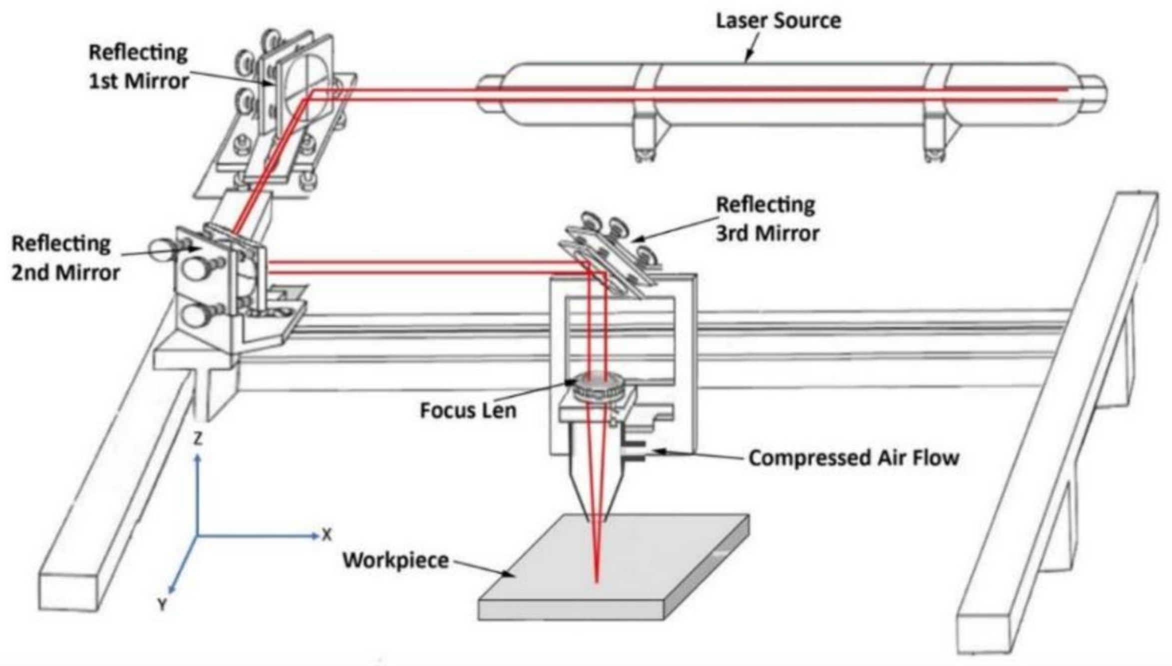
Silva-Neto et al. (2024). TrAC Trends in Analytical Chemistry, 117675.
Blasques et al. (2024). ACS Sustainable Chemistry & Engineering, 12(8), 3061-3072.

CO_2 laser-plotter

Schematic diagram of the laser system

- *Emissiom λ 10.6 μm*
- *Nominal Maximum power output 30 W*
- *Laser spot of 0.04 mm*





LASER-INDUCED NANOSTRUCTURATION MAIN VARIABLES

PRECURSOR MATERIAL & PHOTOTHERMAL CONVERSION

- *Chemistry of the material*
- *Physical characteristics*
- *Mechanical characteristics*
- *Material amount*
- *Material support*

LASER-PLOTTER PARAMETERS

- *Power source*
- *Scanning speed*
- *Engraving density (instrumental and design resolution)*
- *Engraving passings*
- *Beam focus*

WORKING MODE

- *Engraving (nano/micro-structuration)*
- *Cutting (device design)*

Khan et al. (2021). Journal of Manufacturing and Materials Processing, 5(3), 78.

NanoUnite Lab CO_2 laser-plotter for electroanalytical devices

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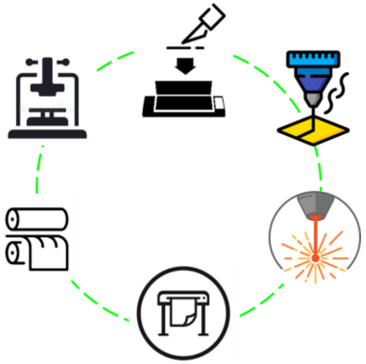
SENSING FILMS OBTAINED VIA CO_2 LASER PLOTTER



- ✓ *Laser-induced graphenic transferable films*
- ✓ *Laser assembled 2D/0D nanocomposites*
- ✓ *Laser nanostructured printed inks*
- *Laser assembled 2D/2D heterostructures*

NANO Bioelectronics & Biosensors Group

UR Universität Regensburg

Universidad de Alcalá

SENSORS

Scroccarello et al. (**2023**). **ACS sensors**, 8(2), 598-609.

Della Pelle et al. (**2023**). **Nanoscale**, 15(15), 7164-7175.

Pidal et al. (**2024**). **Microchimica Acta**, 191(6), 361.

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BIOSENSORS

Zhao et al. (**2023**). **ACS Applied Materials & Interfaces**, 15(7), 9024–9033.

Bukhari et al. (**2024**). **Biosensors and Bioelectronics**, 262, 116544.

Paolini et al. (**2024**). **ACS Applied Materials & Interfaces**, *16*(17), 22443-22454.

Silveri et al. (**2024**). ***Biosensors and Bioelectronics***, *263*, 116620.

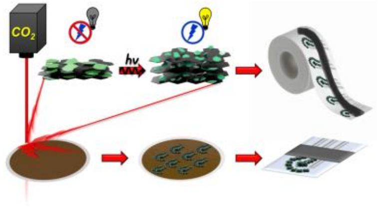
ANALYTICAL DEVICES

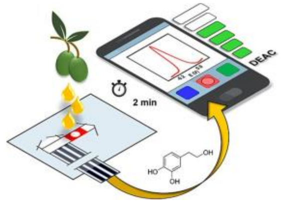
Silveri et al. (**2023**). **Food Chemistry**, *420*, 136112.

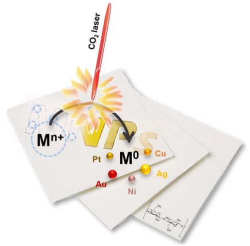
Fiori S. et al. (**2024**). **Sensors and Actuators B: Chemical**, 399, 134768.

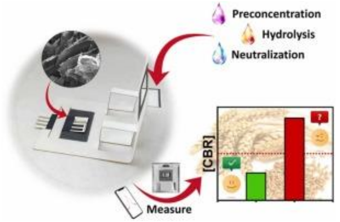
Fiori, S. et al. (**2025**). **Analytical Chemistry**, 97(8), 4293-4298.

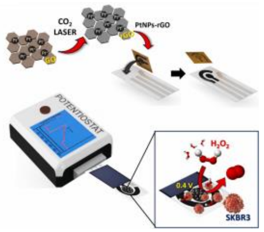
PAPER-BASED DEVICES











Outline

- **Laser-reduced graphene oxide films for sustainable paper-based sensors**
- **CO_2 laser plotter for ePAD manufacturing**
- **Laser based graphene-Pt composites for H_2O_2 detection in cell coltures**
- **Laser- boosted 3rd generation biosensor for fructose**

Recycled and by-products derived papers for L-rGO sensors

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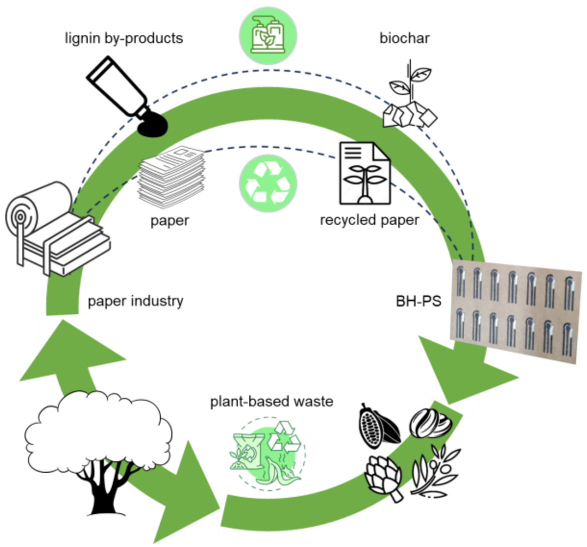
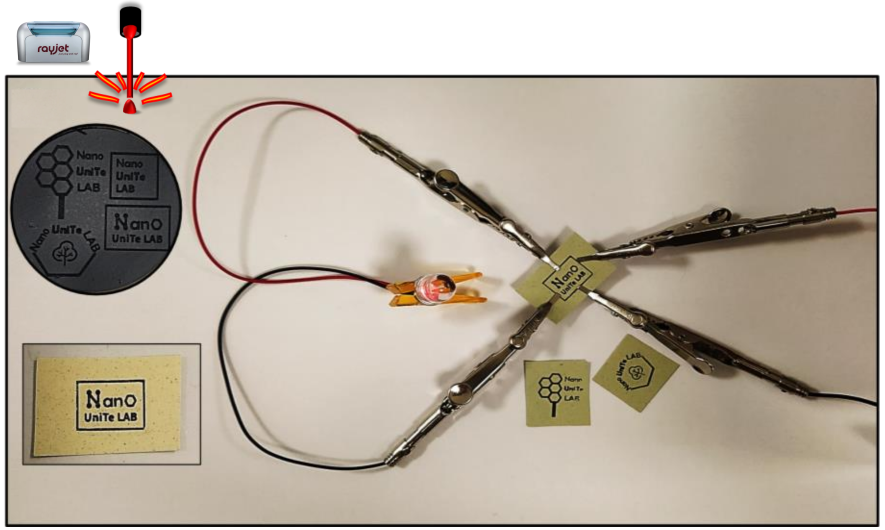
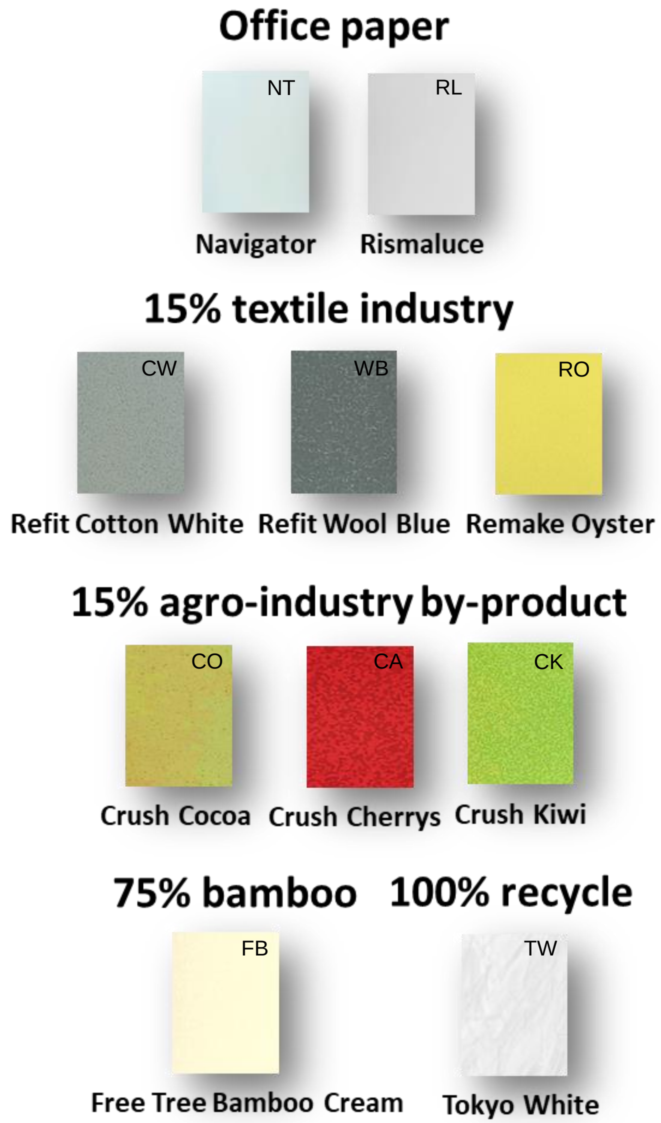
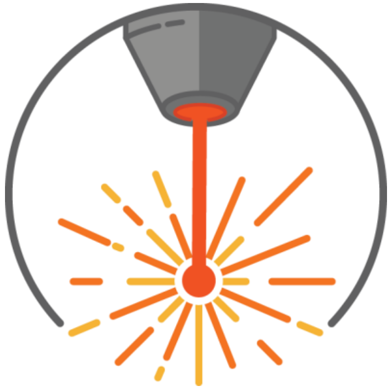




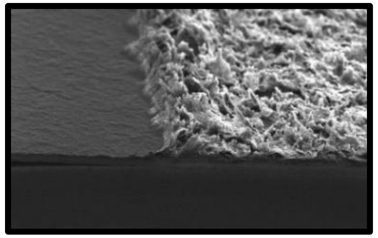
Cellulosic substrates

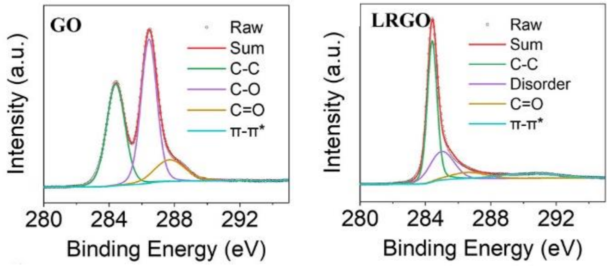


Laser-induced rGO transferable conductive films



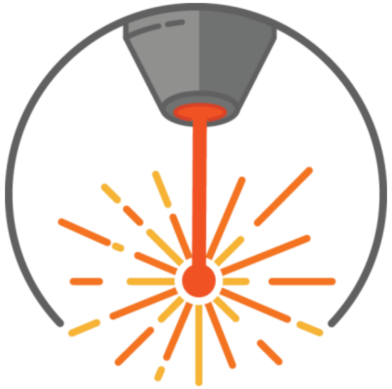
Laser-induced rGO



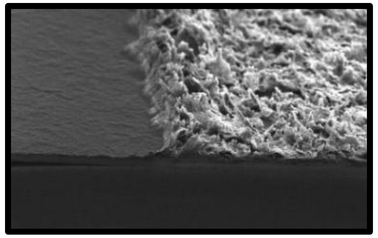


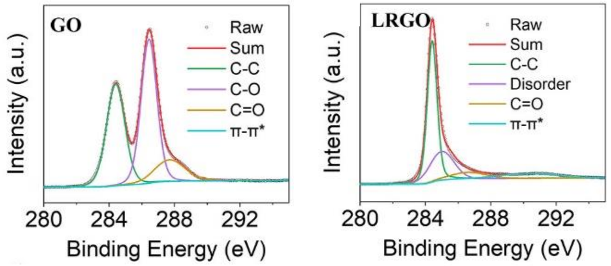
Scroccarello et al. (2023). **ACS sensors**, 2023, 8, 2, 598–609
Zhao et al. (2023). **ACS Appl. Mater. Interfaces,** 15, 7, 9024–9033

Laser-induced rGO transferable conductive films



Laser-induced rGO

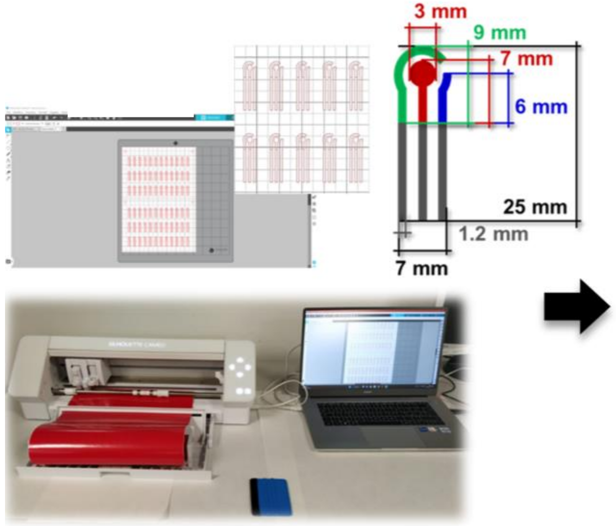




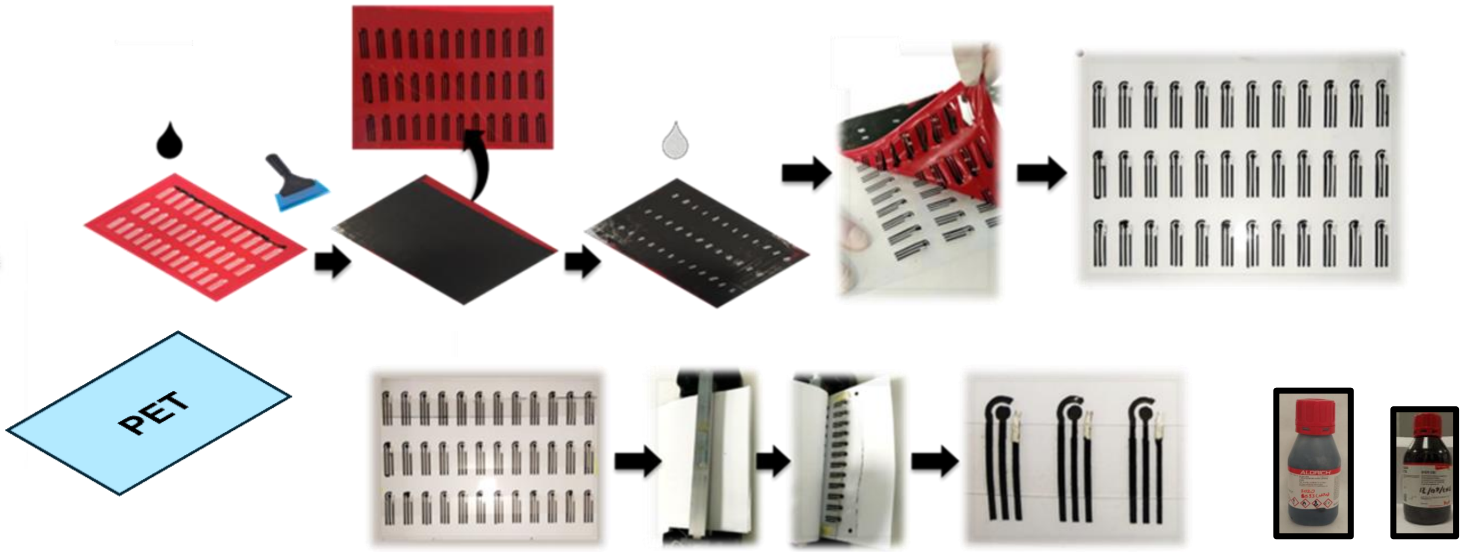
Scroccarello et al. (2023). **ACS sensors**, 2023, 8, 2, 598–609
Zhao et al. (2023). **ACS Appl. Mater. Interfaces,** 15, 7, 9024–9033

Stencil-printing manufacturing

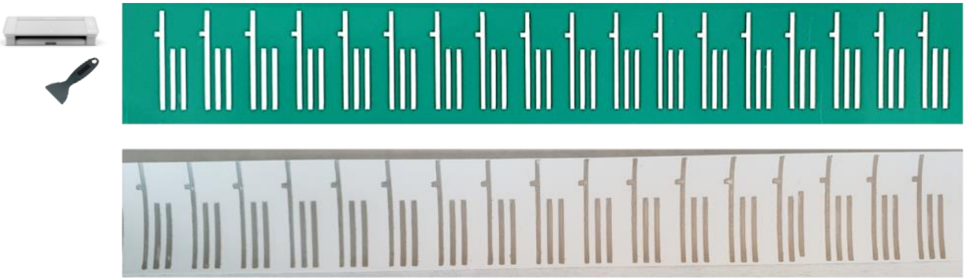
Flexible polymers



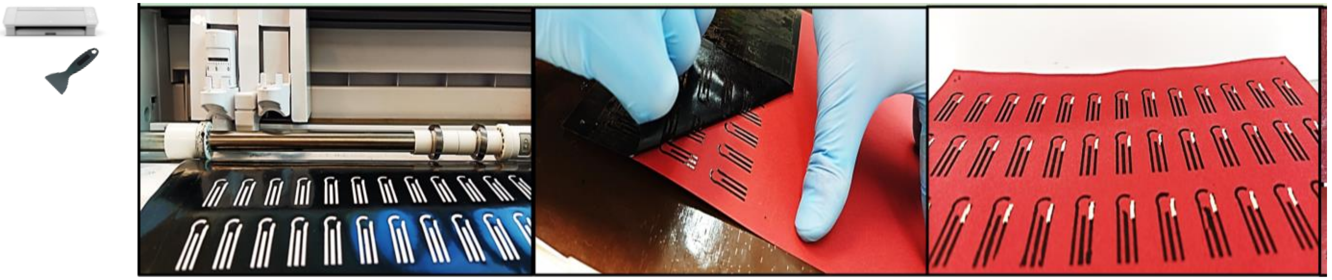
Cutting plotter



Nitrocellulose

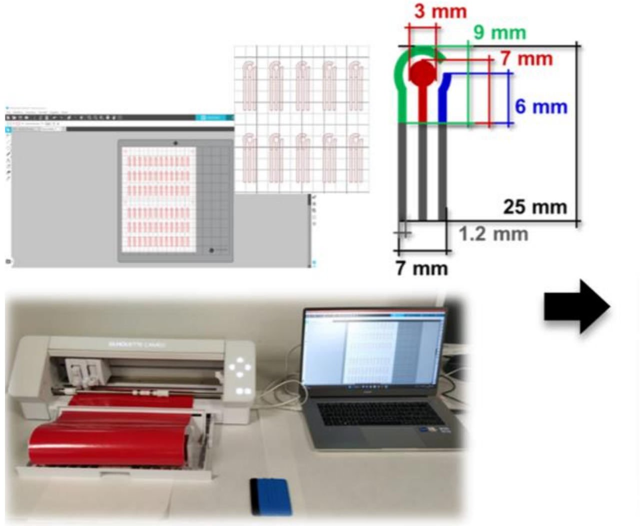


Paper



Silveri et al. (2023). **Biosensors and Bioelectronics**, 237, 115450.
Della Pelle et al. (2023). **Nanoscale**, 15(15), 7164-7175.

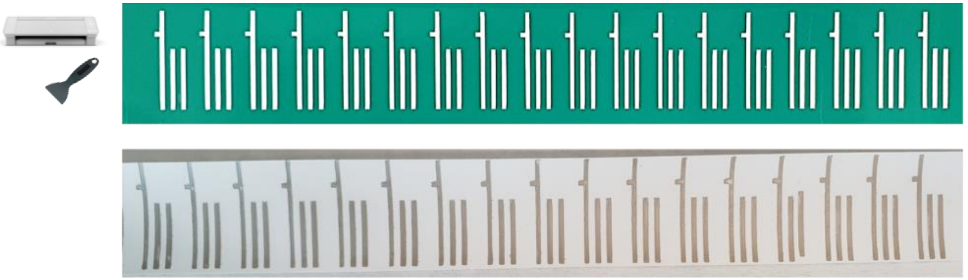
Stencil-printing manufacturing

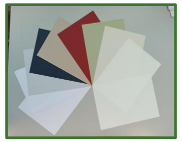


Cutting plotter

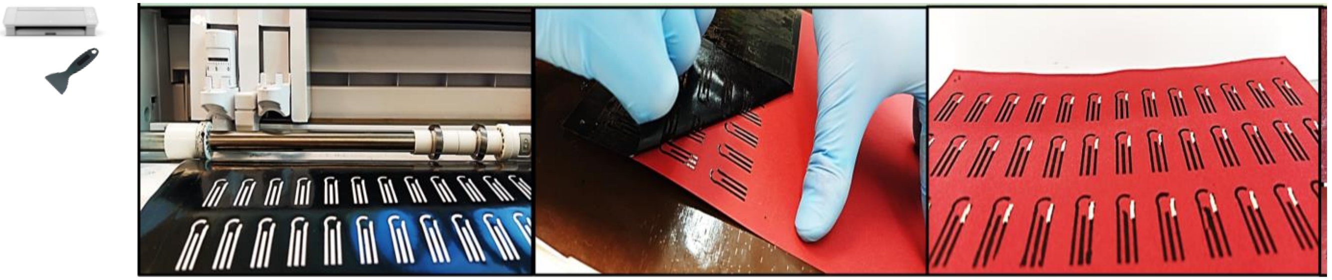
Flexible polymers

Nitrocellulose





Paper



Silveri et al. (2023). **Biosensors and Bioelectronics**, 237, 115450.
Della Pelle et al. (2023). **Nanoscale**, 15(15), 7164-7175.

Recycled and by-products derived papers for L-rGO sensors

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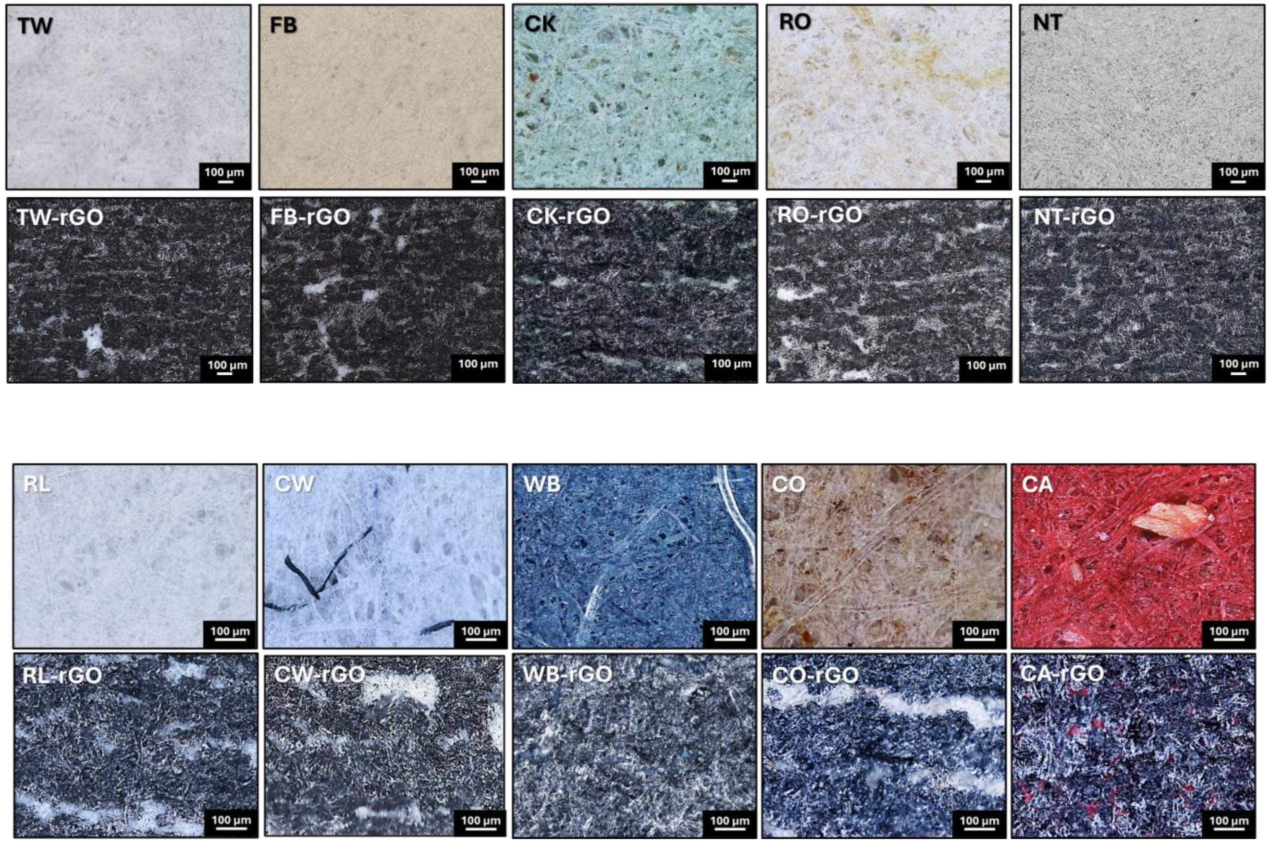
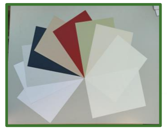
Laser-scribed rGO integration on paper substrates

Stereo microscopy

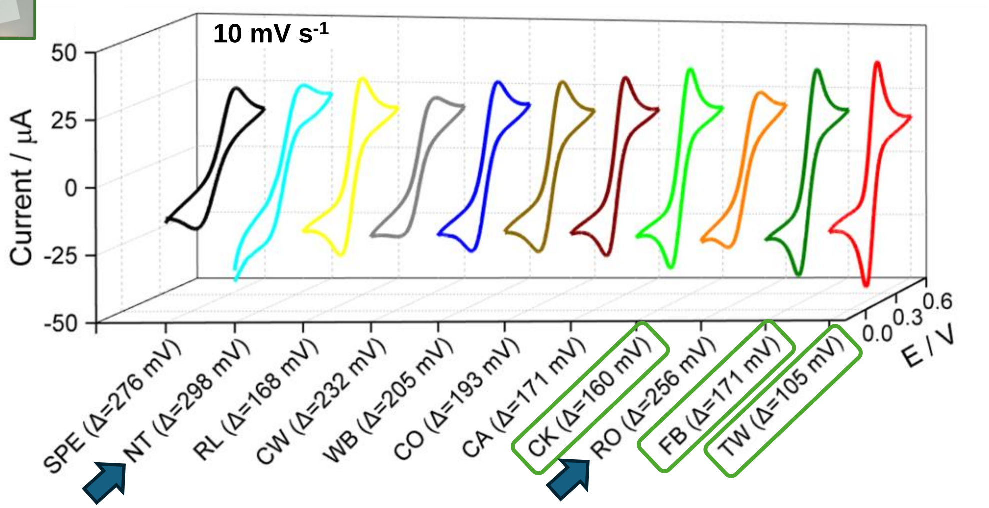


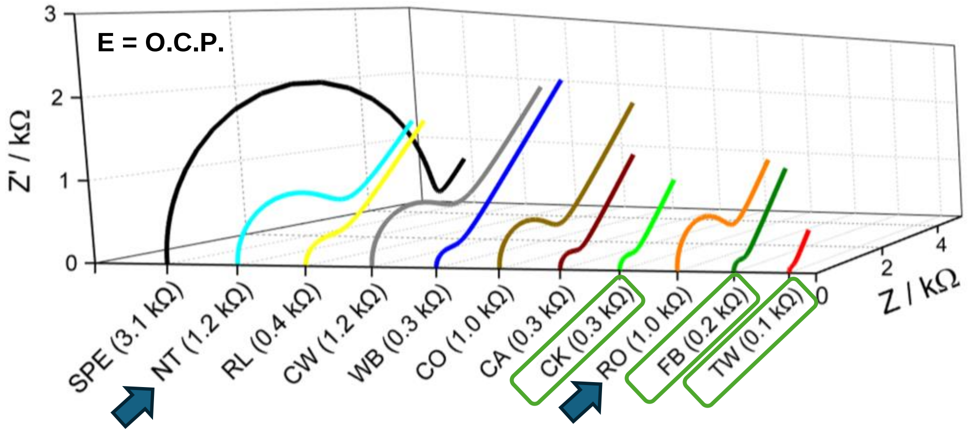
Recycled and by-products derived papers for L-rGO sensors

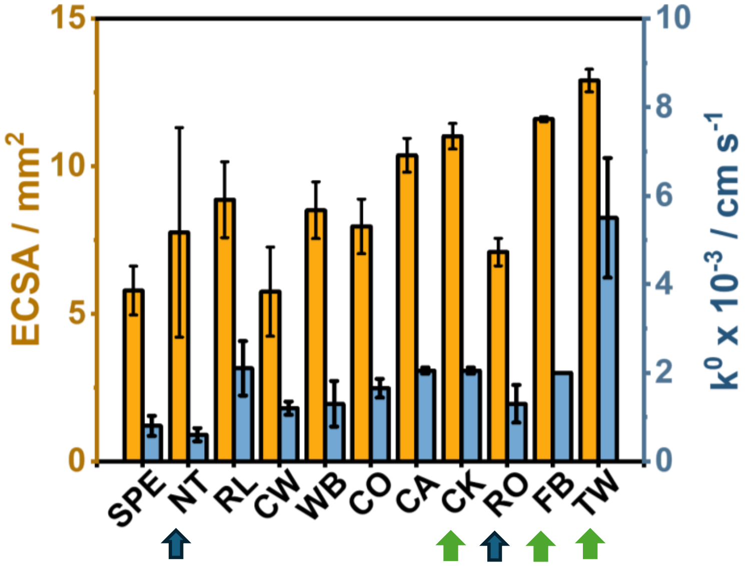
Paper-rGO sensors features comparison and characterization



5 mM $[Fe(CN)_6]^{4-/3-}$







TOKYO WHITE
(100% recycled fibres)

CRUSH KIWI
(15% kiwi wastes, 40% recycled fibres)

FREE TREE BAMBOO CREAM
(75% bamboo fibres, 25% cotton linters)

Recycled and by-products derived papers for L-rGO sensors

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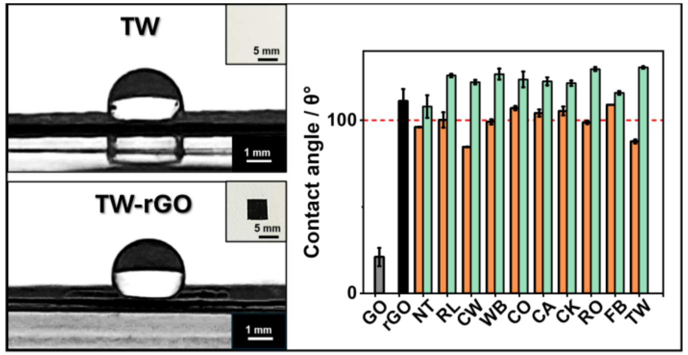
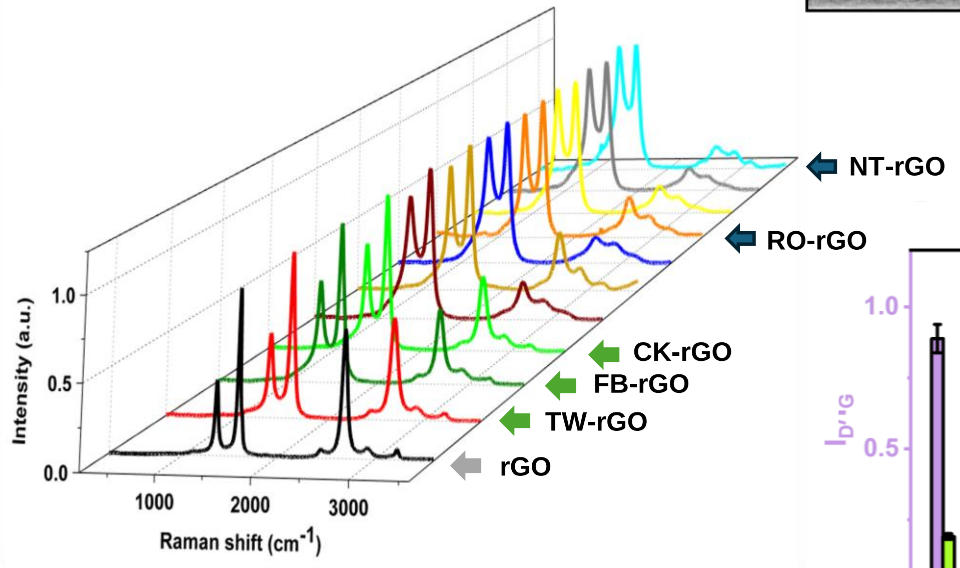
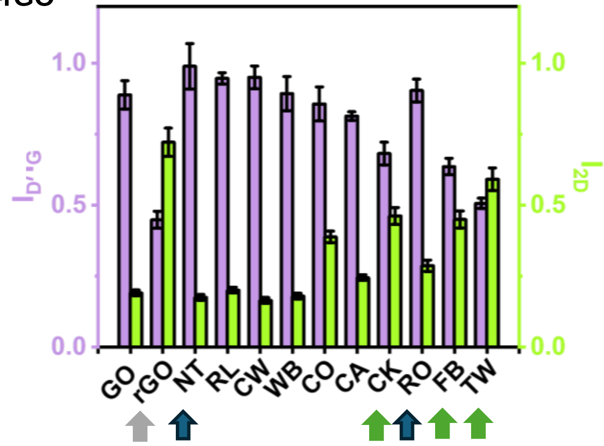
Paper-rGO sensors features comparison and characterization

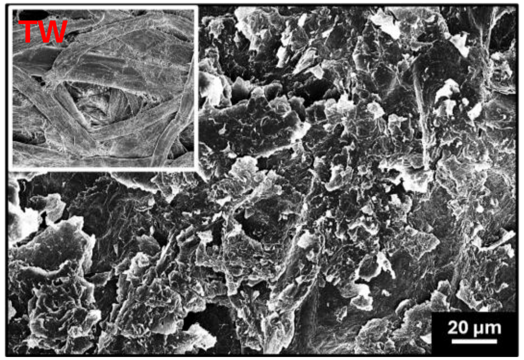




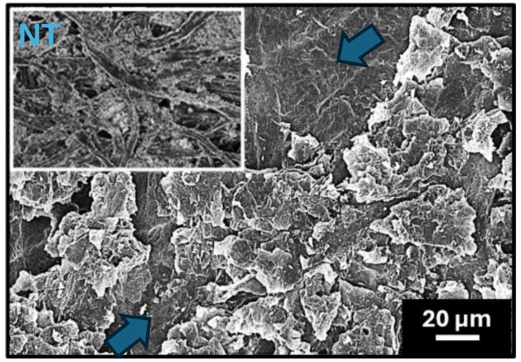
D, G and 2D peaks



TW-rGO



NT-rGO



Recycled and by-products derived papers for L-rGO sensors

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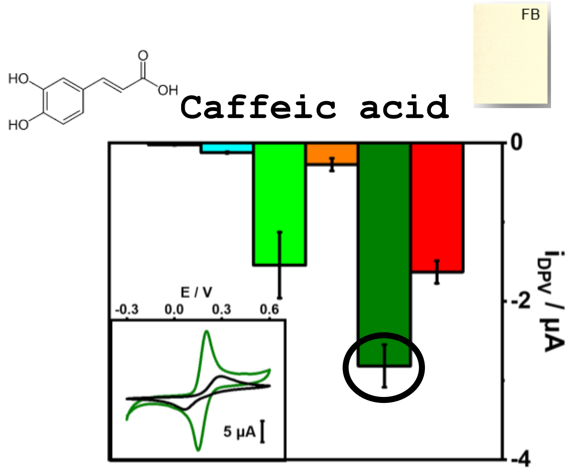
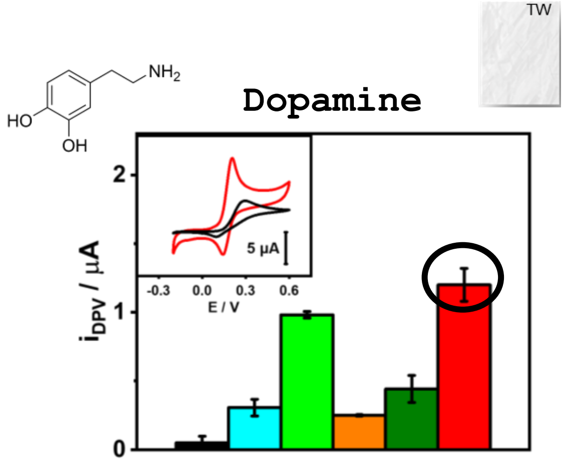
Selection of the most performing papers

SPE NT-rGO CK-rGO RO-rGO FB-rGO TW-rGO



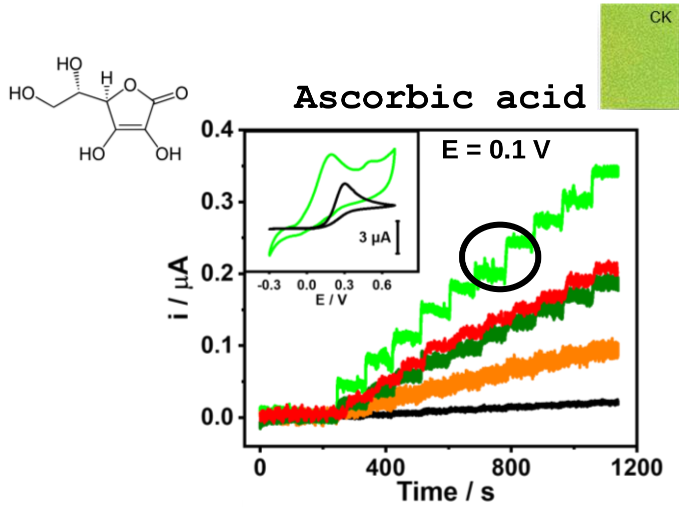
FREE TREE BAMBOO CREAM

(75% bamboo fibres, 25% cotton linters)



TOKYO WHITE

(100% recycled fibres)



CRUSH KIWI

(15% kiwi wastes, 40% recycled fibres)

Recycled and by-products derived papers for L-rGO sensors

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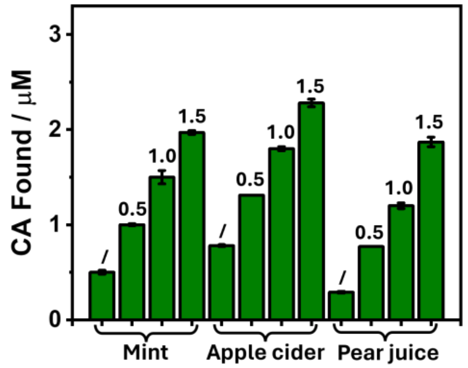
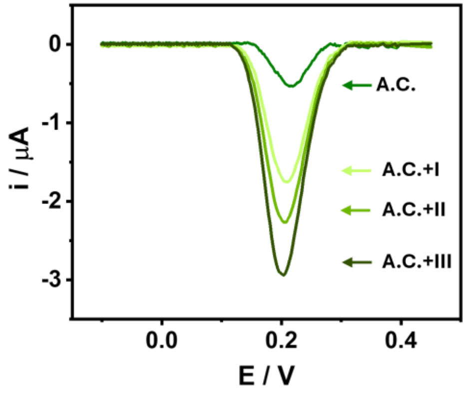
Proofs of applicability in samples analysis

FB-rGO sensor

Food samples

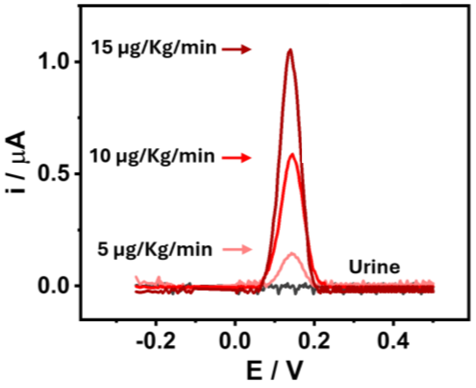


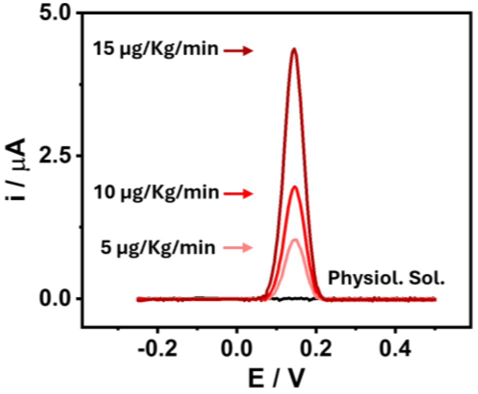


Rec: 91 – 106 %
RSD ≤ 5 % (n = 3)

TW-rGO sensor

DP injection

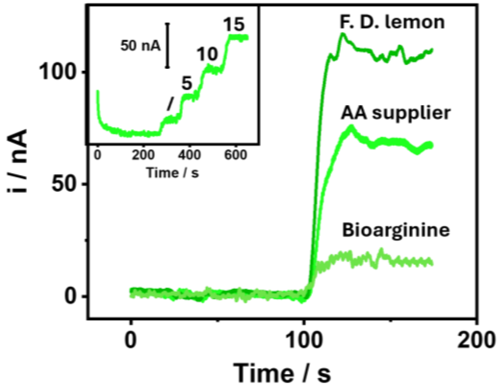


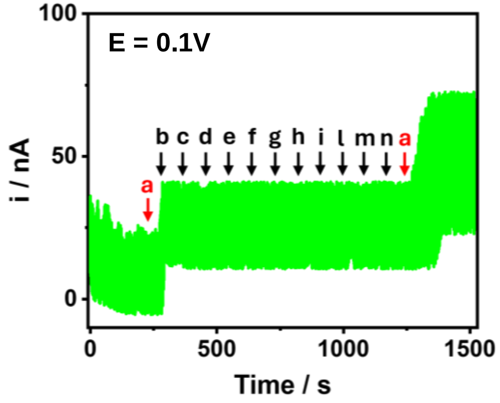


Rec: 92 – 108 %
RSD ≤ 7 % (n = 3)

CK-rGO sensor

Supplements





Rec: 92 – 108 %
RSD ≤ 5 % (n = 3)

Outline

UNIVERSITÀ DEGLI STUDI DI TERAMO UNITE

- Laser-reduced graphene oxide films for sustainable paper-based sensors

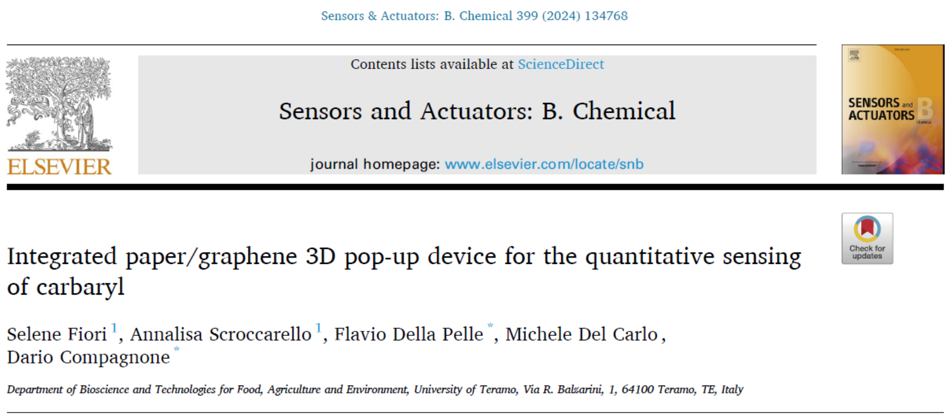
- **<u>CO_2 laser plotter for ePAD manufacturing</u>**

- Laser based graphene-Pt composites for H_2O_2 detection in cell coltures

- Laser- boosted 3rd generation biosensor for fructose

Laser-designed Paper/Graphene 3D pop-up for carbaryl analysis

UNITE UNIVERSITÀ DEGLI STUDI DI TERAMO



Sensors & Actuators: B. Chemical 399 (2024) 134768

Contents lists available at ScienceDirect

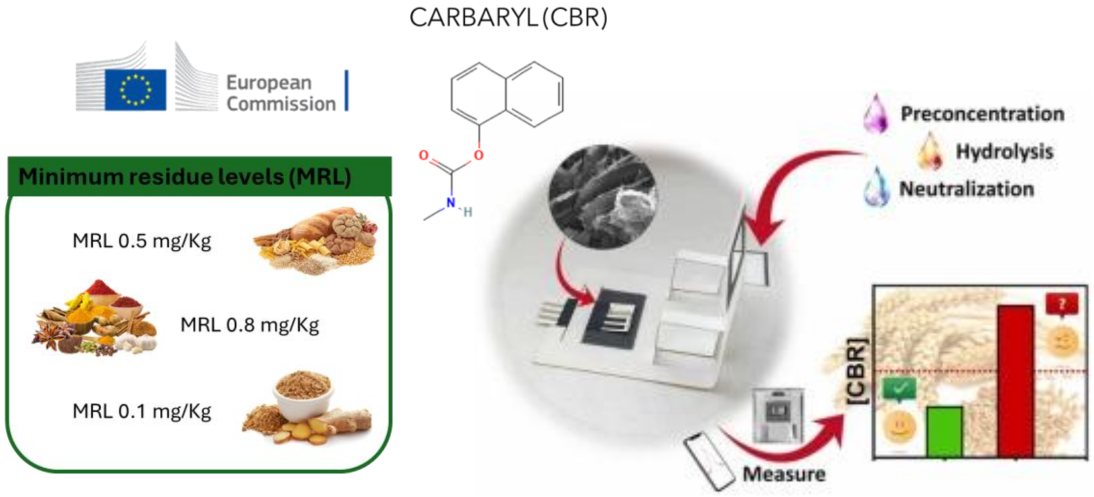
Sensors and Actuators: B. Chemical

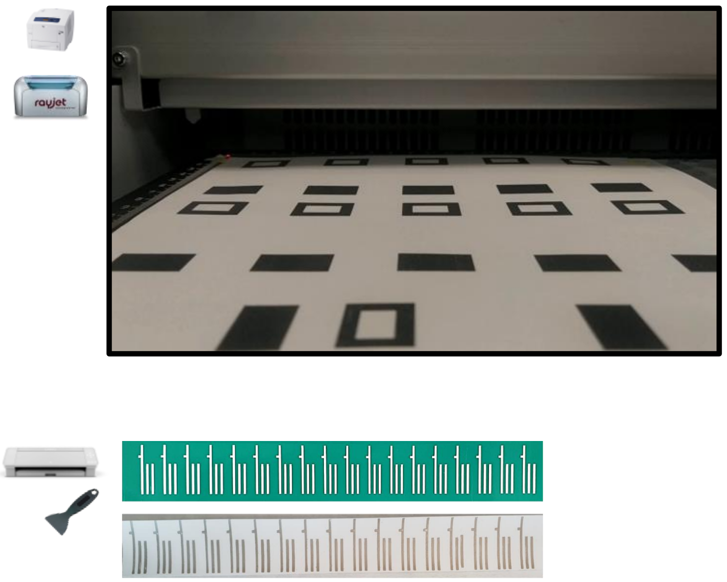
journal homepage: www.elsevier.com/locate/snb

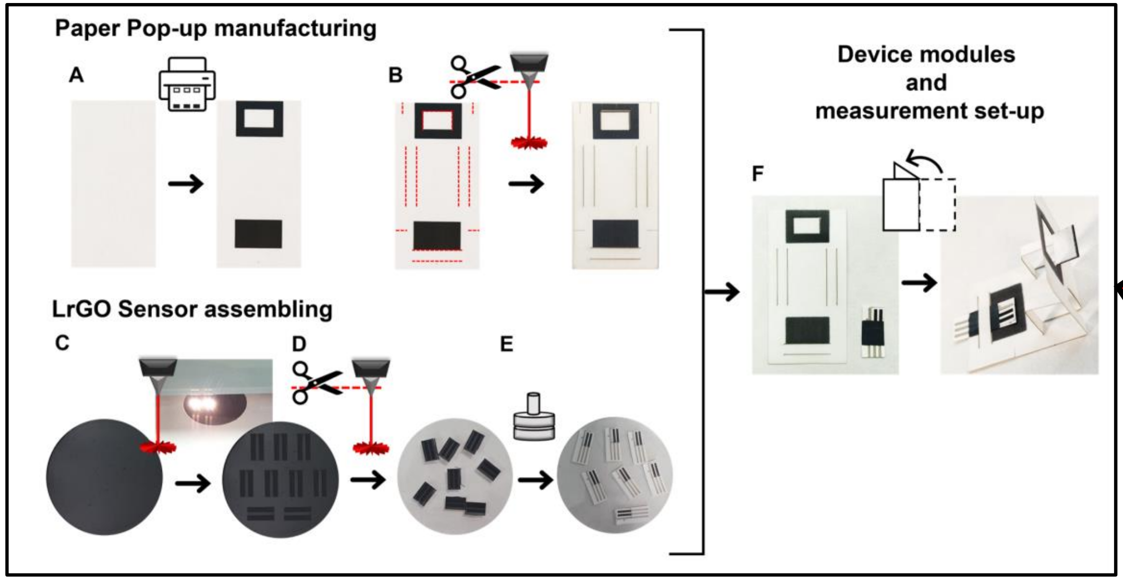
Integrated paper/graphene 3D pop-up device for the quantitative sensing of carbaryl

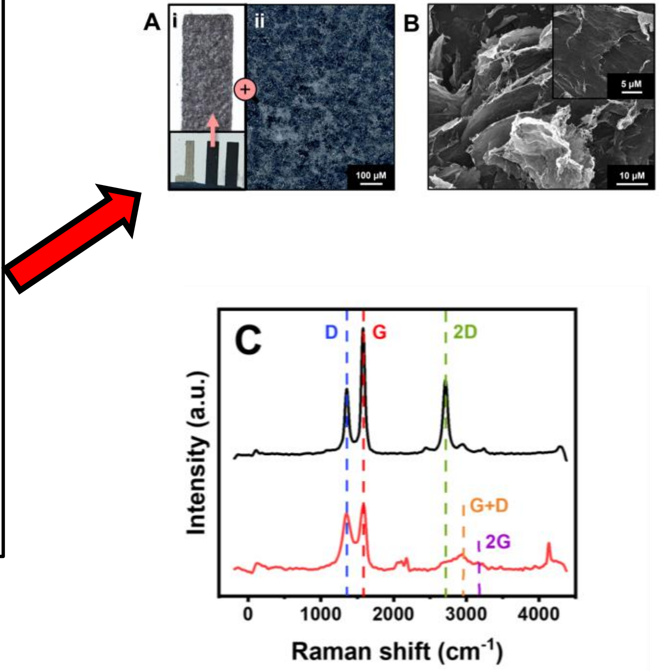
Selene Fiori [1], Annalisa Scroccarello [1], Flavio Della Pelle [*], Michele Del Carlo, Dario Compagnone [*]

Department of Bioscience and Technologies for Food, Agriculture and Environment, University of Teramo, Via R. Balzarini, 1, 64100 Teramo, TE, Italy





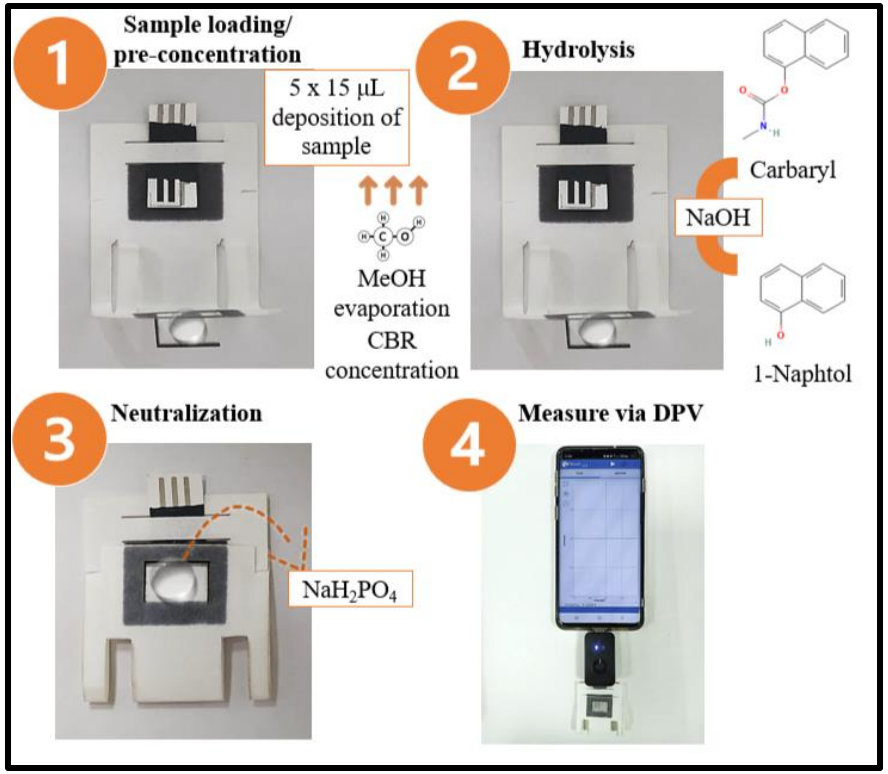


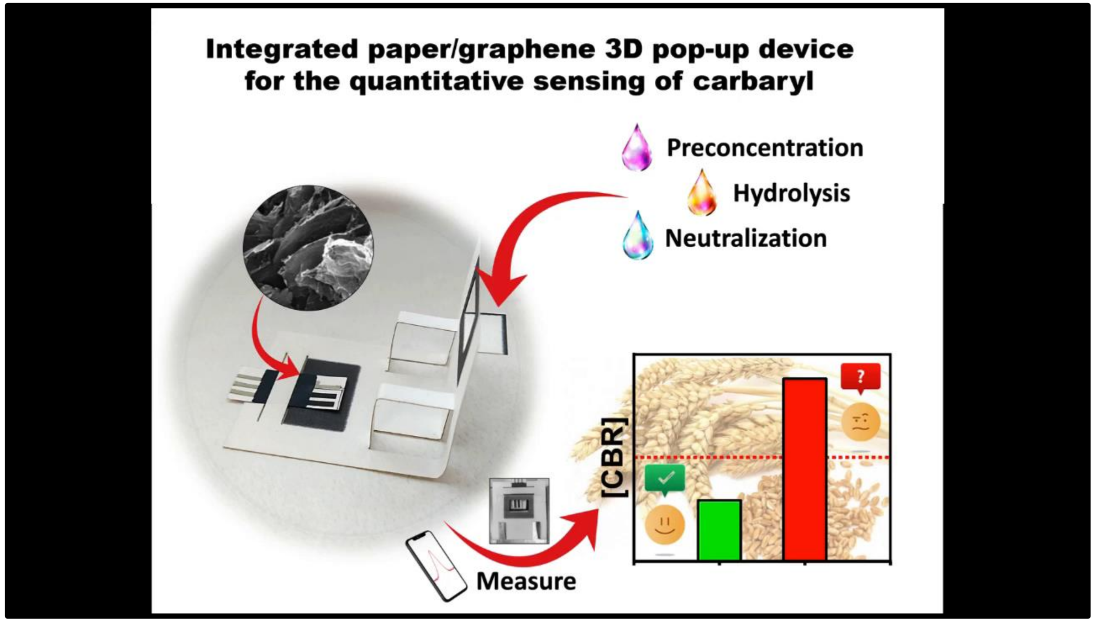


Fiori et al. (2024). **Sensors and Actuators B: Chemical**, 399, 134768.

Laser-designed Paper/Graphene 3D pop-up for carbaryl analysis

Assay format

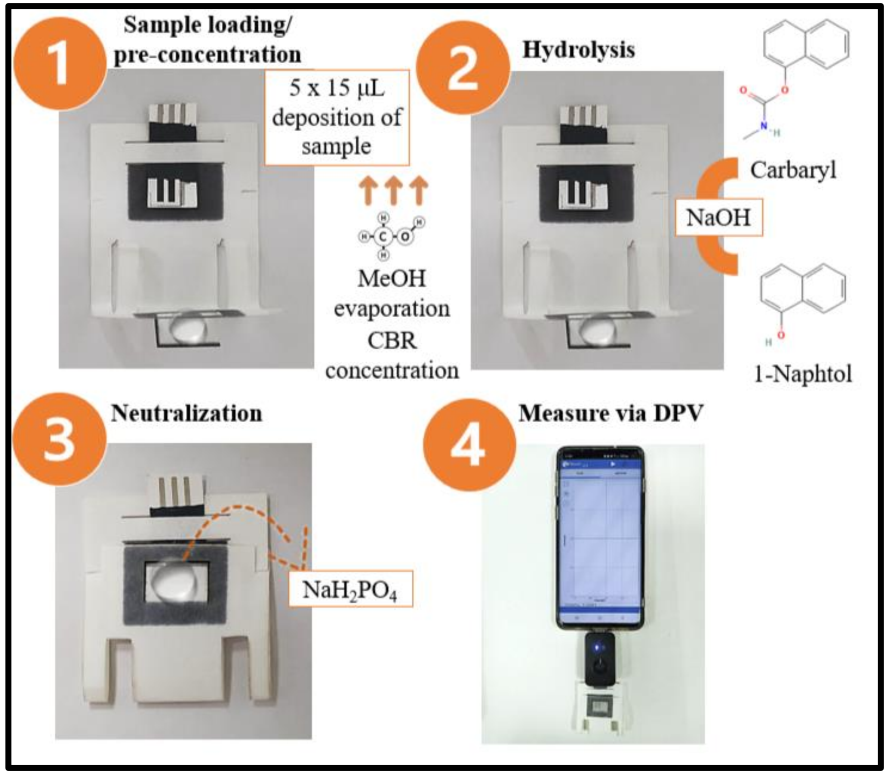




Fiori et al. (2024). **Sensors and Actuators B: Chemical**, 399, 134768.

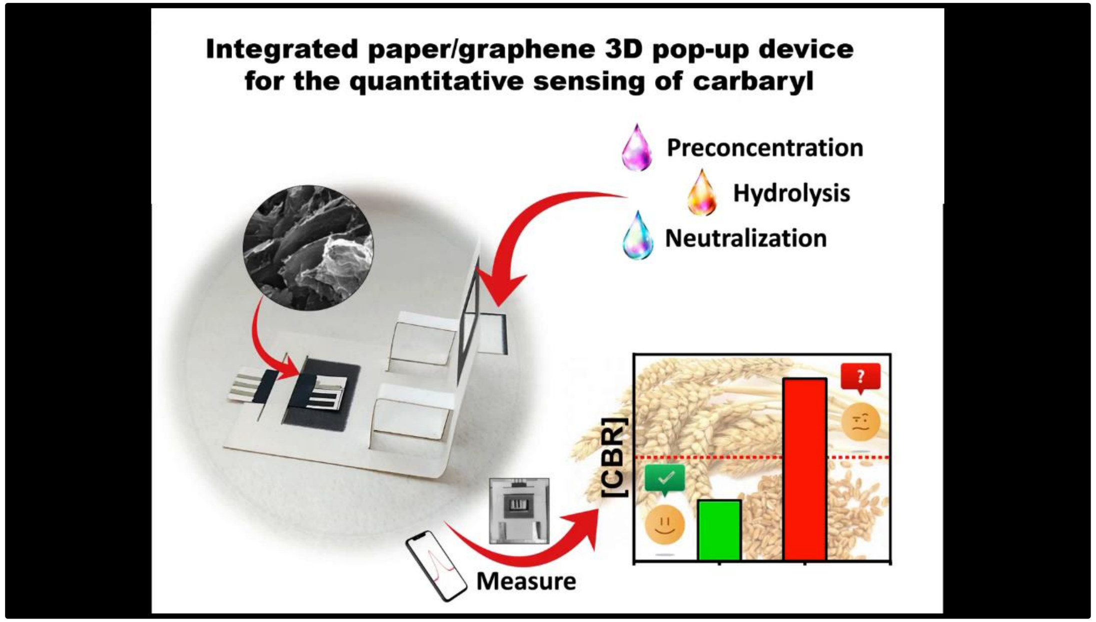
Laser-designed Paper/Graphene 3D pop-up for carbaryl analysis

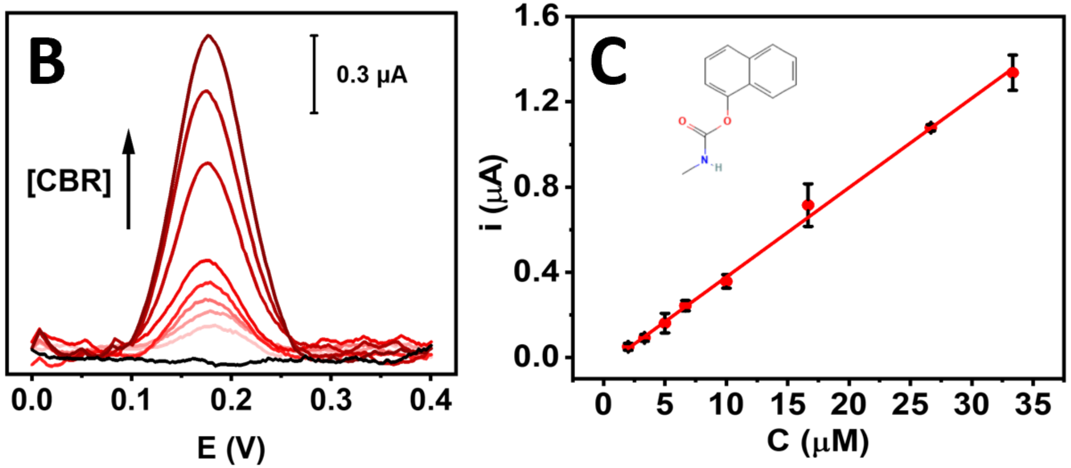
Assay format



LOD = 0.4 µM
L.R.: 1.5-33 µM (R^2 =0.995)
Slope RSD = 8% (n = 3)

Analytical performance

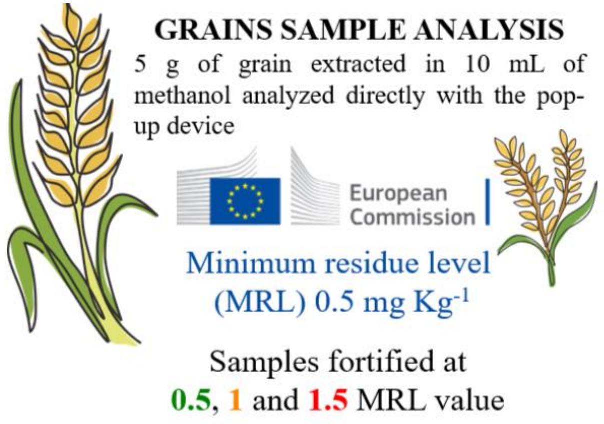


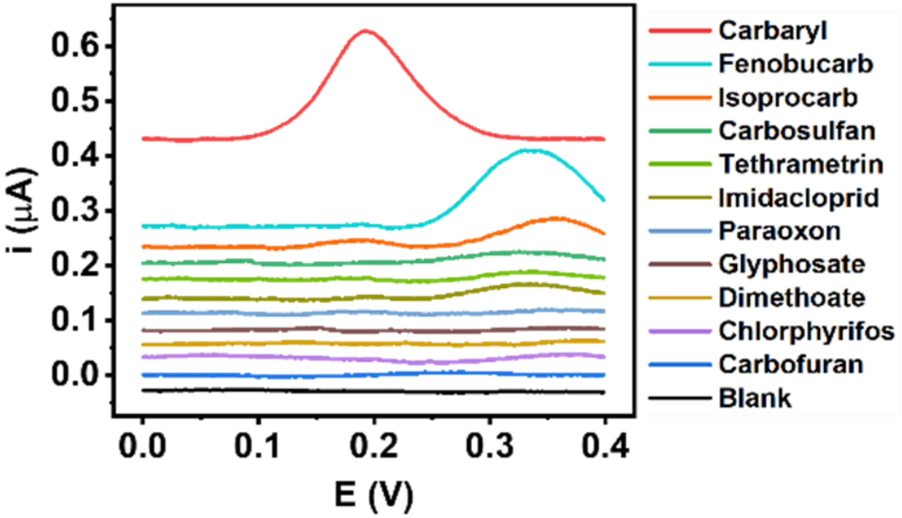


Fiori et al. (2024). **Sensors and Actuators B: Chemical**, 399, 134768.

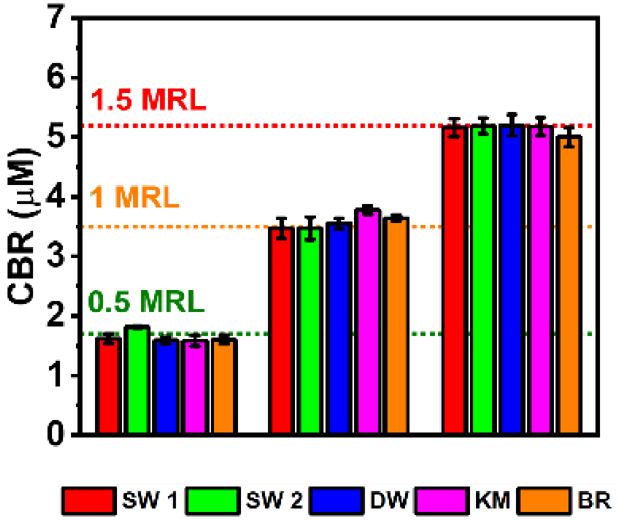
Laser-designed Paper/Graphene 3D pop-up for carbaryl analysis

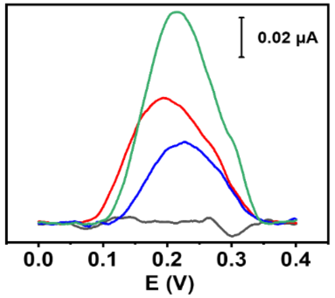
Sample and interferences analysis





```
Soft wheat 1 (SW1)
Soft wheat 2  (SW2)
Durum wheat (DW)
Kamut (KM)
Barley (BR)
```





Rec: 93 – 108 **%**
RSD ≤ 6 **%** (n = 3)

Fiori et al. (2024). **Sensors and Actuators B: Chemical**, 399, 134768.

Outline

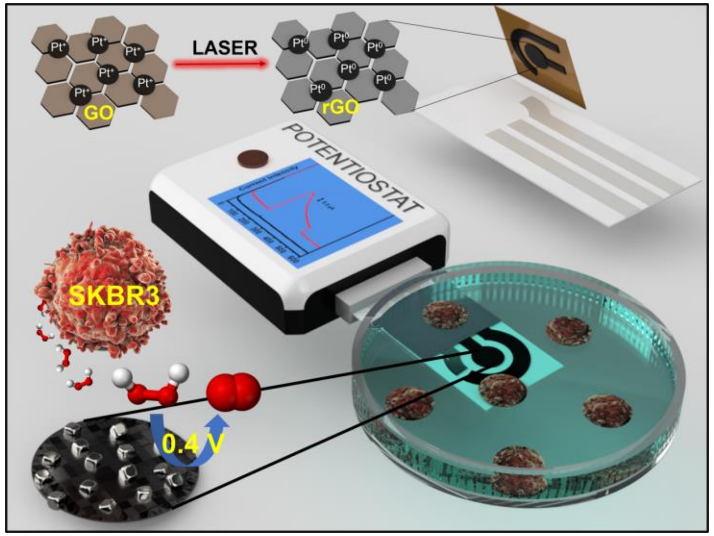
UNIVERSITÀ DEGLI STUDI DI TERAMO

UNITE

- **Laser-reduced graphene oxide films for sustainable paper-based sensors**
- **CO_2 laser plotter for ePAD manufacturing**
- **Laser based graphene-Pt composites for H_2O_2 detection in cell coltures**
- **Laser- boosted 3rd generation biosensor for fructose**

Nanozyme film for real-time detection of H_2O_2 released from cancer cells

Production of rGO-film decorated with MNPs



Biosensors and Bioelectronics 262 (2024) 116544

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

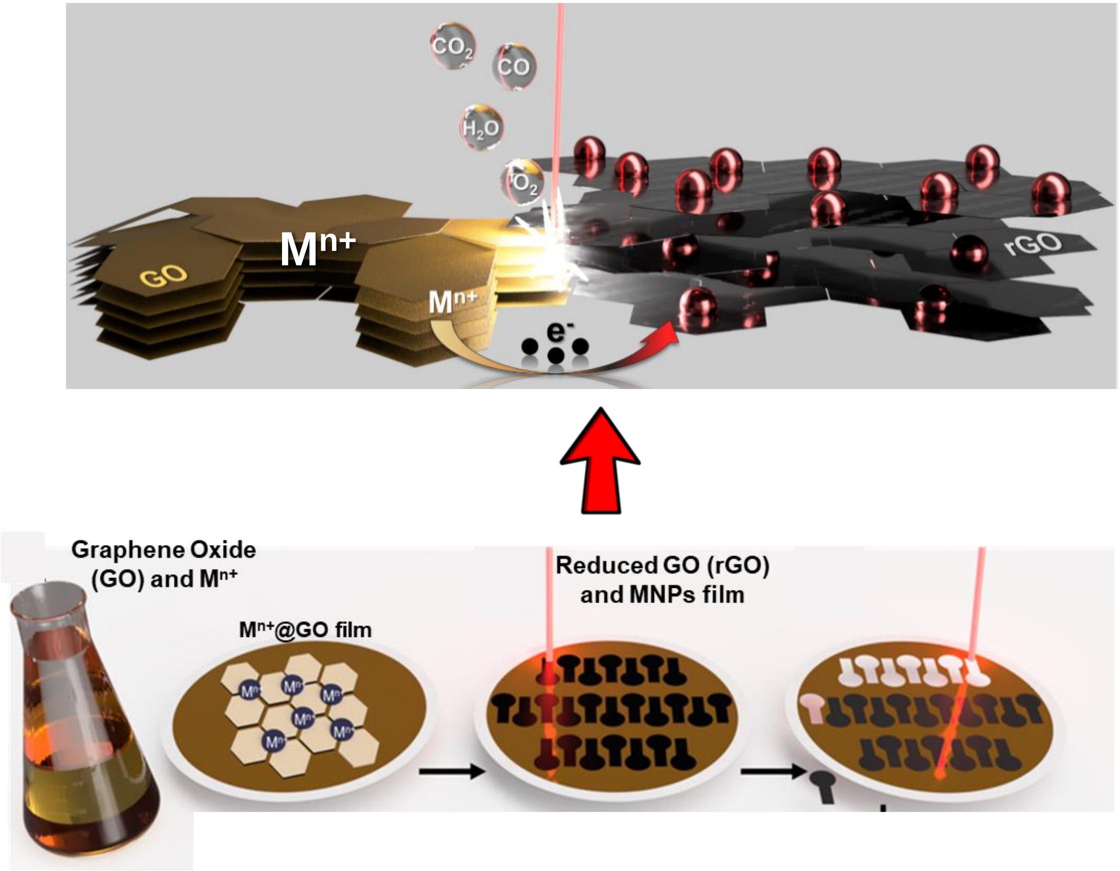
journal homepage: www.elsevier.com/locate/bios

ELSEVIER

Laser-assembled conductive 3D nanozyme film-based nitrocellulose sensor for real-time detection of H_2O_2 released from cancer cells

Qurat U.A. Bukhari [a,b,1], Flavio Della Pelle [b,1], Ruslan Alvarez-Diduk [a,*], Annalisa Scroccarello [b], Carme Nogués [c], Oriol Careta [c], Dario Compagnone [b,**], Arben Merkoçi [a,d,***]

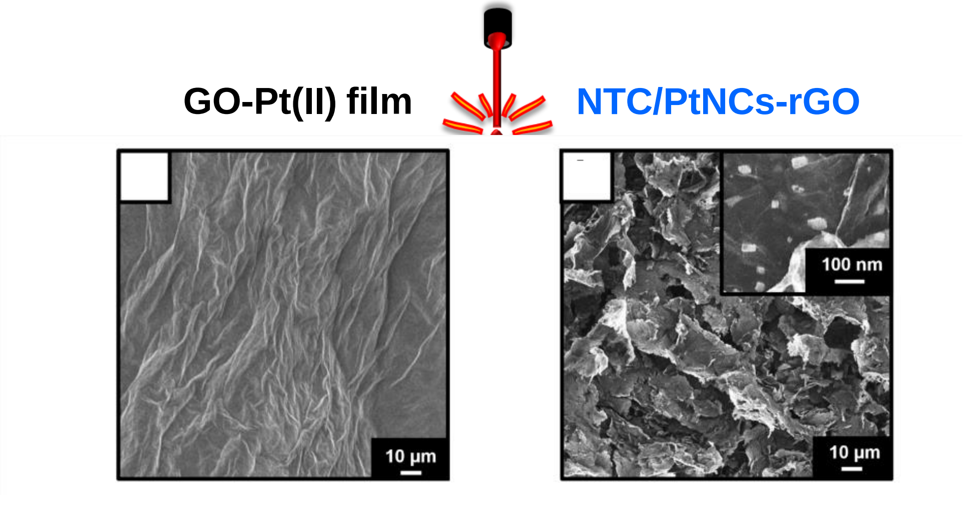
[a] Nanobioelectronics & Biosensors Group, Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus UAB, Bellaterra, Barcelona, Spain
[b] Department of Bioscience and Technology for Food, Agriculture and Environment, University of Teramo, Campus "Aurelio Saliceti" Via R. Balzarini 1, 64100, Teramo, Italy
[c] Departament de Biologia Cellular, Fisiologia i Immunologia, Facultat de Biociencies, Universitat Autonoma de Barcelona (UAB), 08193 Bellaterra, Barcelona, Spain
[d] ICREA Institució Catalana de Recerca i Estudis Avançats, Passeig de Lluís Companys, 23, 08010, Barcelona, Spain



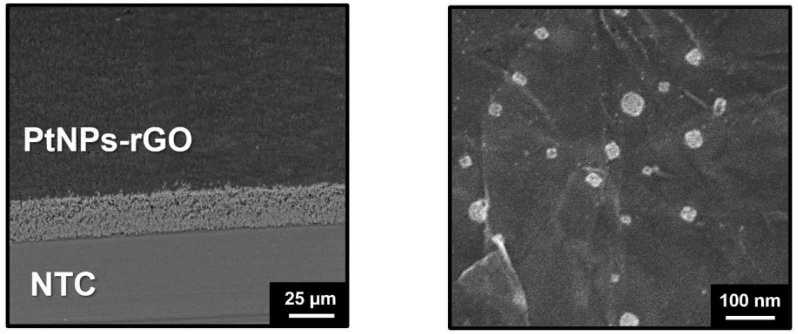
Scroccarello et al. (2023). **ACS sensors**, 2023, 8, 2, 598–609
Bukhari et al. (**2024**). **Biosensors and Bioelectronics**, 262, 116544.

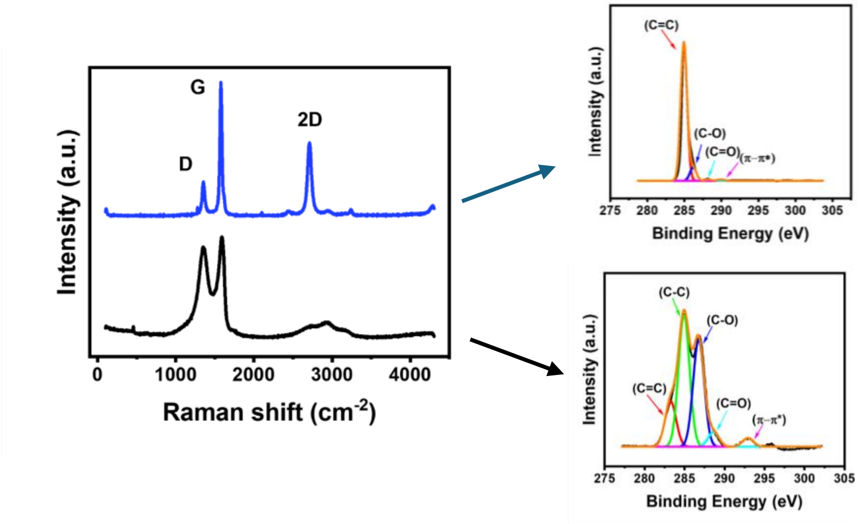
Nanozyme film for real-time detection of H_2O_2 released from cancer cells

rGO-PtNCs film integrated into nitrocellulose

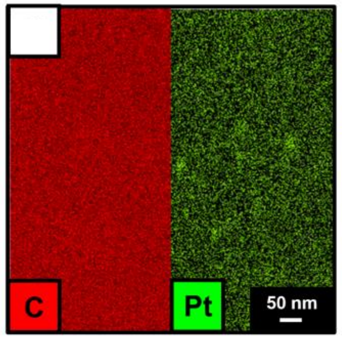


NTC/PtNCs-rGO

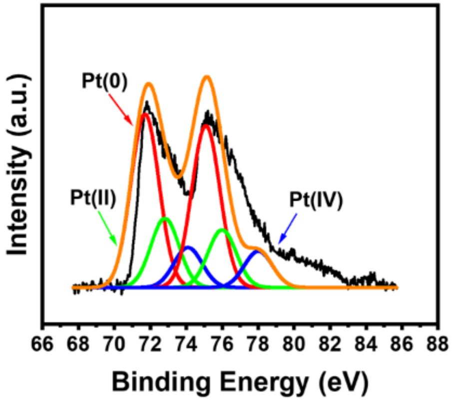




EDX



XPS

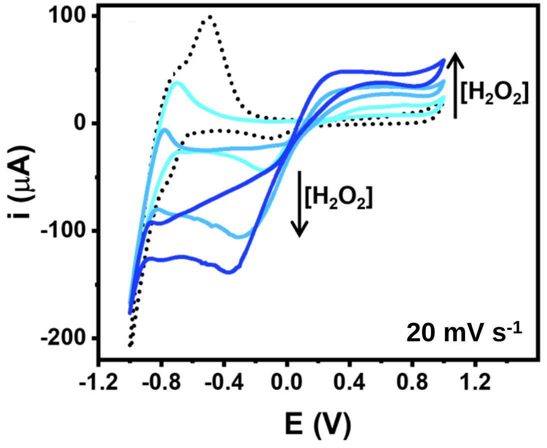


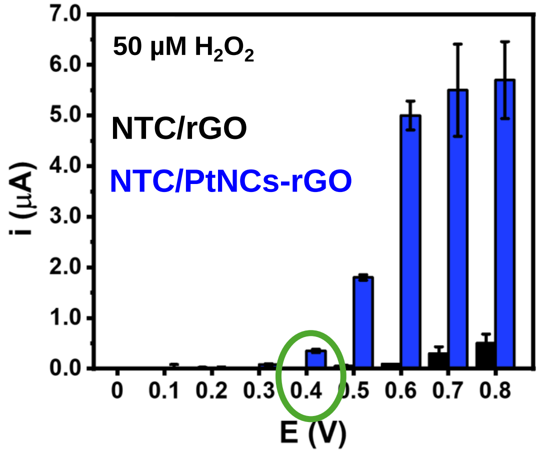
Bukhari et al. (**2024**). **Biosensors and Bioelectronics**, 262, 116544.

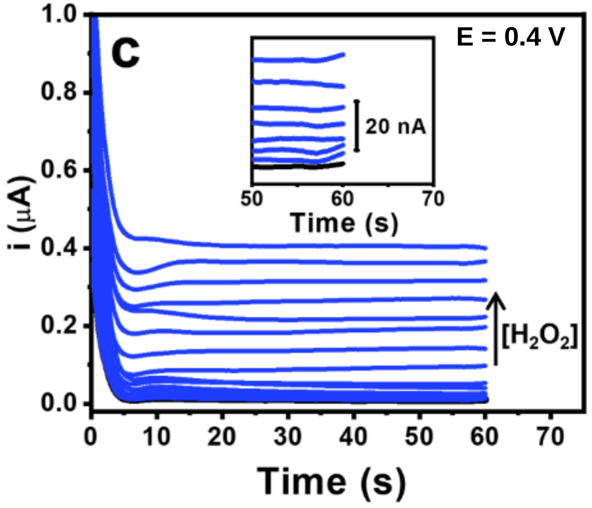
Nanozyme film for real-time detection of H_2O_2 released from cancer cells

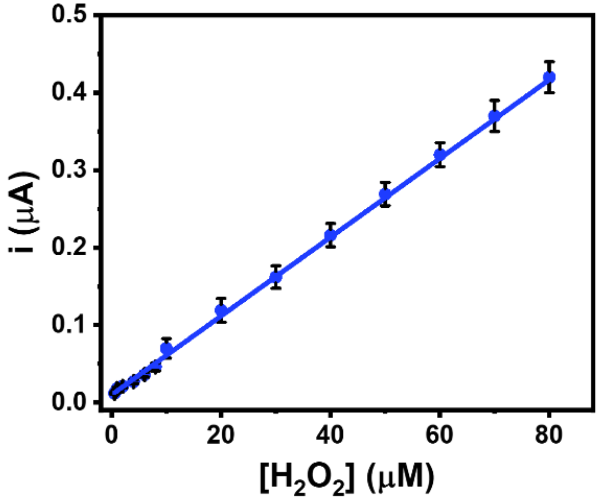
rGO-PtNCs sensor features and performance

1, 3, 6 mM H_2O_2









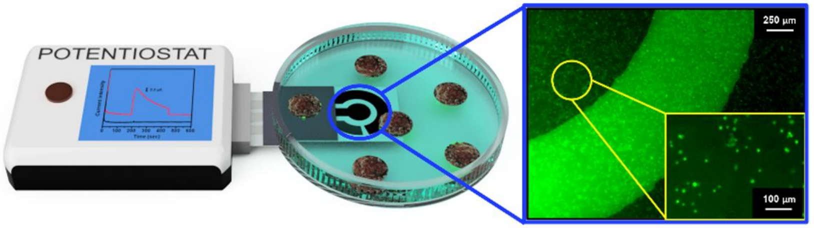
LOD = 0.2 µM
L.R.: 0.5-80 µM (R^2 = 0.994)
Slope RSD = 5 % (n = 3)

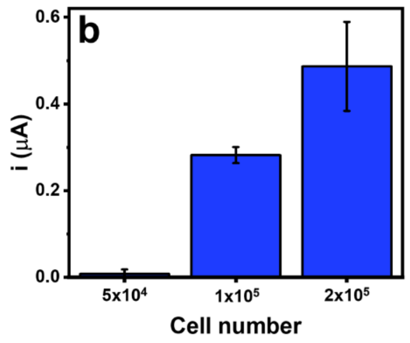
Bukhari et al. (**2024**). **Biosensors and Bioelectronics**, 262, 116544.

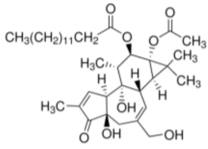
Nanozyme film for real-time detection of H_2O_2 released from cancer cells

Real-time detection of H_2O_2 release under chemical stimulation

12-myristate 13-acetate (**PMA**)



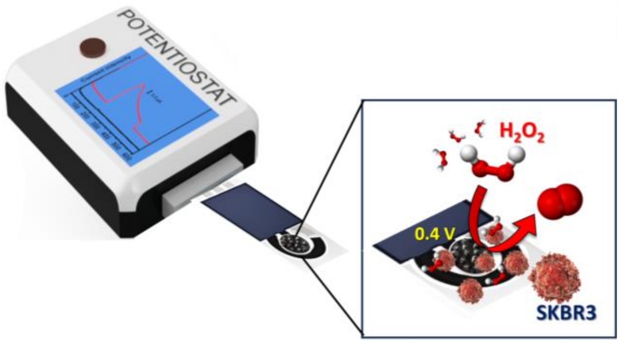


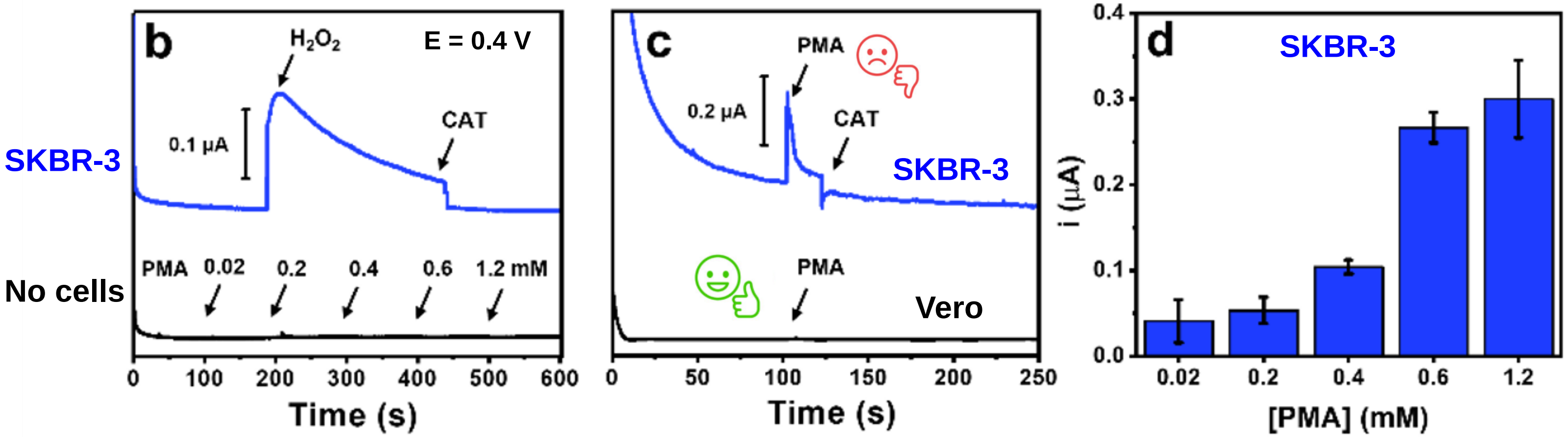


CELL LINES TESTED

SKBR-3
Human breast tumorigenic cells

Vero
non-tumorigenic cells





RSD ≤ 7% (n= 3)

Outline

- Laser-reduced graphene oxide films for sustainable paper-based sensors
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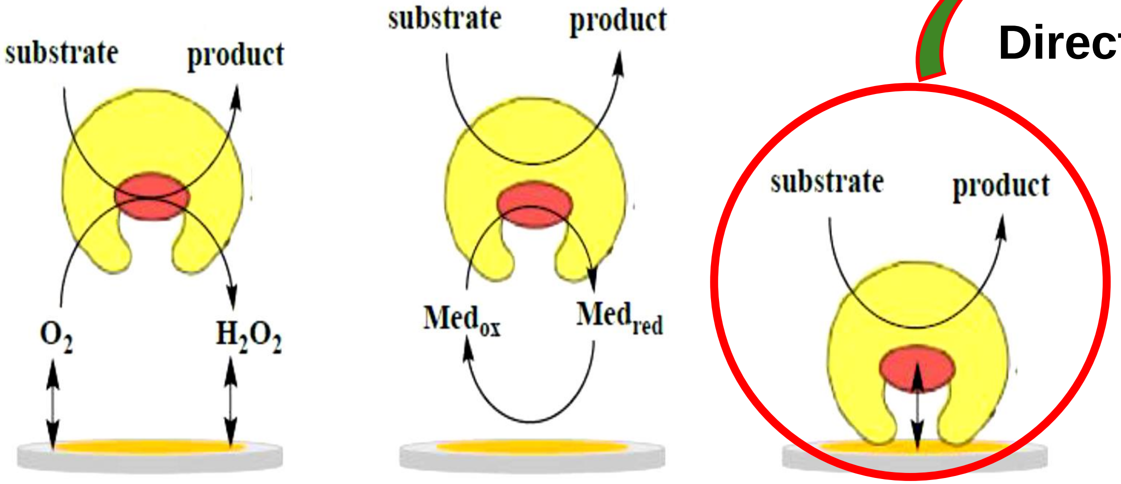
- **Laser- boosted 3rd generation biosensor for fructose**

3rd generation biosensors

UNIVERSITÀ DEGLI STUDI DI TERAMO UNITE

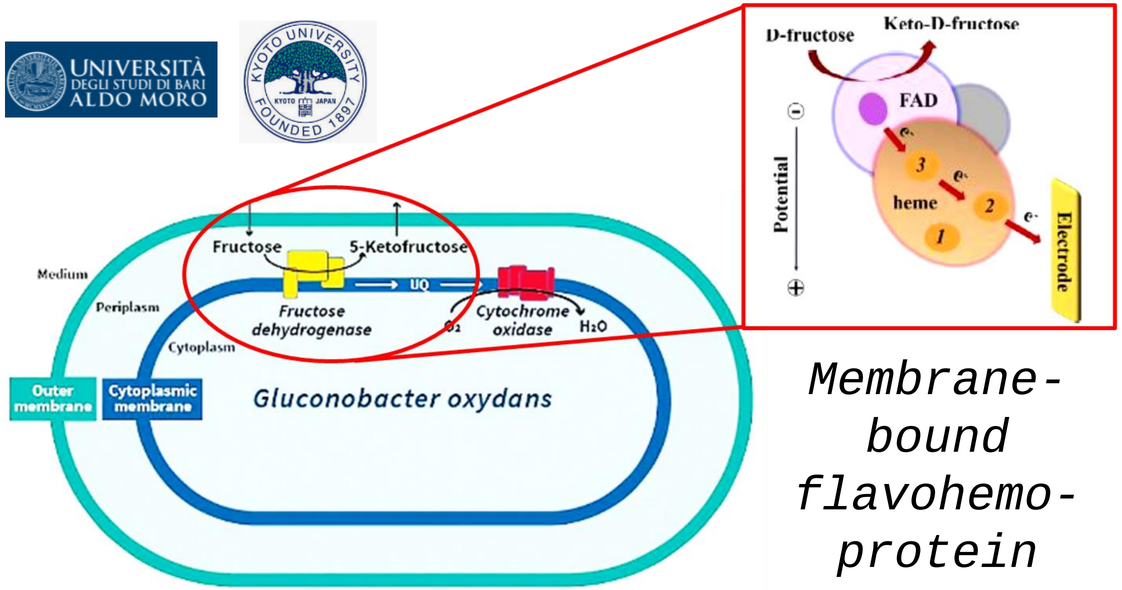
Enzyme-based electrochemical sensors



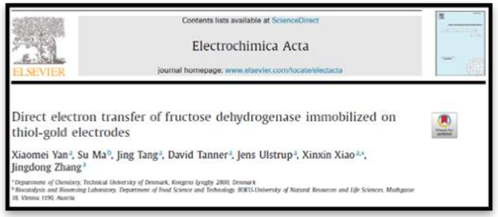
1st generation — 2nd generation — 3rd generation

Direct electron transfer (DET)

Fructose dehydrogenase (FDH)



Membrane-bound flavohemo-protein



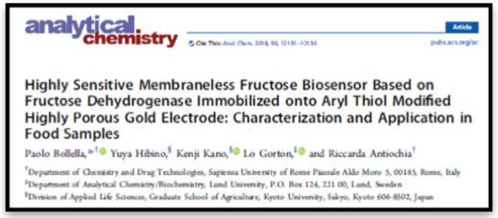
Contents lists available at ScienceDirect

Electrochimica Acta

journal homepage: www.elsevier.com/locate/electacta

Direct electron transfer of fructose dehydrogenase immobilized on thiol-gold electrodes

Xiaomei Yan, Su Ma, Jing Tang, David Tanner, Jens Ulstrup, Xinxin Xiao, Jingdong Zhang



analytical chemistry

Highly Sensitive Membraneless Fructose Biosensor Based on Fructose Dehydrogenase Immobilized onto Aryl Thiol Modified Highly Porous Gold Electrode: Characterization and Application in Food Samples

Paolo Bollella, Yuya Hibino, Kenji Kano, Lo Gorton, and Riccarda Antiochia

ChemPubSoc Europe — DOI: 10.1002/celc.201700861 — CHEMELECTROCHEM Articles

Fructose Dehydrogenase Electron Transfer Pathway in Bioelectrocatalytic Reactions

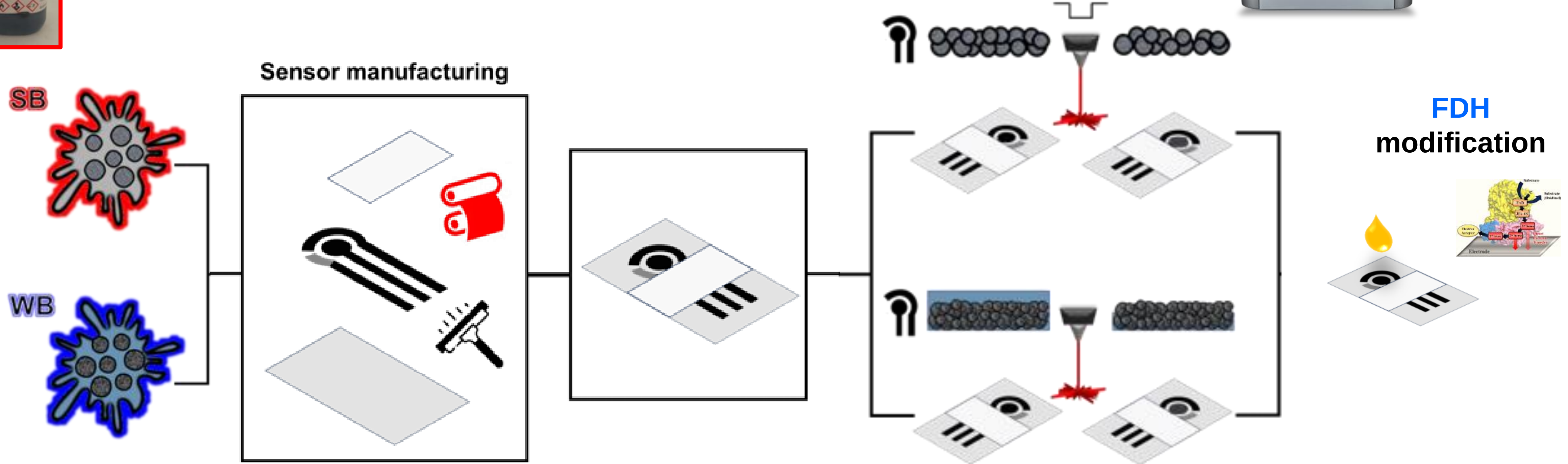
Michal Kizling and Renata Bilewicz

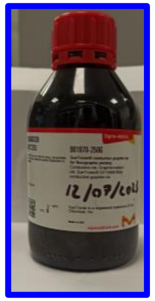
- Chemical modification
- Functionalization with linkers and/or spacers
- Conventional electrochemical transducers
- Porous micro/nano-structured electrodes

Laser-activated FDH-based stencil-printed sensors

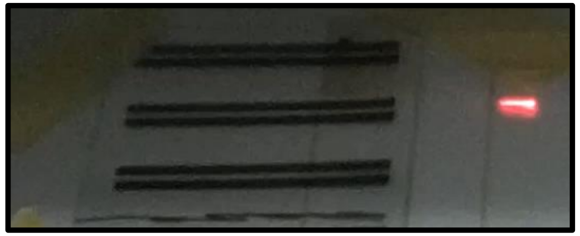
***Solvent* based c-ink (SB)**

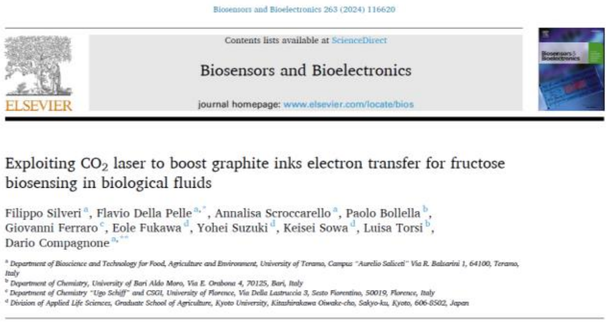
CO_2 laser (λ = 10.6 µm)
activation





***Water* based c-ink (WB)**




Biosensors and Bioelectronics 263 (2024) 116620

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: www.elsevier.com/locate/bios

ELSEVIER

Exploiting CO_2 laser to boost graphite inks electron transfer for fructose biosensing in biological fluids

Filippo Silveri[a], Flavio Della Pelle[a,*], Annalisa Scroccarello[a], Paolo Bollella[b], Giovanni Ferraro[c], Eole Fukawa[d], Yohei Suzuki[d], Keisei Sowa[d], Luisa Torsi[b], Dario Compagnone[a,**]

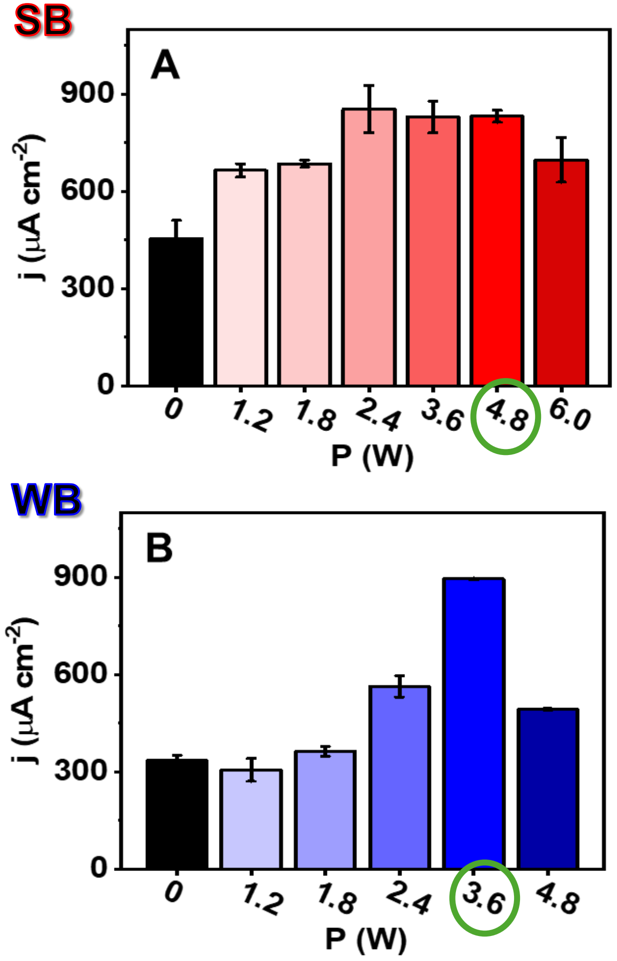
[a] Department of Bioscience and Technology for Food, Agriculture and Environment, University of Teramo, Campus "Aurelio Saliceti" Via R. Balsarini 1, 64100, Teramo, Italy
[b] Department of Chemistry, University of Bari Aldo Moro, Via E. Orabona 4, 70125, Bari, Italy
[c] Department of Chemistry "Ugo Schiff" and CSGI, University of Florence, Via Della Lastruccia 3, Sesto Fiorentino, 50019, Florence, Italy
[d] Division of Applied Life Sciences, Graduate School of Agriculture, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto, 606-8502, Japan

Laser-activated FDH-based stencil-printed sensors

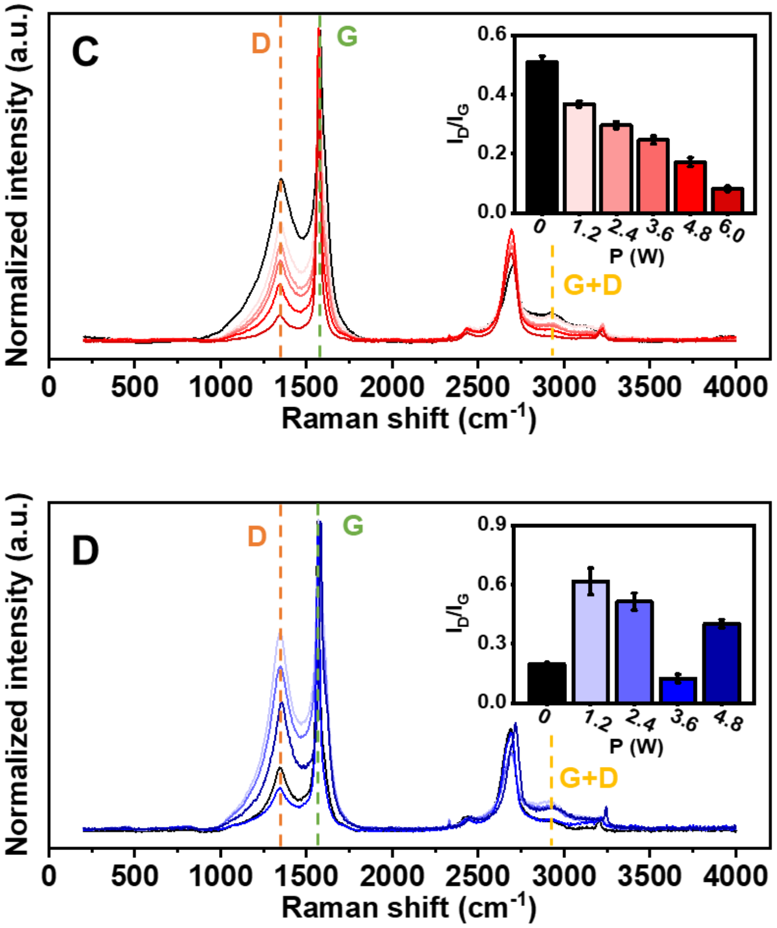
CO_2 laser power investigation

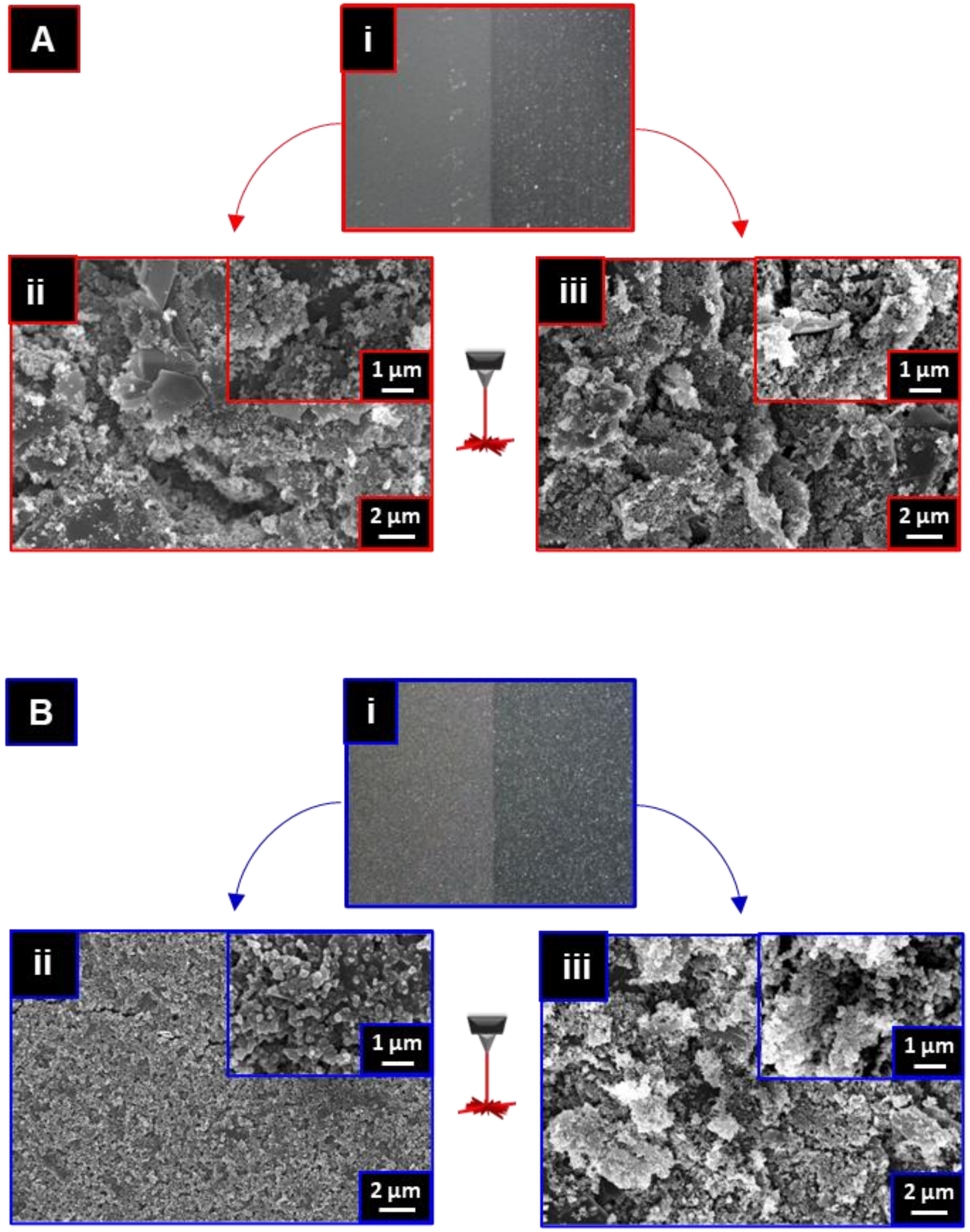
5 mM $[Fe(CN)_6]^{3-/4-}$

CV 25 mV s^{-1}



Raman spectroscopy

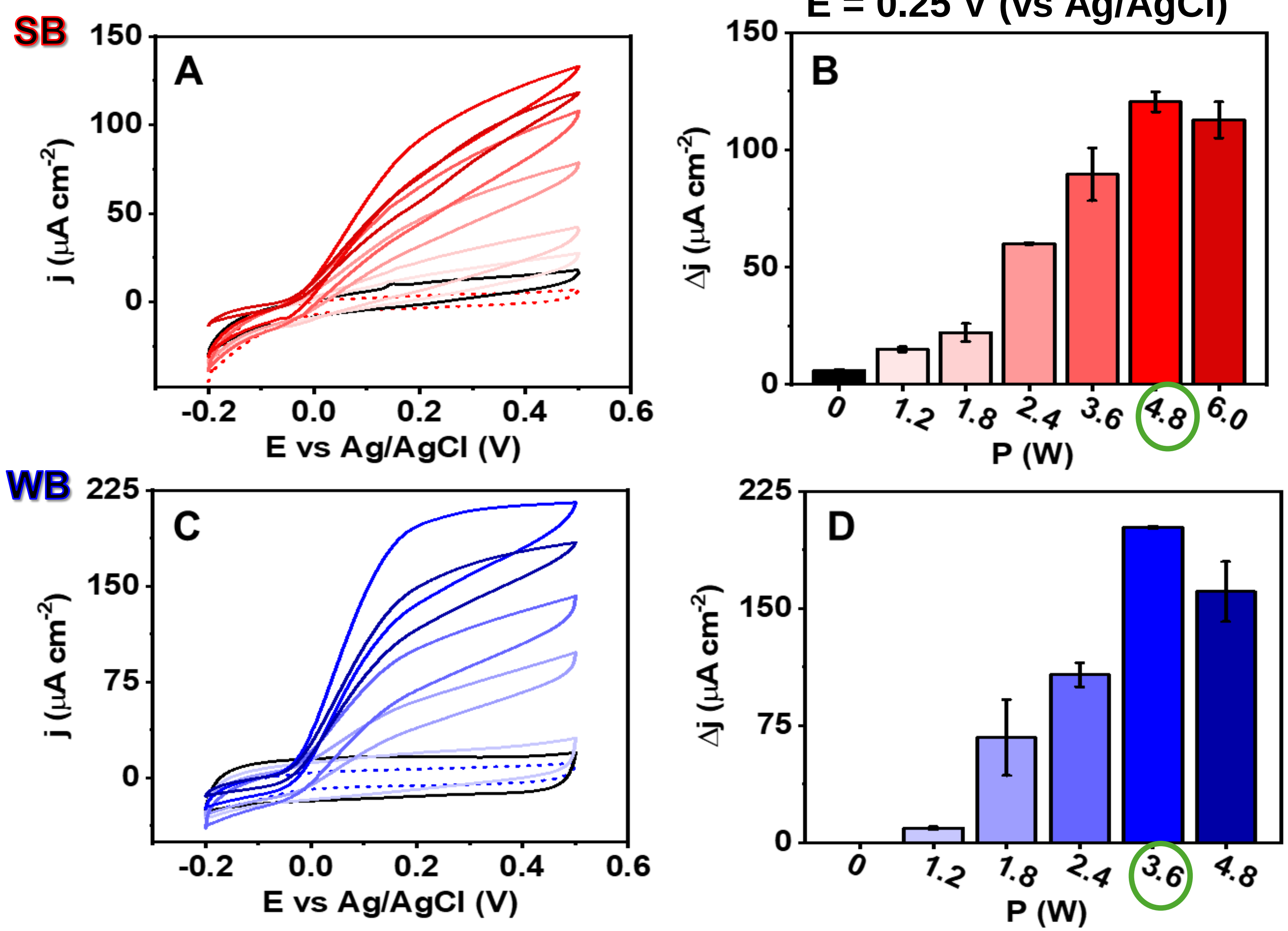


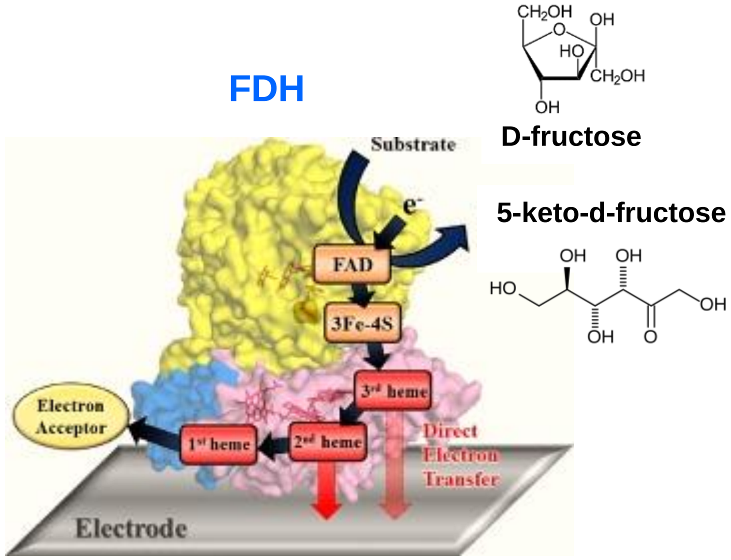


Silveri et al. (2024). **Biosensors and Bioelectronics**, 116620.

Laser-activated FDH-based stencil-printed sensors

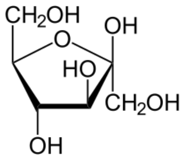
DET studies





Yan et al. (2021). Electrochimica Acta, 392, 138946.

10 mM D-fructose



5 mV s^{-1}

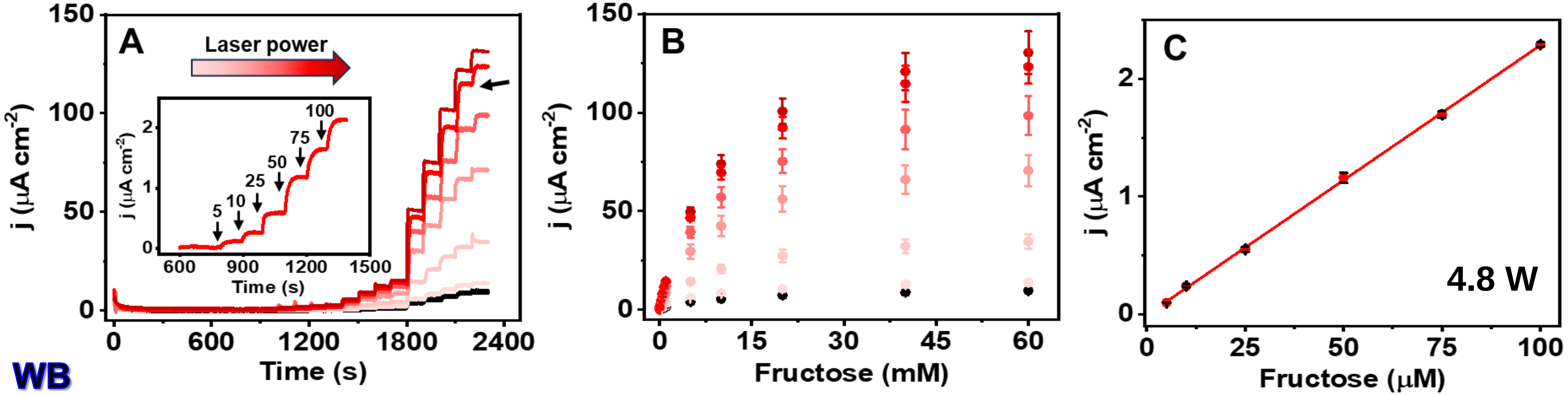
50 mM Acetate buffer pH = 4.5 + 0.1 M KCl

Silveri et al. (2024). **Biosensors and Bioelectronics**, 116620.

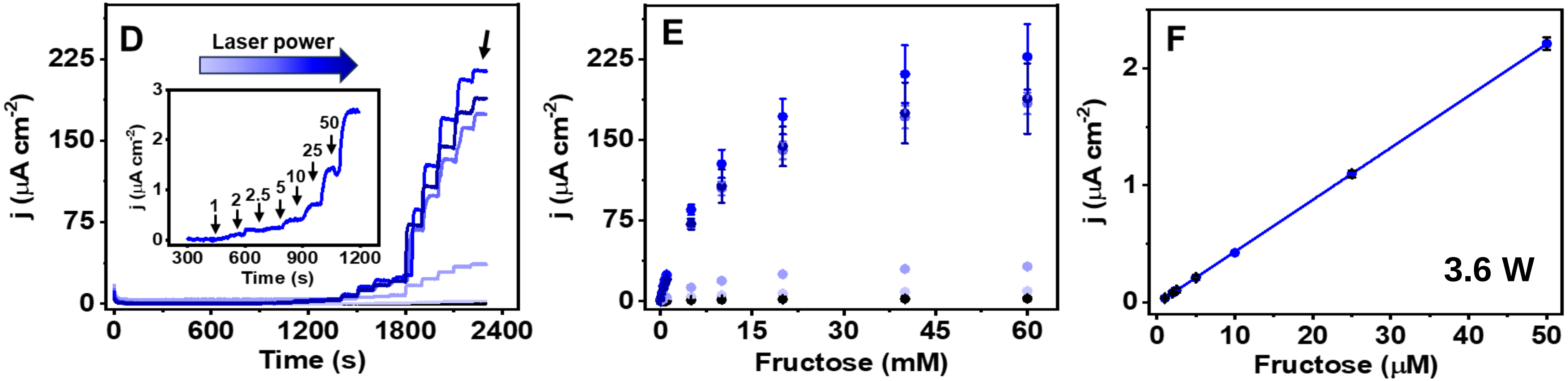
Laser-activated FDH-based stencil-printed sensors

Bioanalytical performance

SB E = 0.15 V (vs Ag/AgCl) | Michaelis-Menten kinetics | Calibration curves



WB



Analytical parameters

SB

LOD = 0.4 µM

L.R.: 5-100 µM

R^2 = 0.999

Slope RSD = 3% (n = 3)

WB

LOD = 0.2 µM

L.R.: 1-50 µM

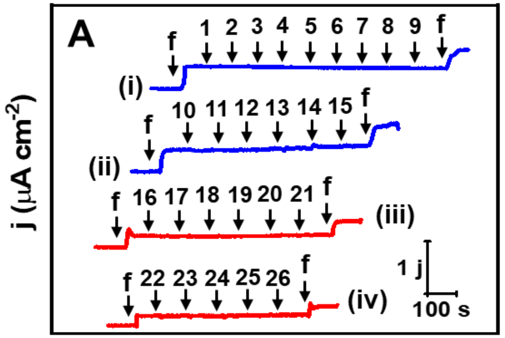
R^2 = 0.999

Slope: RSD = 2% (n = 3)

Silveri et al. (2024). **Biosensors and Bioelectronics**, 116620.

Laser-activated FDH-based stencil-printed sensors

Selectivity study



Legend

The "**f**" stands for 10 µM D-fructose

Organic compounds (**i**): 1 (1 mM urea), 2 (1 mM citric acid), 3 (50 µM L-carnitine), 4 (50 µM choline), 5 (50 µM uric acid), 6 (25 µM glutamic acid), 7 (50 µM lactic acid), 8 (100 µM bovin serum albumin), 9 (10 nM dopamine).

Salts (**ii**): 10 (1 mM $CaCl_2$), 11 (1 mM $MgCl_2$), 12 (1 mM $ZnCl_2$), 13 (1 mM NaCl), 14 (1 mM K_2HPO_4), 15 (1 mM $CaCO_3$).

Sugars (**iii**): 16 (1 mM lactose), 17 (1 mM D-glucose), 18 (1 mM sorbitol), 19 (1 mM sucrose), 20 (1 mM D-galactose), 21 (1 mM D-fucose).

Vitamins (**iv**): 22 (25 µM niacin), 23 (25 µM pyridoxal), 24 (25 µM biotin), 25 (25 µM nicotinic acid), 26 (5 µM ascorbic acid).

Samples analysis

(a) = cerebrospinal fluid (sCSF)
(b) = seminal fluid (aSF)
(c) = formula milk
(d) = donkey milk

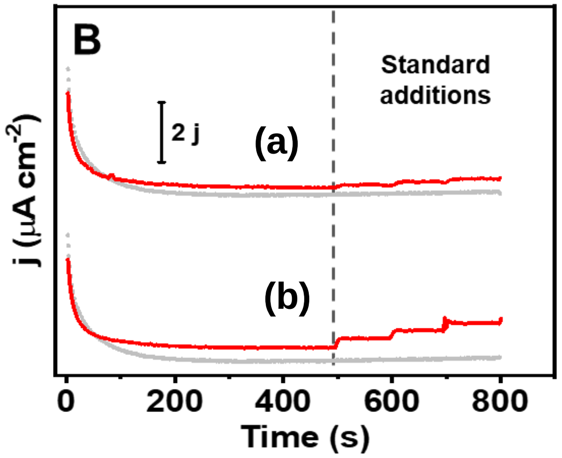
Spiked levels:

sCSF: 100 – 300 – 500 µM

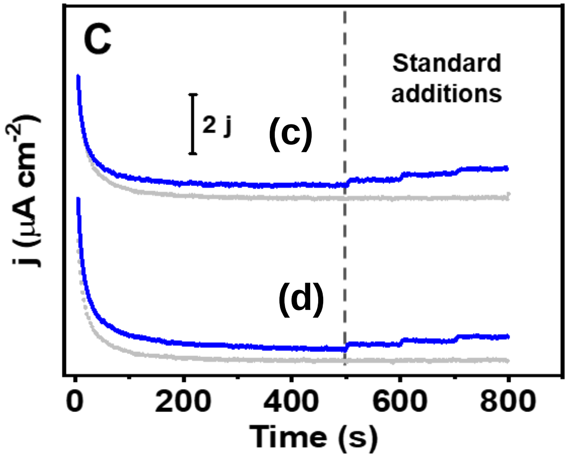
aSF: 5 – 10 – 25 mM

Powder milks: 250 – 375 – 500 µM

S-biological fluids



Powder milks



Rec: 93 – 107 %
RSD ≤ 8 % (n = 3)

Rec: 96 – 112 %
RSD ≤ 8 % (n = 3)

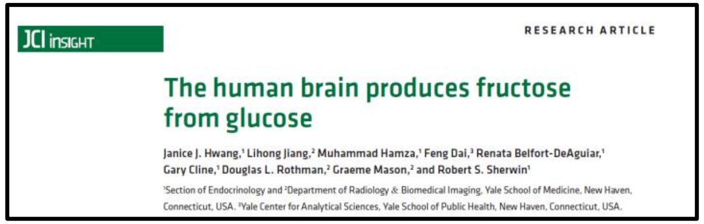
Laser-activated FDH-based stencil-printed sensors

In-continuos measurements in cerebrospinal fluid (sCSF)

Polyol pathway

Glucose intake

Fructose production


JCI insight

RESEARCH ARTICLE

The human brain produces fructose from glucose

Janice J. Hwang,[1] Lihong Jiang,[2] Muhammad Hamza,[1] Feng Dai,[3] Renata Belfort-DeAguiar,[1] Gary Cline,[1] Douglas L. Rothman,[2] Graeme Mason,[2] and Robert S. Sherwin[1]

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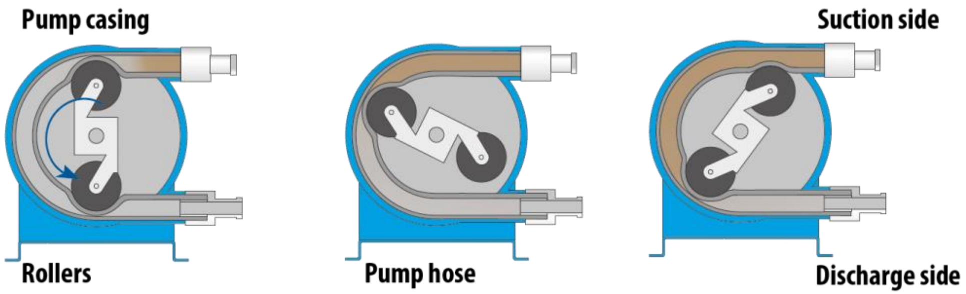
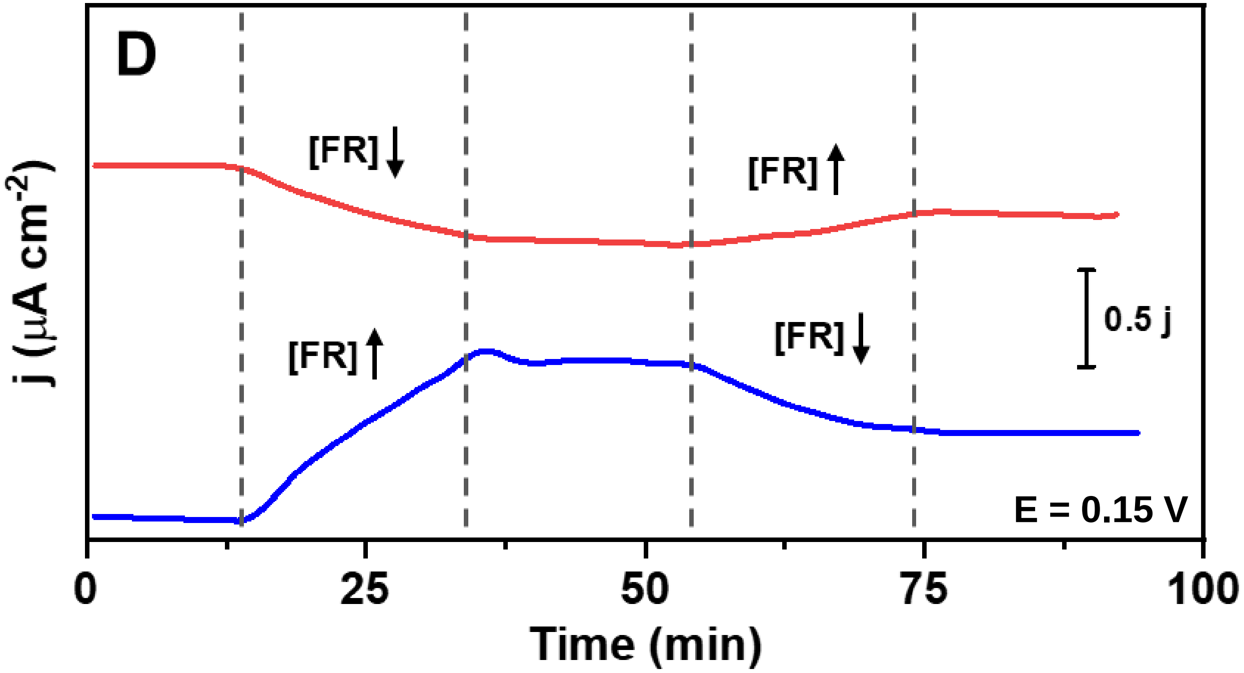
Flow system to simulate [FR] variation in CSF



Electrochemical detection



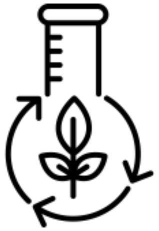
Silveri et al. (2024). **Biosensors and Bioelectronics**, 116620.

Take-home messages

CO_2 laser-plotter has become a routine tool able to generate different types of on-demand nanostructures

.... beyond LIG

Every-one-reach technologies can be used to produce nanostructured electrochemical devices (lab-on-strips)



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