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Nanobiosensors as trend-setting tools for agricultural engineering diagnostics

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1. INTRODUCTION: agriculture & sustainability

- **Agriculture** and **food systems** are closely **linked**, requiring **effective farm management** for global **sustainability** and **food security.**
- **Agricultural practices** directly influence **every stage** of crop production, from germination to post-harvest.
- **Structured management** enhances farmers' **yields** and **profitability**.
- Recent research highlights the growing importance of **nanobiosensor** due to their unique **nanoscale properties**.
- **nanobiosensor** can be effectively used for sensing a variety of **fertilizers**, **herbicides**, **pesticides**, **insecticides**, **pathogens**, **moisture**, and **soil pH.**

This study systematically reviews current literature on nanobiosensor integration in agriculture.

2. NANOBIOSENSOR OVERVIEW: definition & components

A **nanobiosensor**, typically incorporating nanomaterials **(Figure 1),** is a **nanoscale** analytical device that detects **biochemical substances** using a **biological sensing element** (bio-receptor) and a **transducer**. It converts **biological interactions** into measurable signals that can be **optically**, **electronically**, **thermally**, or **magnetically** detected and analyzed.

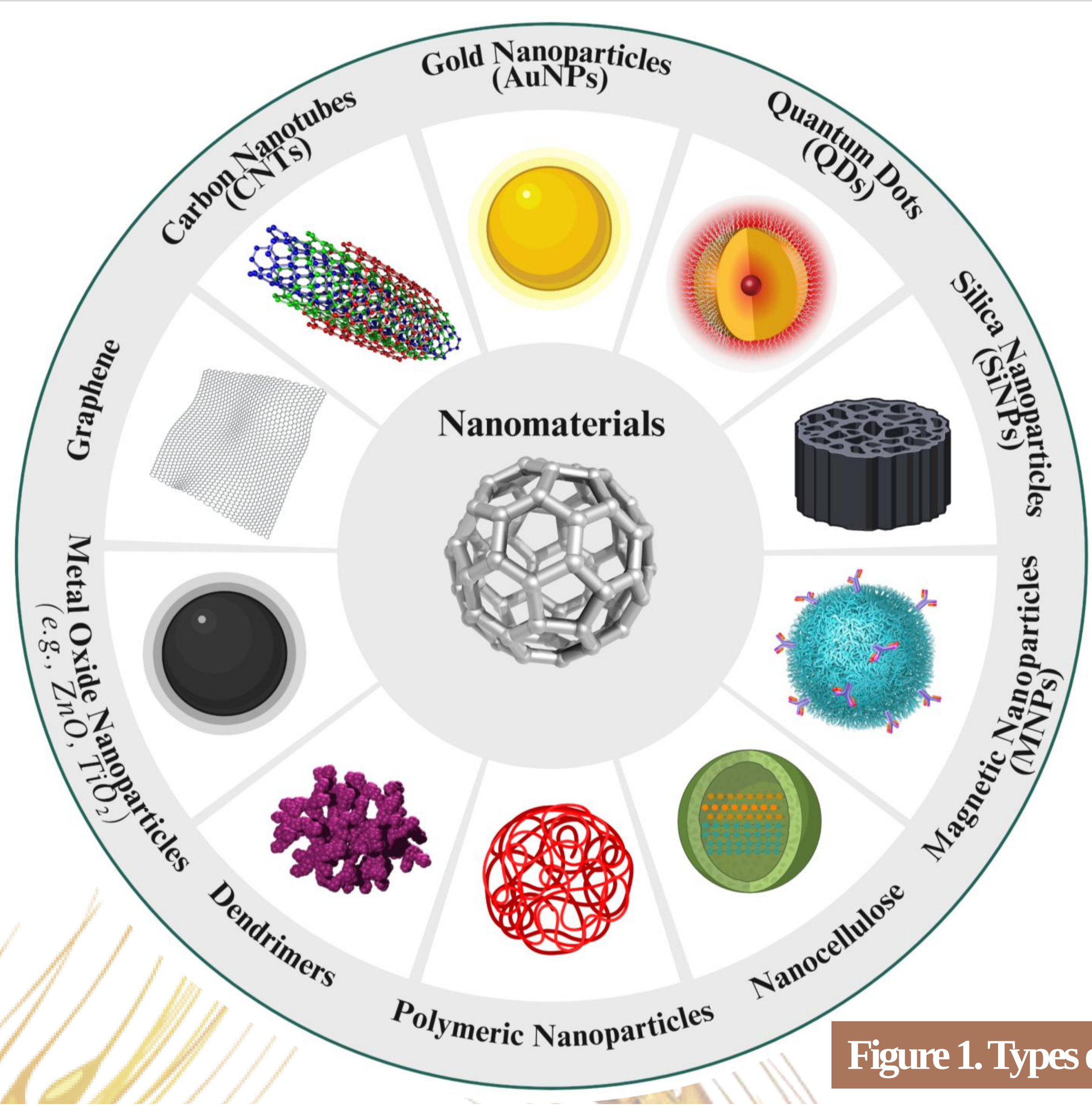

Figure 1. Types of nanomaterials.

3. AGRICULTURAL APPLICATIONS: Pre- & post-harvest use, soil, crop, and stress monitoring

- **Pesticide detection:** e.g. Malathion, paraoxon, gliphosate using fluorescence **(Figure 2)** and enzyme-based **nanobiosensors.**
- **Pathogen detection:** Viruses (e.g., hepatitis E virus), fungi (e.g.,. *Botrytis* spp, *Fusarium* spp.), and bacteria (e.g., *Xylella fastidiosa*).
- **Mycotoxin detection:** ZEA and Ochratoxin A (OTA) (**Figure 3**) in crops like maize and wheat using quantum dot and electrochemical aptasensor sensors.
- **Soil & plant health monitoring:** Detecting phytohormones (e.g., strigolactones, cytokinin, and ethylene) and stress markers (e.g., Random amplified polymorphic DNAs (RAPDs)).
- **VOC (Volatile Organic Compounds) sensing:** Electronic nose (e-noses) for disease and spoilage detection (e.g., ammonia).
- **Fertilizer & nutrient optimization:** Monitor nutrient uptake and minimize excess use
- **Growth enhancement:** **Nanobiosensor** aiding germination and growth (e.g., in cereal crops such as wheat, in tomato or, in chili crops).

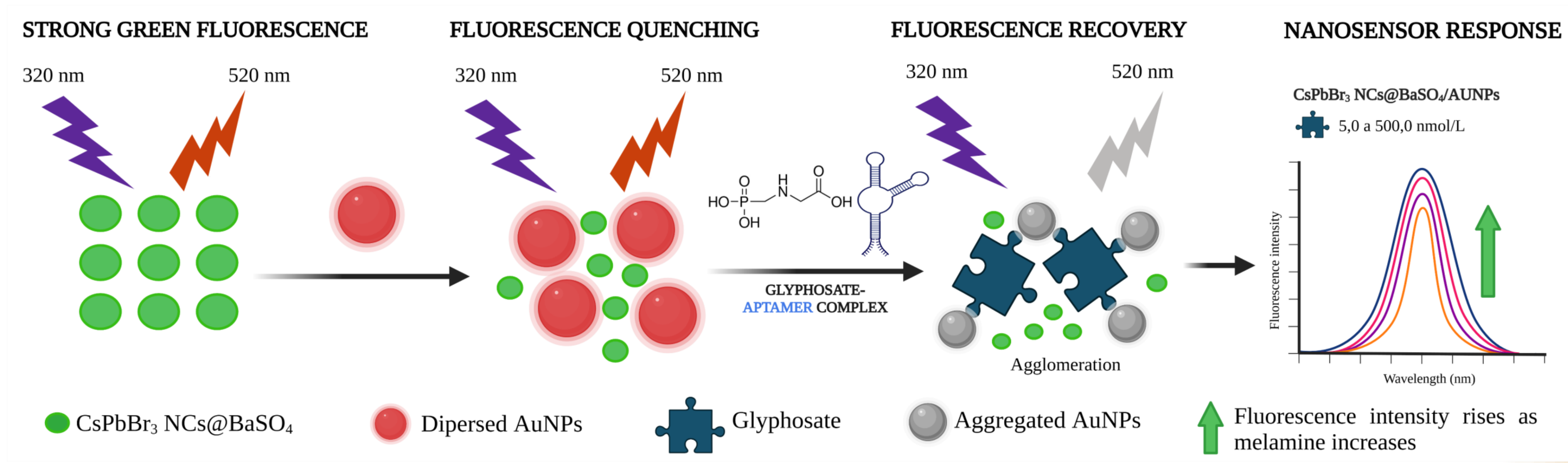

Figure 2. Schematic of the nanocrystal fluorescence aptamer nanobiosensor for agricultural glyphosate detection.

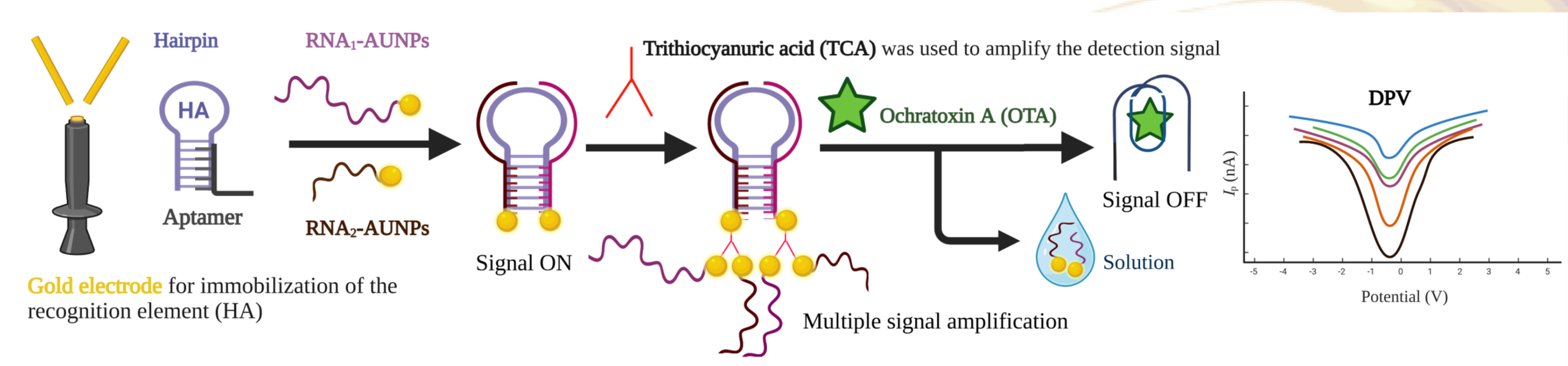

Figure 22 Schematic image of the design of an electrochemical aptasensor for OTA in wheat samples.

4. REAL-WORLD APPLICATIONS OF NANOBIOSENSORs

Target	Sensor component	Detection mechanism	Advantage (LOD, cost/time)	Ref.
Fenitrothion	Nano TiO_2 / Nafion composite	Electrochemistry	0.2 µM	Kumaravel et al., 2011.
Organophosphate-based pesticides	Carbon nanotubes	Electrochemistry	0.145 ppb	Joshi et al., 2005.
Methyl parathion and chlorpyrifos	Carbon nanotubes wrapped by ssDNA	Enzymatic reaction	1×10^{-12} M	Viswanathan et al., 2016.
Pathogens depending on the VOCs released	Carbon NMs	e-nose	30 min with 80%–90% accuracy	Cui et al., 2018a, Cui et al., 2018b.
Urea and urease	Gold NPS	Colorimetry	5 µM, 1.8 U/L	Deng et al., 2016.
VOCs (toxic gases)	Multidimensional carbon nanostructures	Radio frequency signals	5 ppm	Lee et al., 2014.
Ralstonia solanacearum	Au NPs functionalised with ssDNA	Colorimetry	15 ng	Khaledian et al., 2017.
Chlorpyrifos	Enzyme	Coloured reaction	3.3 µg /L, 10 min	Fu et al., 2019.
Pantoea stewartii* subsp. *stewartii	Au NPs	Electrochemistry	7.8×10^3 cfu/mL	Zhao et al., 2014.
Trichoderma harzianum	ZnO NPs–chitosan nanocomposite	Electrochemistry	1.0×10^{-19} mol/L	Siddiquee et al., 2014.
Phytoplasma aurantifolia	QD	Fluorescence	5 ca/µL	Rad et al., 2012.
Malathion	Enzyme	Amperometric	0.001 µg/L	Zhang et al., 2019.
Citrus tristeza virus	CdTe QD–Rd	FRET	220 ng/mL	Safarnejad et al., 2017.

Abbreviations: QD: Quantum dots; NPs: Nanoparticles; NMs: Nanomaterials; FRET: Fluorescence Resonance Energy Transfer; e-nose: Electronic nose.

6. LIMITATIONS AND CHALLENGES OF NANOBIOSENSORs

- Low **selectivity** in complex samples
- Lack of **standardization** and reproducibility
- **Stability** issues (materials and bioreceptors)
- **Toxicity** and environmental concerns
- **Integration** difficulties with existing systems
- High production **costs**
- **Regulatory** hurdles
- **Ethical** and privacy concerns

CONCLUSIONS

Advances in **nanoscaled** materials and analytical tools have enabled a revolution in **crop disease-monitoring**, with **faster**, more **sensitive**, and **on-site deployability.** While there are still limitations in terms of **toxicity** of nanomaterials, **connectivity** of data, and environmental **robustness**, **nanobiosensors** offer promising solutions for **agricultural engineering diagnostics** in **real-time** and **in situ.**

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