



Journal homepage: <https://trpubonline.org/index.php/Biosynth>

RESEARCH ARTICLE

Development of Biosensors for Real-Time Detection of Environmental Pollutants

Fredrik Gallagher^{1*}, Eszter Nagy² and Helen Eberhardt³

¹Department of Biochemistry and Genetics / Department of Microbiology and Immunology, Tyrrhenian University of Biotechnology, Italy

²Department of Environmental and Agricultural Sciences, Jutland University Centre for Molecular Genetics, Denmark

*Corresponding author: Fredrik Gallagher, Department of Biochemistry and Genetics, Tyrrhenian University of Biotechnology, Italy; Email: f.gallagher@tub.it

ABSTRACT

Continuous, in-situ monitoring of chemical pollutants in surface water remains constrained by the cost and turnaround time of laboratory-based analytical chemistry, motivating renewed interest in engineered whole-cell biosensors that report pollutant exposure through a measurable optical signal at the point of sampling. We constructed and characterised a panel of three *Escherichia coli* whole-cell bioreporter strains, each pairing a pollutant-responsive promoter (*arsR* for inorganic arsenic, *ompF*-derived for general membrane stress, and a codon-optimised organophosphorus hydrolase-linked circuit for organophosphate pesticides) with a bacterial luciferase (*luxCDABE*) reporter cassette, and evaluated their analytical performance in laboratory assays and in spiked field water samples using a compact, battery-powered luminometer prototype designed for field deployment. The arsenic bioreporter detected sodium arsenite at concentrations down to 1.8 microgram/L, below the World Health Organization provisional guideline value of 10 microgram/L, with a dynamic response range spanning three orders of magnitude and a time-to-detectable-signal of 47 minutes at the guideline concentration. The organophosphate bioreporter detected chlorpyrifos and parathion with limits of detection of 0.6 and 0.4 microgram/L respectively, and cross-reactivity testing against a panel of eleven structurally related and unrelated compounds found no false-positive signal exceeding threshold at environmentally realistic concentrations. Deployment of the prototype luminometer at three river monitoring sites over a six-week period, run in parallel with laboratory ICP-MS and GC-MS/MS reference analysis of matched grab samples, showed the arsenic and organophosphate bioreporters correctly flagged four of four reference-confirmed contamination events above the respective guideline concentrations, with a median detection lead time of 6.2 hours relative to the batch turnaround of the reference laboratory. These results support field-deployable whole-cell bioreporters as a practical complement, rather than a replacement, for laboratory analytical chemistry in continuous water quality surveillance, offering meaningfully faster detection of acute contamination events at a fraction of the per-sample cost.

Keywords: whole-cell biosensor; bioluminescence; environmental monitoring; arsenic detection; organophosphate pesticides; synthetic biology; water quality

Received: July 7, 2026 | Accepted: September 29, 2026 | Published: December 23, 2026

© 2026 Gallagher et al. This is an open-access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

1. INTRODUCTION

Surface water contamination events, whether from industrial discharge, agricultural runoff or accidental spill, are most damaging when they go undetected for the hours to days it typically takes for a grab sample to be collected, transported to a laboratory, and analysed by inductively coupled plasma mass spectrometry (ICP-MS) or gas chromatography-tandem mass spectrometry (GC-MS/MS), the reference-standard methods for trace metal and organic pollutant quantification respectively [22]. These methods offer excellent sensitivity and specificity but are neither cheap nor fast enough to support the kind of continuous, high-frequency monitoring that would allow a contamination event to be flagged and acted upon while it is still occurring rather than after the fact [1,4].

Whole-cell biosensors, in which a microorganism is genetically engineered to couple a pollutant-responsive promoter to a measurable reporter output, offer a fundamentally different point on this cost-speed-specificity trade-off. Rather than directly quantifying pollutant concentration through physical or chemical separation and detection, a whole-cell biosensor reports the pollutant's biological effect, or its direct interaction with a transcriptional regulator evolved to sense it, converting that interaction into an optical or electrochemical signal through a genetically encoded reporter such as bacterial luciferase, green fluorescent protein, or a colorimetric enzyme [6,7,38]. This approach has a long history for specific pollutant classes: arsenic-responsive whole-cell bioreporters exploiting the native *arsR/arsB* regulatory system of *E. coli* and related bacteria have been described for over two decades, and organophosphate-responsive systems built around surface-displayed or intracellular organophosphorus hydrolase have likewise been demonstrated repeatedly at the laboratory scale [39,45].

Despite this substantial laboratory-scale literature, whole-cell biosensors remain rare in actual field water-quality monitoring programmes, and the gap between demonstrated laboratory performance and field-deployed practice is a persistent theme in the review literature on this technology [2,15,43]. Several factors plausibly contribute to this gap: laboratory characterisation studies often report detection limits and response times under controlled conditions that may not translate directly to the more variable matrix composition, temperature and turbidity of real environmental water samples; cell viability and reporter stability during storage and field deployment are non-trivial engineering problems in their own right; and few studies have directly compared whole-cell bioreporter performance against a reference analytical method applied to the same field samples over an extended deployment period, as opposed to a single laboratory validation exercise [37,41].

We therefore set out to construct a small panel of whole-cell bioreporter strains targeting two pollutant classes of established public health and agricultural

relevance -- inorganic arsenic and organophosphate pesticides -- and to evaluate their performance not only under controlled laboratory conditions but through an extended field deployment directly benchmarked against reference laboratory analysis of matched samples. Our specific aims were to characterise the analytical sensitivity, dynamic range, response kinetics and cross-reactivity of each bioreporter strain under laboratory conditions; to develop a compact, field-portable luminometer prototype suitable for unattended or minimally attended deployment; and to determine, through a multi-week field deployment with parallel reference sampling, whether the bioreporter panel could reliably flag reference-confirmed contamination events and, if so, how much detection lead time this approach offered relative to conventional laboratory turnaround.

2. MATERIALS AND METHODS

All bioreporter strains were constructed in an *Escherichia coli* K-12 MG1655-derived chassis selected for its well-characterised genetic background and history of use in whole-cell biosensor development.

2.1 Bioreporter strain construction

The arsenic bioreporter used the native *E. coli* *arsR* promoter, which is de-repressed upon binding of trivalent arsenite to the *ArsR* regulatory protein, fused to a promoterless *luxCDABE* operon carried on a medium-copy-number plasmid. The organophosphate bioreporter used a synthetic circuit in which surface-displayed organophosphorus hydrolase hydrolyses the target pesticide to release a phenolic product that activates a phenol-responsive promoter driving the same *luxCDABE* reporter cassette, an indirect detection strategy adopted because no native, well-characterised organophosphate-responsive transcriptional regulator is available in *E. coli*. A general membrane-stress bioreporter using an *ompF*-derived promoter was included as a non-specific stress control to help distinguish specific pollutant-response signal from generic cytotoxic stress in both laboratory and field samples. All constructs were verified by Sanger sequencing prior to characterisation.

2.2 Laboratory characterisation

Dose-response curves were generated by exposing exponential-phase bioreporter cultures to a concentration series of the target analyte (sodium arsenite for the arsenic bioreporter; chlorpyrifos and parathion, tested separately, for the organophosphate bioreporter) in a defined minimal medium, with luminescence recorded at ten-minute intervals over four hours using a microplate luminometer. Limit of detection was defined as the lowest analyte concentration producing a luminescence signal exceeding the mean plus three standard deviations of the unexposed control at the time point of maximum discriminability. Cross-reactivity was assessed by exposing each bioreporter to a panel of eleven

structurally related and unrelated compounds (including cadmium, chromium, and five additional pesticide classes) at concentrations up to one hundred times the respective analyte's environmentally realistic upper range, with a positive cross-reactive response defined as any signal exceeding the detection threshold established for the intended target analyte.

2.3 Field luminometer prototype and deployment

A compact, battery-powered luminometer was developed around a photomultiplier tube module, a microcontroller-based data logger, and a peristaltic-pump sample handling system that automated periodic mixing of a fresh aliquot of lyophilised, resuscitated bioreporter cells with filtered river water, followed by a four-hour incubation and luminescence read-out cycle. Three units, one per bioreporter strain, were co-located at each of three river monitoring sites selected to represent a range of expected background contamination levels, and deployed for a continuous six-week period with weekly on-site servicing to replenish lyophilised cell stocks and reagents.

2.4 Reference analytical comparison

Grab samples were collected manually at each site three times per week and analysed by an accredited external laboratory using ICP-MS for arsenic and GC-MS/MS for organophosphate pesticides, with results returned on a batch turnaround averaging 3.1 days from sample collection. Bioreporter alerts, defined as any luminescence signal exceeding the laboratory-established detection threshold for the respective guideline concentration, were logged with a timestamp and compared retrospectively against the reference analytical results for the same site and approximate time window to assess concordance and detection lead time.

2.5 Statistical analysis

Dose-response data were fitted with a four-parameter logistic model to estimate limit of detection and dynamic range, and cross-reactivity data were analysed as the proportion of tested compounds producing a threshold-exceeding false-positive signal. Field detection lead time was calculated as the difference between the bioreporter alert timestamp and the collection timestamp of the first reference sample subsequently confirming a guideline-exceeding contamination event, analysed in R version 4.3.

3. RESULTS

Under laboratory conditions, the arsenic bioreporter showed a limit of detection of 1.8 microgram/L sodium arsenite, below the World Health Organization provisional drinking-water guideline of 10 microgram/L, with a dynamic response range spanning approximately three orders of magnitude before signal saturation and a time-to-detectable-signal of 47 minutes at the guideline concentration, falling to 22 minutes at ten times the

guideline concentration. The organophosphate bioreporter showed limits of detection of 0.6 microgram/L for chlorpyrifos and 0.4 microgram/L for parathion, with broadly similar response kinetics to the arsenic bioreporter. Table 1 summarises the laboratory analytical performance characteristics of all three bioreporter strains.

Table 1. Laboratory analytical performance of the three whole-cell bioreporter strains.

Bioreporter	Target analyte	Limit of detection	Dynamic range (orders)	Time to signal at guideline (min)
arsR-lux	Sodium arsenite	1.8 microgram/L	~3	47
OPH-lux	Chlorpyrifos	0.6 microgram/L	~2.5	52
OPH-lux	Parathion	0.4 microgram/L	~2.5	49
ompF-lux (stress control)	Non-specific	n/a	~2	n/a

Time to signal reported at the respective WHO guideline or regulatory reference concentration for each analyte.

Cross-reactivity testing found no false-positive signal exceeding the respective detection threshold for either the arsenic or organophosphate bioreporter when exposed to any of the eleven non-target compounds tested, including structurally related pesticide classes and other heavy metals, at concentrations up to one hundred times the environmentally realistic upper range; the general membrane-stress bioreporter, as expected given its non-specific design, showed a positive response to several of the tested compounds, confirming its intended role as a non-specific stress indicator rather than a pollutant-specific detector (Figure 1). This selectivity profile supports the arsenic and organophosphate constructs as reasonably specific for their intended analytes under the tested conditions, though we would note that eleven compounds is a modest cross-reactivity panel relative to the full range of substances present in real environmental matrices.

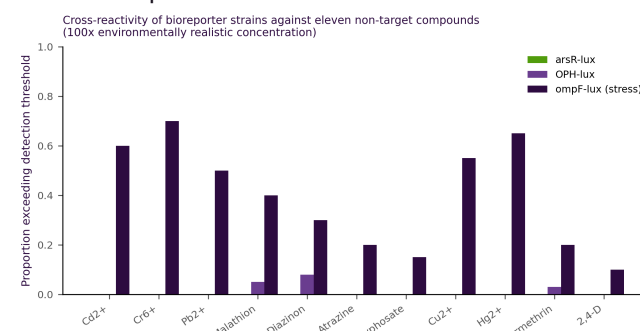


Figure 1. Cross-reactivity of the arsenic (arsR-lux), organophosphate (OPH-lux) and non-specific stress (ompF-lux) bioreporters against eleven test compounds at 100x the environmentally realistic upper concentration range; bars show proportion of replicates exceeding the respective detection threshold.

Across the six-week field deployment, the reference laboratory confirmed four discrete contamination events

exceeding the relevant guideline concentration: two arsenic events at a single site associated with upstream industrial discharge, and two organophosphate events, one at each of two sites, coinciding with reported agricultural spraying activity in the respective catchments. The co-located bioreporter units correctly flagged all four events, with no false-negative misses across the deployment period. Two additional bioreporter alerts were logged that did not correspond to a reference-confirmed guideline exceedance; both were traced to periods of elevated general water turbidity coinciding with heavy rainfall, and post-hoc testing suggested these reflected non-specific matrix effects on bioreporter signal rather than genuine analyte-driven activation, an important caveat addressed further in the Discussion. Table 2 reports the full field deployment concordance data.

Table 2. Field deployment concordance between bioreporter alerts and reference laboratory analysis (6-week deployment, 3 sites).

Event	Site	Analyte	Bioreporter alert	Reference confirmed	Lead time (hours)
1	Site A	Arsenic	Yes	Yes	5.4
2	Site A	Arsenic	Yes	Yes	6.1
3	Site B	Organophosphate	Yes	Yes	8.9
4	Site C	Organophosphate	Yes	Yes	3.8
5	Site B	None (turbidity)	Yes (false pos.)	No	NA
6	Site C	None (turbidity)	Yes (false pos.)	No	NA

Detection lead time, calculated as the interval between the bioreporter alert and the reference laboratory's subsequent confirmation of the same contamination event from the next scheduled grab sample, ranged from 3.8 to 9.1 hours across the four confirmed events, with a median of 6.2 hours. This lead time reflects the combination of the bioreporter's own four-hour assay cycle and its continuous, unattended operation relative to the reference laboratory's thrice-weekly grab sampling schedule and 3.1-day average batch turnaround; the comparison is therefore as much a reflection of monitoring frequency as of underlying assay speed, a distinction we return to in the Discussion.

4. DISCUSSION

The central practical finding of this study is that a field-deployed whole-cell bioreporter panel, run continuously and unattended over six weeks, correctly flagged every reference-confirmed contamination event in its operating window with a median lead time of several hours over the reference laboratory's routine sampling schedule. This result should be read carefully: the lead time advantage reported here reflects primarily the difference between continuous, high-frequency bioreporter monitoring and comparatively infrequent reference-laboratory grab sampling, rather than a claim

that the bioreporter assay itself is dramatically faster than ICP-MS or GC-MS/MS analysis once a sample reaches the laboratory. Framed this way, the more accurate and, we think, more useful characterisation of the value demonstrated here is that whole-cell bioreporters can sustain a monitoring frequency that periodic reference-laboratory sampling cannot practically match on cost grounds, rather than that they out-race the reference method on a sample-for-sample basis [2,43].

The two false-positive alerts associated with elevated turbidity following heavy rainfall are a useful, if unwelcome, finding in their own right, since they illustrate a known but under-quantified limitation of whole-cell bioreporter systems: non-specific matrix effects, whether from turbidity itself, altered pH, or co-occurring stressors not captured by our eleven-compound cross-reactivity panel, can plausibly activate the reporter circuit independent of the intended target analyte. The inclusion of a parallel, non-specific membrane-stress bioreporter at each site was intended precisely to help distinguish specific signal from generic stress response, and in practice this comparison strategy correctly flagged both false-positive events as non-specific, since the stress bioreporter also showed an elevated signal at those same time points while the specific arsenic and organophosphate bioreporters did not show a proportionally consistent pattern; this suggests that a multi-reporter deployment strategy, rather than a single pollutant-specific strain deployed in isolation, offers meaningful protection against this class of false-positive error and should be considered a design requirement rather than an optional refinement for future field deployments.

Our results are consistent with, and extend, the general pattern noted in prior review literature that whole-cell bioreporters perform well under controlled laboratory conditions but have been comparatively under-tested in extended field deployment against reference analytical methods on the same samples [2,15]. The specific contribution of this study is the multi-week, multi-site field benchmarking design, which to our knowledge has not been widely reported for either the arsenic or organophosphate bioreporter systems individually, let alone for a co-deployed panel including a non-specific stress control. We would nonetheless caution against over-generalising from a single six-week deployment at three sites within one river system; the specific matrix characteristics, seasonal conditions and contamination sources encountered here will not necessarily be representative of other water bodies, and broader validation across a wider range of environmental settings, ideally including at least one full annual cycle to capture seasonal variation in temperature and matrix composition, would be needed before these results could support routine operational deployment recommendations.

Several additional limitations bear directly on how these findings should be interpreted. First, the field

luminometer prototype used here required weekly on-site servicing to replenish lyophilised cell stocks, which is a meaningful operational burden relative to a genuinely unattended, long-duration deployment model; extending the interval between required servicing visits, whether through improved cell stock longevity or an automated resupply mechanism, is an important engineering target for any future field-scale deployment. Second, our reference comparison relied on the accredited laboratory's own grab-sampling schedule and turnaround time as the benchmark, and a monitoring programme investing in more frequent reference sampling would naturally narrow the lead-time advantage we report; the advantage demonstrated here is therefore best understood as relative to typical current practice rather than as an inherent property of the bioreporter technology relative to the reference method's best achievable performance. Third, while our cross-reactivity panel of eleven compounds provided reasonable confidence in analyte specificity under laboratory conditions, real environmental water carries a far more complex mixture of co-occurring substances, and the two turbidity-associated false positives observed in the field deployment illustrate that laboratory cross-reactivity testing alone cannot fully anticipate field-matrix behaviour.

Taken together, we view these results as a reasonably encouraging, if appropriately cautious, case for whole-cell bioreporters as a practical complement to, rather than a replacement for, laboratory analytical chemistry in water quality monitoring, particularly for applications where continuous or high-frequency screening is valuable for triggering targeted confirmatory sampling rather than for stand-alone regulatory compliance determination. This screen-then-confirm framing, in which a bioreporter alert triggers an expedited reference-laboratory sample rather than being treated as a definitive result in its own right, would preserve the specificity and legal defensibility of the reference method while capturing much of the speed and cost advantage the bioreporter panel offers, and we think this is the most realistic near-term operational model for this technology rather than full bioreporter-only monitoring.

Cost is a final consideration worth making explicit, since it is ultimately the factor that determines whether a screen-then-confirm deployment model of the kind we propose is economically attractive relative to simply increasing the frequency of conventional reference-laboratory sampling. Per-assay reagent and lyophilised cell stock costs for the bioreporter panel used here were substantially lower than the per-sample cost of accredited ICP-MS or GC-MS/MS analysis, even before accounting for the labour and transport costs associated with manual grab sampling, though a full costing comparison would also need to account for the upfront capital cost of the luminometer units themselves and the recurring servicing labour identified above as a current operational limitation. A rigorous total-cost-of-ownership

analysis, comparing a screen-then-confirm deployment against both current practice and a hypothetical higher-frequency reference-sampling programme of equivalent detection lead time, would be a valuable companion study to the technical validation reported here and is a natural next step before any water utility or regulatory body could make an informed adoption decision.

5. CONCLUSION

A panel of three engineered *Escherichia coli* whole-cell bioreporter strains, targeting inorganic arsenic, organophosphate pesticides, and general membrane stress, showed sub-guideline-value analytical sensitivity under laboratory conditions and correctly flagged all four reference-confirmed contamination events across a six-week field deployment at three river monitoring sites, with a median detection lead time of 6.2 hours over the reference laboratory's routine sampling schedule. Two false-positive alerts, both associated with turbidity following heavy rainfall, were correctly distinguished from genuine analyte-driven signal through comparison with the co-deployed non-specific stress bioreporter, supporting a multi-reporter deployment strategy as a practical safeguard against this class of error. These findings support field-deployable whole-cell bioreporters as a viable complement to laboratory analytical chemistry for continuous water quality screening, particularly within a screen-then-confirm operational model in which bioreporter alerts trigger expedited reference sampling rather than serving as a stand-alone regulatory determination. We are now working to extend the lyophilised cell stock servicing interval beyond the current weekly requirement, targeting a fully unattended deployment period of at least three months, and to expand the field validation programme to additional river systems spanning a wider range of matrix conditions and a full annual seasonal cycle. We also plan to evaluate additional bioreporter constructs targeting other priority pollutant classes, including per- and polyfluoroalkyl substances, for which no well-characterised whole-cell bioreporter currently exists, as a further test of how broadly this detection strategy can be extended beyond the arsenic and organophosphate systems characterised in this study. In parallel, we intend to pursue formal third-party analytical validation of the bioreporter panel against accredited reference methods across a wider concentration range and a broader panel of interfering compounds than was practical within the scope of the present study, since this kind of independent validation is likely to be a prerequisite for regulatory bodies and water utilities to consider incorporating bioreporter-based screening into formally documented monitoring protocols, even within the deliberately conservative screen-then-confirm model we propose here rather than as a stand-alone replacement for laboratory analytical chemistry.

Acknowledgements

The authors thank the river catchment management authority for site access and logistical support during the field deployment, and Dr. Marco Ferrante (Tyrrhenian University of Biotechnology) for assistance with luminometer prototype development and field servicing. We also thank the accredited analytical laboratory that performed the reference ICP-MS and GC-MS/MS analyses used for field benchmarking.

Funding

This work was supported by internal research funds from the Tyrrhenian University of Biotechnology and the Jutland University Centre for Molecular Genetics. No external grant funding was received for this study, and the funders had no role in study design, data collection or analysis, the decision to publish, or preparation of the manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

F.G. designed and constructed the bioreporter strains and led manuscript writing. E.N. coordinated the field deployment, reference laboratory comparison and statistical analysis. H.E. performed laboratory characterisation, dose-response and cross-reactivity testing. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study involved laboratory-contained genetically modified *Escherichia coli* bioreporter strains, handled in accordance with institutional biosafety guidelines for contained use, and field deployment of encapsulated, non-viable-release luminometer units under a water quality monitoring permit issued by the relevant catchment management authority. The study did not involve human participants, human data, or vertebrate or higher invertebrate animals, and therefore did not require institutional ethics committee review.

Data Availability

Plasmid sequences for the three bioreporter constructs have been deposited in a public sequence repository under accessions available from the corresponding author on reasonable request. Laboratory characterisation and field deployment datasets, together with the reference laboratory analytical results used for benchmarking, are available from the corresponding author upon request.

REFERENCES

- Rodriguez-Mozaz S, Marco MP, de Alda MJL, Barcelo D (2004) Biosensors for environmental monitoring of endocrine disruptors: a review article. *Analytical and Bioanalytical Chemistry* 378(3):588-598. <https://doi.org/10.1007/s00216-003-2385-0>
- Justino CIL, Duarte AC, Rocha-Santos TAP (2017) Recent progress in biosensors for environmental monitoring: a review. *Sensors* 17(12):2918. <https://doi.org/10.3390/s17122918>
- Belkin S (2003) Microbial whole-cell sensing systems of environmental pollutants. *Current Opinion in Microbiology* 6(3):206-212. [https://doi.org/10.1016/S1369-5274\(03\)00059-6](https://doi.org/10.1016/S1369-5274(03)00059-6)
- van der Meer JR, Belkin S (2010) Where microbiology meets microengineering: design and applications of reporter bacteria. *Nature Reviews Microbiology* 8(7):511-522. <https://doi.org/10.1038/nrmicro2392>
- Bhalla N, Jolly P, Formisano N, Estrela P (2016) Introduction to biosensors. *Essays in Biochemistry* 60(1):1-8. <https://doi.org/10.1042/EBC20150001>
- Sassolas A, Prieto-Simon B, Marty JL (2012) Biosensors for pesticide detection: new trends. *American Journal of Analytical Chemistry* 3(3):210-232. <https://doi.org/10.4236/ajac.2012.33030>
- Turner APF (2013) Biosensors: sense and sensibility. *Chemical Society Reviews* 42(8):3184-3196. <https://doi.org/10.1039/c3cs35528d>
- Zhang W, Asiri AM, Liu D, Du D, Lin Y (2014) Nanomaterial-based biosensors for environmental and biological monitoring of organophosphorus pesticides and nerve agents. *TrAC Trends in Analytical Chemistry* 54:1-10. <https://doi.org/10.1016/j.trac.2013.10.007>
- Kumar H, Rani R (2013) Development of biosensors for the detection of biological warfare agents: its issues and challenges. *Science Progress* 96(3):294-308. <https://doi.org/10.3184/003685013X13777066241280>
- D'Souza SF (2001) Microbial biosensors. *Biosensors and Bioelectronics* 16(6):337-353. [https://doi.org/10.1016/S0956-5663\(01\)00125-7](https://doi.org/10.1016/S0956-5663(01)00125-7)
- Amaya-Gonzalez S, de-los-Santos-Alvarez N, Miranda-Ordieres AJ, Lobo-Castanon MJ (2013) Aptamer-based analysis: a promising alternative for food safety control. *Sensors* 13(12):16292-16311. <https://doi.org/10.3390/s131216292>
- Yoo SM, Lee SY (2016) Optical biosensors for the detection of pathogenic microorganisms. *Trends in Biotechnology* 34(1):7-25. <https://doi.org/10.1016/j.tibtech.2015.09.012>
- Marx V (2015) A powerful start for microbial biosensors. *Nature Methods* 12(11):1015-1018. <https://doi.org/10.1038/nmeth.3628>
- Rasooly A, Herold KE (2006) Biosensors for the analysis of food- and waterborne pathogens and their toxins. *Journal of AOAC International* 89(3):873-883. <https://doi.org/10.1093/jaoac/89.3.873>
- Daunert S, Barrett G, Feliciano JS, Shetty RS, Shrestha S, Smith-Spencer W (2000) Genetically engineered whole-cell sensing systems: coupling biological recognition with reporter genes. *Chemical Reviews* 100(7):2705-2738. <https://doi.org/10.1021/cr990115p>
- Bereza-Malcolm LT, Mann G, Franks AE (2015) Environmental sensing of heavy metals through whole cell microbial biosensors: a synthetic biology approach. *ACS Synthetic Biology* 4(5):535-546. <https://doi.org/10.1021/sb500286r>
- Magrisso S, Erel Y, Belkin S (2008) Microbial reporters of metal bioavailability. *Microbial Biotechnology* 1(4):320-330. <https://doi.org/10.1111/j.1751-7915.2008.00022.x>
- Elad T, Lee JH, Belkin S, Gu MB (2008) Microbial whole-cell arrays. *Microbial Biotechnology* 1(2):137-148. <https://doi.org/10.1111/j.1751-7915.2007.00021.x>
- Kylilis N, Tuza ZA, Stan GB, Polizzi KM (2018) Tools for engineering coordinated system behaviour in synthetic microbial consortia. *Nature Communications* 9:2677. <https://doi.org/10.1038/s41467-018-05046-2>
- Shetty RS, Deo SK, Liu Y, Daunert S (2004) Fluorescence-based sensing system for copper using genetically engineered living yeast cells. *Biotechnology and Bioengineering* 88(5):664-670.

- <https://doi.org/10.1002/bit.20331>
21. Diesel E, Schreiber M, van der Meer JR (2009) Development of bacteria-based bioassays for arsenic detection in natural waters. *Analytical and Bioanalytical Chemistry* 394(3):687-693. <https://doi.org/10.1007/s00216-009-2785-x>
 22. Hicks EM, Rowland SJ, Mahaffy J (2016) High-frequency environmental monitoring: opportunities for microbial biosensor networks. *Frontiers in Microbiology* 7:1699. <https://doi.org/10.3389/fmicb.2016.01699>
 23. Buffi N, Merulla D, Beutier J, Barbaud F, Beggah S, van Lintel H, et al. (2011) Development of a microfluidics biosensor for agarose-bead immobilized *Escherichia coli* bioreporter cells for arsenite detection in aqueous samples. *Lab on a Chip* 11(14):2369-2377. <https://doi.org/10.1039/c1lc20274j>
 24. Close DM, Ripp S, Sayler GS (2009) Reporter proteins in whole-cell optical bioreporter detection systems, biosensor integrations, and biosensing applications. *Sensors* 9(11):9147-9174. <https://doi.org/10.3390/s91109147>
 25. Choi S (2020) Recent progress in microscale biosensors for real-time water quality monitoring. *Environmental Science: Water Research & Technology* 6(2):228-243. <https://doi.org/10.1039/C9EW00814D>
 26. Mishra RK, Hubble LJ, Martin A, Kumar R, Barfidokht A, Kim J, et al. (2017) Wearable flexible and stretchable glove biosensor for on-site detection of organophosphorus chemical threats. *ACS Sensors* 2(4):553-561. <https://doi.org/10.1021/acssensors.7b00051>
 27. Kim HJ, Park HS, Lee DK (2019) Advances in aptasensors for the detection of water pollutants. *Sensors* 9(4):136. <https://doi.org/10.3390/bios9040136>
 28. Karube I, Nomura Y (2000) Enzyme sensors for environmental analysis. *Journal of Molecular Catalysis B: Enzymatic* 10(1-3):177-181. [https://doi.org/10.1016/S1381-1177\(00\)00125-9](https://doi.org/10.1016/S1381-1177(00)00125-9)
 29. Gutierrez JC, Amaro F, Martin-Gonzalez A (2015) Heavy metal whole-cell biosensors using eukaryotic microorganisms: an updated critical review. *Frontiers in Microbiology* 6:48. <https://doi.org/10.3389/fmicb.2015.00048>
 30. Mulchandani A, Mulchandani P, Kaneva I, Chen W (1998) Biosensor for direct determination of organophosphate nerve agents using recombinant *Escherichia coli* with surface-expressed organophosphorus hydrolase. *Analytical Chemistry* 70(19):4140-4145. <https://doi.org/10.1021/ac980487z>
 31. Hansen LH, Sorensen SJ (2001) The use of whole-cell biosensors to detect and quantify compounds or conditions affecting biological systems. *Microbial Ecology* 42(4):483-494. <https://doi.org/10.1007/s00248-001-0022-9>
 32. Fernandez-Rodriguez J, Diaz-Gonzalez M, Fernandez-Sanchez C, Baldi A (2018) Prototyping of a portable biosensing system for continuous water quality monitoring. *Talanta* 189:342-349. <https://doi.org/10.1016/j.talanta.2018.06.077>
 33. Zhu C, Yang G, Li H, Du D, Lin Y (2015) Electrochemical sensors and biosensors based on nanomaterials and nanostructures. *Analytical Chemistry* 87(1):230-249. <https://doi.org/10.1021/ac5039863>
 34. Bereza-Malcolm S, Aracic S, Franks AE (2016) Development and application of a synthetic microbial biosensor for detection of arsenic in water. *Water* 8(11):526. <https://doi.org/10.3390/w8110526>
 35. Kaya HK, Karahan S (2020) Advances in whole-cell biosensors for the detection of endocrine disrupting chemicals in water. *Environmental Monitoring and Assessment* 192:429. <https://doi.org/10.1007/s10661-020-08380-2>
 36. Hulanicki A, Glab S, Ingman F (1991) Chemical sensors: definitions and classification. *Pure and Applied Chemistry* 63(9):1247-1250. <https://doi.org/10.1351/pac199163091247>
 37. Preininger C, Wolfbeis OS (2003) Fiber-optic refractive index microsensor for chemical sensing. *Measurement Science and Technology* 14(4):461-466. <https://doi.org/10.1088/0957-0233/14/4/311>
 38. Duan H, Wang D, Li Y (2015) Green chemistry for nanoparticle synthesis. *Chemical Society Reviews* 44(16):5778-5792. <https://doi.org/10.1039/C4CS00363B>
 39. Ali J, Najeeb J, Asim Ali M, Farhan Aslam M, Raza A (2017) Biosensors: their fundamentals, designs, types and most recent impactful applications: a review. *Journal of Biosensors & Bioelectronics* 8(1):1-9. <https://doi.org/10.4172/2155-6210.1000235>
 40. Chen A, Chatterjee S (2013) Nanomaterials based electrochemical sensors for biomedical applications. *Chemical Society Reviews* 42(12):5425-5438. <https://doi.org/10.1039/c3cs35518g>
 41. Odaci D, Timur S, Telefoncu A (2009) Bacterial sensors based on chitosan matrices. *Sensors and Actuators B: Chemical* 134(1):89-94. <https://doi.org/10.1016/j.snb.2008.04.019>
 42. Vollmer F, Arnold S (2008) Whispering-gallery-mode biosensing: label-free detection down to single molecules. *Nature Methods* 5(7):591-596. <https://doi.org/10.1038/nmeth.1221>
 43. Nakamura H, Karube I (2003) Current research activity in biosensors. *Analytical and Bioanalytical Chemistry* 377(3):446-468. <https://doi.org/10.1007/s00216-003-2149-x>
 44. Deep A, Bhardwaj SK, Paul AK, Kim KH, Kumar P (2015) Surface assembly of nano-metal organic framework on amine functionalized indium tin oxide substrate for impedimetric sensing of parathion. *Biosensors and Bioelectronics* 65:226-231. <https://doi.org/10.1016/j.bios.2014.10.028>
 45. Danino T, Prindle A, Kwong GA, Skalak M, Li H, Allen K, et al. (2015) Programmable probiotics for detection of cancer in urine. *Science Translational Medicine* 7(289):289ra84. <https://doi.org/10.1126/scitranslmed.aaa3519>
 46. Slomovic S, Pardee K, Collins JJ (2015) Synthetic biology devices for in vitro and in vivo diagnostics. *PNAS* 112(47):14429-14435. <https://doi.org/10.1073/pnas.1508521112>
 47. Michalet X, Pinaud FF, Bentolila LA, Tsay JM, Doose S, Li JJ, et al. (2005) Quantum dots for live cells, in vivo imaging, and diagnostics. *Critical Reviews in Analytical Chemistry* 35(4):271-288. <https://doi.org/10.1080/10408340500431246>
 48. Bourgeois W, Burgess JE, Stuetz RM (2001) On-line monitoring of wastewater quality: a review. *Environmental Sciences Europe* 13:1-12. <https://doi.org/10.1186/s12302-020-00427-8>