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Design and implementation of an open-access arsenic biosensor

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Arsenic contamination in groundwater is a critical global issue, affecting over 140 million people worldwide and posing severe public health risks, particularly in low-resource and rural communities. Argentina alone has approximately 4 million people exposed to arsenic. The measurement of arsenic in private wells is often limited by high costs, specialized personnel requirements, and geographical distances to analytical laboratories. In this paper, we describe the design and implementation of a portable, open-access arsenic biosensor that combines synthetic biology and industrial design. The biosensor employs genetically modified *Escherichia coli* and a colorimetric readout to detect arsenic concentrations as low as 5 µg/L. Validation studies on 61 samples yielded a sensitivity of 98.1% and specificity of 99.0%. By using paper-based, dehydrated bacterial modules and a 3D-printed housing, this device is cost-effective, easy to use, and amenable to replication in low-resource settings. In addition, the open-access approach ensures that critical knowledge such as plasmid sequences, device schematics, and protocols can be freely shared and locally adapted. Beyond the technical advantages, this biosensor can potentially influence global policies and Argentinian programs on water quality monitoring, empowering communities to take charge of arsenic surveillance and safeguard public health.

Keywords Arsenic, Biosensor, Groundwater monitoring, Whole cell, Colorimetric detection, *E. coli* whole-cell biosensor, Open source hardware, µPAD

Arsenic contamination: A global and local challenge

Access to safe drinking water is recognized as a fundamental human right[1–3], yet over two billion people worldwide still lack reliable access[4–6]. One significant factor contributing to unsafe water is the presence of both natural and anthropogenic contaminants. Among these, arsenic poses one of the most severe risks to public health due to its toxicity and carcinogenic properties[7–9]. Chronic exposure to elevated arsenic levels is associated with cancers (skin, lung, bladder, and kidney, among others), and non-carcinogenic illnesses such as arsenicosis, diabetes mellitus, and various cardiovascular and respiratory diseases[8,10,11] .

While arsenic contamination in groundwater is a global concern -affecting regions in Bangladesh, India, China, and the United States[9]- it is particularly significant in Latin America, with over 14 million people consuming water exceeding WHO's 10 µg/L guideline for arsenic[12]. Argentina is among the most affected nations; estimates suggest around 4 million individuals, especially in the Chaco-Pampean plain and various other peripheral regions, rely on arsenic-contaminated water sources (Fig. 1)[11–14]. Vulnerable populations in these areas often have limited awareness of arsenic-related health risks, and are geographically and economically constrained from accessing accurate testing or mitigation solutions[15].

Arsenic in water is odorless, tasteless, and colorless, making it imperceptible to human senses and posing a hidden threat.

Limitations of existing detection methods

Current standard analytical methods for arsenic, such as atomic absorption spectroscopy (AAS) and inductively coupled plasma mass spectrometry (ICP-MS), provide high sensitivity and specificity[21]. However, these techniques are costly, require trained personnel, and necessitate specialized laboratory facilities, making them impractical for routine monitoring in remote or underprivileged regions. On the other end, affordable field kits (often colorimetric based on chemical reagents) sometimes lack the required accuracy or reproducibility to confidently detect arsenic at or below the WHO guideline[22–24].

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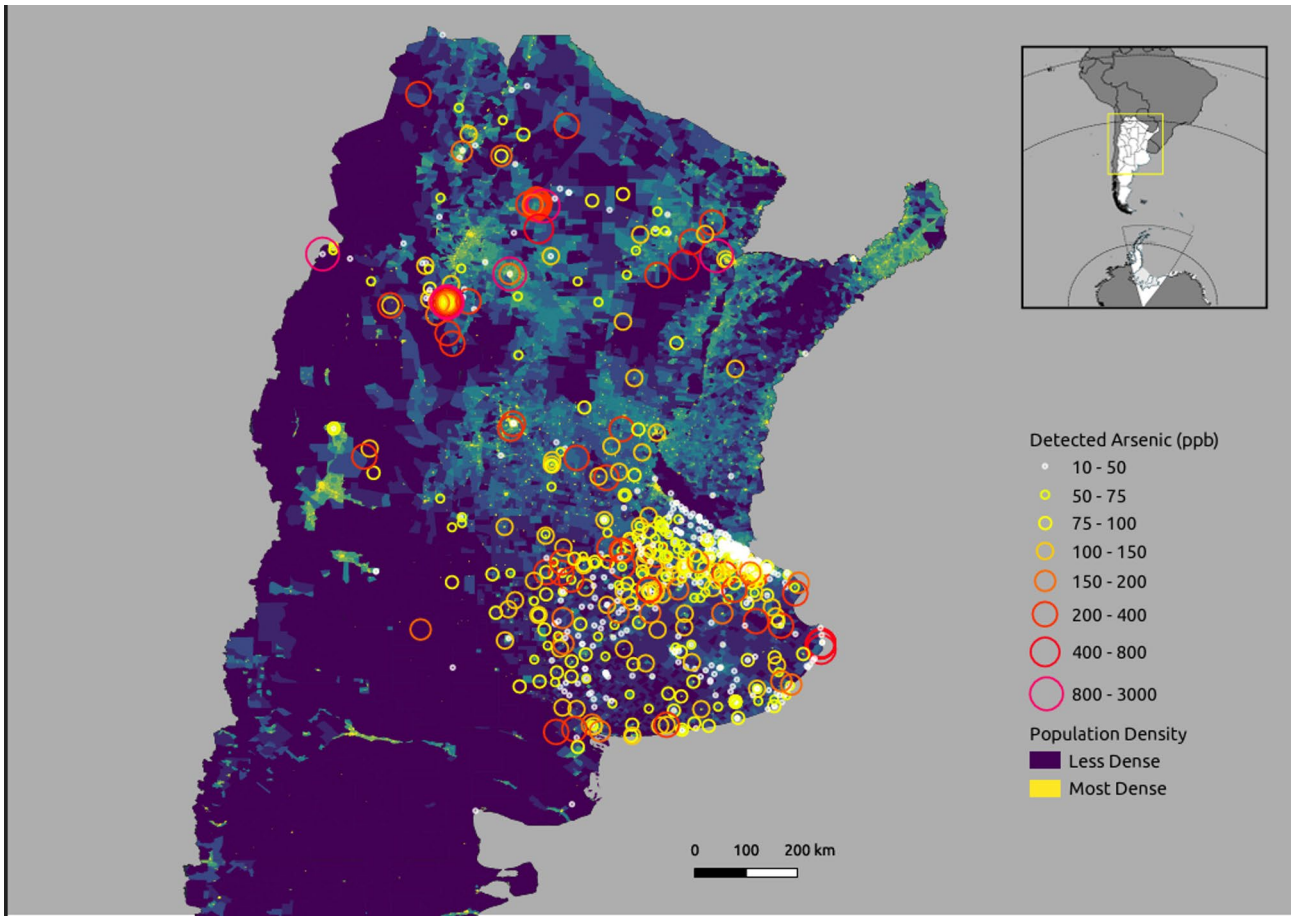

Fig. 1. Arsenic survey in Argentina. Population density (violet/yellow gradient) and measured arsenic concentrations (circles) across Argentina. Arsenic data was compiled from the arsenic measurement databases and reports of the Technical Institute of Buenos Aires (ITBA)[16,17], the Toxicological Argentinian Association (ATA)[18], and the Food Security Network of the National Council of Science and Technology (RSA-CONICET)[16]. The figure was generated using the software QGIS (QGIS v3.40, released under the GNU General Public License (GPL); qgis.org), incorporating geographic divisions from the census tract map[19], and the Human Settlements Database of Argentina[20].

Argentina's situation illustrates this challenge: many residents obtain water from private wells in rural areas, where infrequent or expensive testing can delay intervention until serious health effects emerge[10,13,14]. Consequently, there is a growing need for community-friendly, low-cost, robust, and highly sensitive detection technologies to enable timely decision-making on water potability.

Biosensors for arsenic detection

Biosensors engineered to detect arsenic offer a promising solution that balances cost, accuracy, and ease of operation[24–26]. These devices harness biological components -such as bacteria or enzymes- to produce measurable signals (e.g., color changes) upon exposure to arsenic. By integrating synthetic biology with user-centric industrial design, biosensors can be made portable, simple, and resilient enough for wide-scale deployment in resource-constrained settings[24,25,27].

Our previous biological device was based on a red colored protein whose lower limit was hardly 50 µg/L and took several hours to reach a color level detectable by the naked eye (particularly difficult for people with the most frequent red color blindness). Thus, we evaluated alternatives to improve the detection limit and response time[28,29].

Here, we describe the conception, design, and validation of an open-access arsenic biosensor, optimized for low-cost manufacturing and decentralized distribution. Our approach leverages genetically modified *Escherichia coli* to yield a colorimetric response in the presence of arsenic concentrations as low as 5 µg/L. We also introduce an ergonomic, 3D-printed housing that simplifies assay operation and ensures user safety. The device's open-access model is central to our mission: all plasmid sequences, device blueprints, and protocols are publicly shared to foster local production, encourage user-driven improvements, and lower barriers to adoption.

Materials and methods

Biosensor module: genetically engineered *E. coli*

The biosensor module consists of *E. coli* DH5α cells carrying the pMV-arsR-ABS1595 plasmid[30], which places the *lacZ* (β-galactosidase) gene under an arsenic-responsive promoter. In the absence of arsenite, ArsR binds operator sequences, repressing transcription. Cytosolic As(III) binds ArsR, lowers its DNA affinity, and derepresses lacZ. The expressed β-galactosidase cleaves X-gal (5-bromo-4-chloro-3-indolyl-β-D-galactopyranoside) to yield 5-bromo-4-chloro-indoxyl, which dimerizes to the insoluble blue chromophore (5,5′-dibromo-4,4′-dichloro-indigo). The blueing intensity increases with arsenite concentration.

Although the system is configured to detect As(III), As(V) is converted to As(III) by the chromosomally encoded arsenate reductase in E. coli DH5α, as has been previously described[30,31].

Bacterial growth

E. coli DH5α was grown in Luria-Bertani (LB) medium with 100 µg/mL ampicillin at 30 °C, 215 rpm, overnight. Cells were harvested by centrifugation at 2,800 × g for 5 min and resuspended in a solution containing 34% (w/v) trehalose and 1.5% (w/v) polyvinylpyrrolidone to OD = 2.

Dehydration on paper

Aliquots (12 µL) of the resuspended cells were deposited onto 10 × 7 mm pieces of Whatman 3MM chromatography paper. Paper strips were placed in 2 mL Eppendorf tubes and dehydrated for 2 h using a SpeedVac vacuum concentrator. These dried, bacteria-impregnated strips (biosensor modules) can be stored at room temperature for up to 30 days without significant loss of responsiveness (Supplementary Figure S4).

3D-Printed device fabrication

To ensure ease of use, portability, and user safety, we designed a multi-part device using parametric Computer-Aided Design (CAD) software (Solidworks 3d CAD, Waltham, MA). The device includes (see Fig. 3):

Sample holder (Part 1)

Three wells (blank, sample, and arsenic standard) for fluid loading.

Plastic circuit holder (Part 4)

Houses the paper biosensor module and facilitates capillary flow.

Paper components (A, B, C, D)

A layered arrangement of dehydrated bacteria (B), substrate-containing paper (D), and flow paths (A, C) to direct samples to the bacteria.

All plastic parts were printed with polylactic acid (PLA) filament (1.75 mm diameter) on a standard RepRap FDM 3D printer at 0.15 mm layer height. The final device assembly ensures a sealed environment for the bacterial module, preventing user contact with live microorganisms. Once the assay is complete, the used module can be inactivated with bleach and discarded.

Assay procedure

1. **Activation Buffer**: An activation solution (LB broth : 20 mg/mL X-gal in DMSO : 0.4 M EDTA at an 8:1:1 ratio) is added to the dehydrated strip (12 µL) to rehydrate the bacteria.
2. **Sample Loading**: 1 mL of water sample or standard arsenic solution is introduced into the designated well on the sample holder. The sample flows via capillary action through the biosensor module, contacting the *E. coli* cells.
3. **Incubation and Detection**: The device is kept at ambient temperature (16–25 °C) for 8–16 h. If arsenic is present, β-galactosidase expression results in a visible blue color, which intensifies with increasing arsenic concentrations.
4. **Color analysis script**: The images are analyzed with a python-based script written on Python using OpenCV library[32] for image analysis (https://github.com/SensAr-Biosensor).The script produces a monotonic color metric derived from the reaction zone, yielding a numerical readout that correlates with arsenic-dependent color development. The color is analyzed within a user-defined region of interest from a JPG image. For each pixel in the selected area, the RGB channels are extracted and inverted. The output value is calculated as the ratio between the red channel intensity and the sum of the blue and green channel intensities, averaged over *n* pixels. This metric increases proportionally with the intensity of the blue color generated by the biosensor, which in turn reflects arsenic concentration. The same processing is applied to the in-frame blank and the 10 µg/L reference standard, which are subsequently used for normalization and comparison.The resulting metric increases proportionally with the intensity of the blue color generated by the biosensor and correlates with arsenic concentration, as supported by the validation and linearity data presented in this study.

The output value is calculated as follows:

$$Output = \frac{\sum \frac{red\ channel\ value}{(blue\ channel\ value + green\ channel\ value)}}{n\ pixels}$$

5. **Smartphone Data Capture** (optional): An Android-based app ("SensAr") assists with color analysis. Users align the device's reaction zones on their phone camera; the app automatically measures color intensities, geotags the location, and uploads data to a central database for map-based arsenic tracking. To limit variability, users capture a single image containing the blank, sample, and standard simultaneously, without flash. This within-image normalization mitigates uniform illumination and white-balance effects across cameras. A matte hood around the reaction zones is recommended to reduce glare from ambient light.
6. **Disposal**: After completing the assay, each used paper module should be immersed in a 10% (v/v) household bleach solution for 30 min to ensure inactivation of E. coli cells. Treated strips can then be discarded as regular waste, in accordance with local biosafety regulations. This step complies with standard BSL−1 disposal protocols[1], mitigating any potential release of viable genetically modified microorganisms into the environment.

Validation with field samples

A total of 61 water samples from Buenos Aires Province (Argentina) were collected by the National Water Institute ($N = 32$) and Instituto de Hidrología de Llanuras "Dr. Eduardo Jorge Usunoff" (IHLLA; $N = 29$) as part of routine arsenic monitoring campaigns[33]. Arsenic concentrations in these samples ranged from below detection limits to 101.7 µg/L (mean ± SD = 36.1 ± 24.4 µg/L), as measured by AAS-hydride generation performed in a Shimadzu, model AA-7000 and following standard methods (APHA Standard Methods 3113, 3114)[1,21].

To validate the biosensor, each sample was tested qualitatively against a 10 µg/L cutoff. Sensitivity, specificity, and false positive/negative rates were calculated as follows:

$$Sensitivity = \frac{TP}{TP + FN}\ ;\ Specificity\ =\ \frac{TN}{TN + FP}$$

$$False\ Positive\ Rate\ =\ \frac{FP}{TN + FP}\ ;\ False\ Negative\ Rate\ =\ \frac{FN}{TP + FN}$$

Where TP = true positives, TN = true negatives, FP = false positives, and FN = false negatives[34].

Statistical analysis of colorimetric responses

Images of the biosensor strips were taken under consistent lighting conditions using a standard smartphone camera. Color intensities (RGB channels) were quantified using a Python-based script yielding a numerical readout that correlates with the visible blue hue. Repeated-measures ANOVA with Tukey's post hoc test was used to compare mean intensities at different arsenic concentrations. Limit of detection was estimated by comparing blank measurements to increasing arsenic concentrations using a repeated-measures ANOVA with Dunnett's post hoc test. (GraphPad Prism 8, GraphPad Software, Inc.).

Results

Biosensor performance and sensitivity

Among the different constructs we evaluated including SensAr variants with mRFP, GFP or β-galactosidase as reporter[28], the one with best performance was construction 1595 from Stocker et al.[30] generously sent by Drs J.R. Van der Meer and V. Sentchilo, with a robust and sharp response in the range 0–1000 µg/L (Supplementary Figure S1), and a linear range between 0 and 50 µg/L. The optimal response time was between 2 and 4 hs at 30°C (Supplementary Figure S3).

To evaluate the response to arsenic, the biosensor modules were re-hydrated in 48 wells plates with 500 µl of arsenic standards prepared from 100 mg/L sodium arsenite stock solution and incubated at room temperature for 8–16 h. After the induction period, papers were taken out and the excess of water was absorbed with tissue paper. Color development was evaluated on images taken under even white background and fluorescent tube illumination with a standard cell-phone camera without flash. A single image was taken for all the modules to be analyzed on each bath in order to avoid differences on white balance or illumination intensity.

On every 17 independent assays made on different days, the response produced increased at each concentration step 0 to 50 µg/l As (Fig. 2A). Although individual values, including blanks, were not stable between days, the analysis of each assay independently gave a consistent increasing response. Assays were conducted under ambient conditions without strict temperature control (16–25℃) and the reported kinetics reflect the temperatures recorded during each experiment (8–16 h) in order to resemble uncontrolled user operator conditions and evaluate robustness at the same time. Furthermore, despite blank modules showed background color development (Mean color 0 µg/l As = 0.301 ± 0.017), the mean response produced at 5, 10 and 50 µg/l were significantly higher than blank and between them (Mean color 5 µg/l As = 0.379 ± 0.021; Mean color 10 µg/l As = 0.448 ± 0.024; Mean color 50 µg/l As = 0.531 ± 0.026; $p < 0.0001$; repeated measures ANOVA, Tukey post hoc test) (Fig. 2B.). The limit of detection was 5 µg/L (Repeated Measure ANOVA, Dunnet's post hoc test, $p = 0.0002$).

Thus, colorimetric assays performed under ambient conditions (16–25 °C) showed robust and consistent detection of arsenic concentrations as low as 5 µg/L. Despite some day-to-day variation in absolute color values, the biosensor demonstrated consistent increases in blue color intensity from 0 to 50 µg/L (Fig. 2).

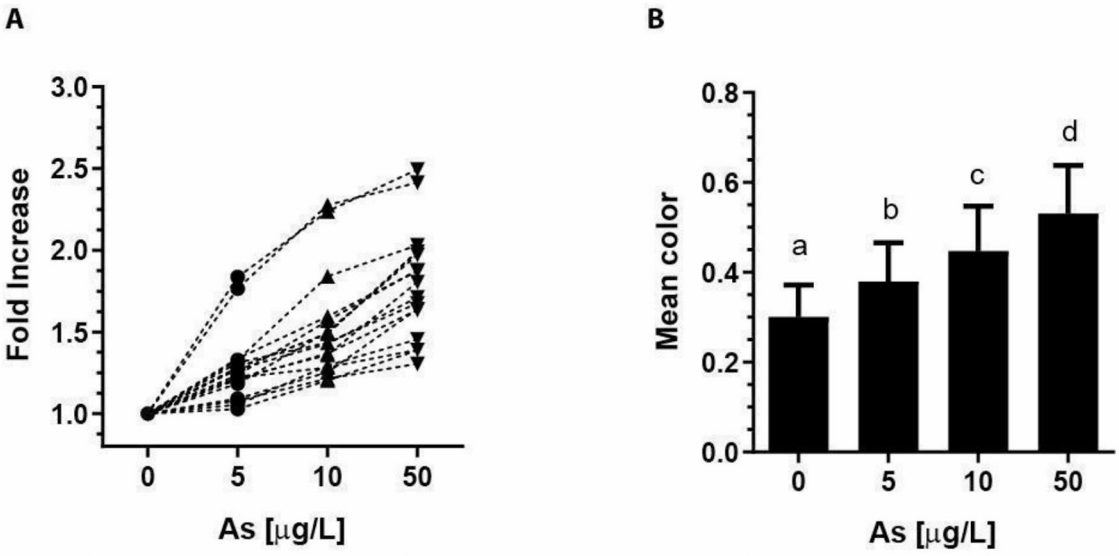

Fig. 2. Arsenic Induction Assay. (**A**) Fold increase in color intensity (relative to blank) for 5, 10, and 50 µg/L arsenic solution ($n = 16$). (**B**) Mean color intensity of 16 independent assays captured via the OpenCV-based script. Letters indicate statistical difference (Repeated measure ANOVA, Tukey post´hoc test; $p < 0.01$).

Parameter	Value
Number of Samples	61
Total Positives (TP)	52
Total Negatives (TN)	9
False Positives (FP)	1
False Negatives (FN)	1
False Positive Rate	0.0100
False Negative Rate	0.0189
Sensitivity	98.1%
Specificity	99.0%

Table 1. Validation results comparing biosensor qualitative output with AAS Measurements. Arsenic level in field samples ranged from < 1 to 101.7 µg/L. Cut-off for positivity: 10 µg/L.

Validation with field samples

In order to validate the performance of the assay we analyzed samples from the Buenos Aires Province of Argentina obtained during 2020 from annual water analysis campaigns performed by the National Water Institute and IHLLA (see Supplementary Table 1). The arsenic concentrations on the samples were analyzed by those Institutions laboratories using the gold standard atomic absorption spectrometry method. The arsenic level ranged from not detectable to 101.7 µg/L (Mean ± SD = 36.1 ± 24.4 µg/L).

When tested against the 61 field samples with known arsenic concentrations, including 9 negative samples; 52 positive samples (As≥ 10 µg/L) of which 19 had high arsenic concentration (As≥ 50 µg/L)[21]. The biosensor accurately classified samples above or below the 10 µg/L threshold, with only one false positive and one false negative (Table 1). Overall sensitivity was 98.1% and specificity was 99.0%, indicating excellent performance relative to standard laboratory methods.

Device assembly and operation

The final prototype, called "SensAr," was designed and developed in order to be cost effective, accessible and as easy to use, with a graphical and ergonomic interface that does not require a qualified user. It consists of 3D-printed PLA parts holding layered paper components impregnated with dehydrated *E. coli* and X-gal (Fig. 3). Its parts are joined and sealed after the bacteria are placed, resulting in a safe and tight compartment. The modular design allows easy assembly and replacement of individual components. Operation is straightforward, involving sample loading, passive incubation, and a final color readout. The integrated smartphone application can optionally quantify results and provide a geo-referenced data log (Fig. 3C).

The µPAD device consists of paper components (A-D) which make up the biosensor circuit itself, and PLA plastic components (parts 1–5) that form the circuit and sample holders. The sample holder (1) contains three wells where the blank, sample, and arsenic standard are placed. The circuit holder (4) contains the paper

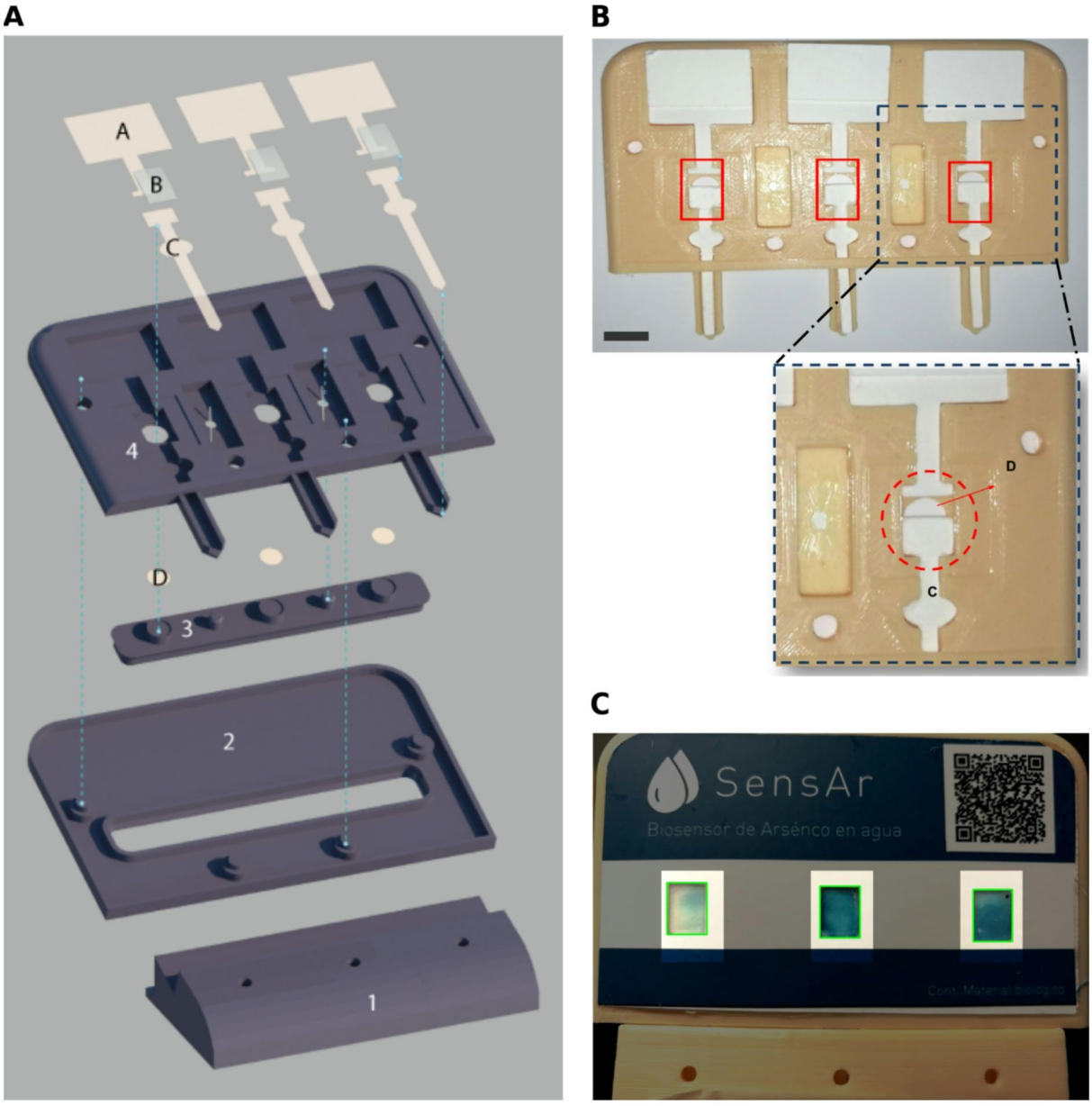

Fig. 3. Portable arsenic biosensor device SensAr. (**A**) Exploded 3D render of the SensAr device, showing its 3D-printed plastic parts (labeled 1–4) and paper layers (labeled **A**-**D**). (**B**) Partially assembled device, showing the paper flow circuit. Red rectangle highlights paper B. The inset highlights paper D, impregnated with X-gal, positioned 0.5 mm below paper C. Scale bar: 10 mm. (**C**) Smartphone screen capture of the SensAr app automatically detecting the reaction zones. The app darkens the rest of the interface, highlighting each reaction area with green rectangles. The assembled device measures 33.5 mm height, 89.6 mm width × 71,5 mm depth and weighs 55 g.

components of the device and facilitates liquid flow through the biosensor module. The X-gal carrying paper is secured to the button with paper glue, which is supported on the back of the device. The paper circuit contains the input impregnated with dehydrated LB, which allows the sample to enter via capillarity. The sample then flows through the biosensor module and onto an absorbent PAD.

Device assembly

Three pieces of paper, denoted as D, are each loaded with 1.5 µL of X-gal (20 mg/mL DMSO). Subsequently, part 3 is inserted onto part 2, and the resulting 2–3 set is attached to part 1 using ethyl cyanoacrylate super glue (UHU, Germany) adhesive. The paper circuit is then assembled on the plastic circuit holder (4) in a specific order. Firstly, parts A and C are placed at the base of the holder. Secondly, the biosensor modules (B) are gently laid on top, ensuring that they are in contact with their corresponding parts A and C. Finally, a PET lid is firmly sealed on top of the circuit using liquid silicone adhesive (UHU, Germany) ensuring the integrity of the device.

All adhesives are fully cured prior to use and are positioned outside the capillary path. The only silicone bead seals the PET lid and does not contact the X-gal zone. In our assembly design, the wicking paper forms a continuous barrier between adhesives and the biosensing readout region (Fig. 3B inset), minimizing leachate risk. We observed no qualitative differences between assemblies using the specified adhesives versus a press-fit prototype.

X-gal is applied as a small volume (1.5 µL of 20 mg/mL in DMSO) onto paper D and allowed to dry completely before sealing. The dried substrate is contained within a closed module; liquids flow by capillarity, and no free solvent is present during transport or use. A visual leak test is part of assembly QC; the module remains sealed until post-assay bleach inactivation.

Device operation

The sample holder (1 in Fig. 3) is used to load the sample, blank, and standard solution (1 mL) onto their respective wells using either a Pasteur pipette or a syringe. The assay is initiated by inserting the circuit holder (4 + 3+2 in Fig. 3 assembled and sealed) onto the sample holder, which triggers the absorption of the sample through the PADs. The flow is sustained for 1.5 h, after which button 3 is pressed firmly from behind, causing the X-gal paper D to push up the B. This action has two effects: it interrupts the circuit by separating B from A, and it allows the X-gal substrate to come into contact with the bacteria. The results are assessed and documented using the SensAr Android application after 4 h.

Design choices balance manufacturability and robustness: (i) three wells (blank/sample/standard) enable in-frame normalization; (ii) a capillary-fed paper stack isolates the bacterial module and homogenizes flow; (iii) the post-flow 'press' engages X-gal only after wicking, reducing background; and (iv) 3D-printed PLA parts support local fabrication and easy replacement of modules.

Android app usage

After the user has signed in on the SensAr. The following sample information is entry: data source (well/red/fresh), the temperature of the assay and other observations concerning the sample. The app will ask to acquire the QR code info (date and batch data is obtained from the QR code). Afterwards, three zones will be displayed to frame the image in the three reaction zones. The app detects and delimit the rectangles automatically and the user can record the image by tapping the screen. If the user confirms that the zones are well located, the app will save the image and perform the analysis. The result is reported instantly, and a complete report can be sent by mail or shared through other smartphone apps. Also, the results are sent to a database including the geolocation of the analysis obtained from the phone.

Discussion

In this work we described the design and implementation of a portable, open-access arsenic biosensor useful for low cost and field monitoring of contaminant levels. The biosensor employs genetically modified Escherichia coli and a colorimetric readout with limit of detection as low as 5 µg/L. Our original design included an incoherent feed forward system to make the signal independent of the evaluation time and only depend on the contaminant concentration[28,29]. However, the complexity of the design, which required the incorporation of several extra genes, made it less robust to operate under uncontrolled conditions. Thus, we decided to exclude the incoherent feed forward and rely on an internal growth and color development reference. In addition we switched from mRFP to b-galactosidase as a reporter which improved the sensitivity, speed and detection for red color blind people. Precise colors quantification is done with an Android application developed for this purpose. The reference standard was set to 10 micrograms per liter, in line with WHO limit to drinking water and Argentinian regulation[35,36] and can be easily modified to fit changes in local regulation.

The arsenic biosensor in water has been designed to be distributed as a kit that allows a determination of the water in evaluation by an unqualified user. Being open access, its production can be decentralized, though it needs some infrastructure that is easily available in most science schools and universities. The ease by which the bacteria can reproduce and the low bacterial concentration required, make the product easy to be massively produced and with a very low cost of the active agent. Furthermore, being based on bacteria, purification of active ingredients is not required. The biomass that is generated when cultivating bacteria is directly the "system" of measurement. These characteristics result in a very low production cost and mostly independent of imported supplies.

Our normalization against an internal blank and an in-frame 10 µg/L standard, together with a scale-invariant color ratio, improves reproducibility under variable field lighting and across smartphones. The effectiveness of the internal control for determining whether a sample lies above or below the cut-off value is evidenced in Fig. 2A, where the curves, despite exhibiting some variability across replicates, show strong intra-assay consistency. Given this intrinsic assay-to-assay variability, the choice of the analytical readout becomes critical for reliable field deployment. Under these conditions, fixed color charts are unlikely to provide reliable classification—particularly near the decision threshold—whereas smartphone-based analysis enables normalized, objective readout across assays. A limitation of this study is that the biosensor was not systematically evaluated in highly turbid or strongly colored waters. High turbidity may affect capillary flow, while colored dissolved organic matter could bias colorimetric readouts. However, the tool was designed for water expected to be potable except for unknown arsenic concentration, conditions under which such interferences are not anticipated.

Validation studies on 61 samples yielded a sensitivity of 98.1% and specificity of 99.0%. Nevertheless, the limited representation of borderline arsenic concentrations in the present dataset represents a limitation; future validation using cohorts enriched near the decision threshold would further refine performance estimates. Several strategies could further reduce false positive and false negative classifications in future iterations of SensAr, including optimization of incubation time and decision thresholds, replicate strips, improved sealing

and storage, engineered reporters with reduced background, and additional internal controls (e.g., a viability control) to identify invalid runs. The system can also be tuned to favor false positives over false negatives, thereby minimizing the risk of overlooking samples exceeding the regulatory threshold.

By using paper-based, dehydrated bacterial modules and a 3D-printed housing, this device is cost-effective, easy to use, and amenable to replication in low-resource settings.

Comparative analysis with existing arsenic detection technologies

A variety of arsenic detection techniques are available, each with distinct strengths and limitations:

Laboratory-Based methods

Atomic Absorption Spectroscopy (AAS) and *Inductively Coupled Plasma Mass Spectrometry (ICP-MS)* exhibit detection limits down to parts-per-trillion levels and offer high precision[21]. However, they require specialized equipment, well-trained operators, and sample transport to centralized labs, making routine surveillance expensive and logistically challenging for remote communities[21–23].

Chemical field test kits

Conventional test kits (e.g., based on Gutzeit with mercuric bromide indicator) are more affordable and portable than AAS or ICP-MS[21–23]. Yet, they often struggle to reliably detect arsenic near the 10 µg/L threshold, can suffer from interfering substances (e.g., sulfide), and may yield subjective or semi-quantitative colorimetric readings. Similarly, several paper-based field assays, while extremely low-cost and rapid, can face comparable limitations in sensitivity near the regulatory threshold and susceptibility to matrix interferences[37,38].

Electrochemical sensors

Electroanalytical methods (e.g., anodic stripping voltammetry) can achieve low detection limits[21–23,39]. Still, they typically require instrumentation (potentiostats) and often need careful calibration, limiting accessibility in low-resource settings[40].

Biosensors

Several previously reported whole-cell biosensors achieve comparable or higher sensitivity and faster response times; however, they are typically not available as deployable kits for out-of-laboratory use by untrained users, or are not provided as fully open technologies. In this context, SensAr prioritizes operational accessibility, robustness, and openness, positioning it as a complementary screening and decision-support tool rather than an alternative to electrochemical sensors or advanced laboratory-based techniques[25,26,41].

To position SensAr among existing options, Supplementary Table S2 summarizes reported detection limits, assay times, per-test costs, operational burden, and biosafety/regulatory considerations across laboratory assays (ICP-MS/AAS), chemical field kits, electrochemical methods, and whole-cell biosensors. SensAr's strength is low-cost (details of the per-test consumable cost are provided in Supplementary Table S3), on-site screening at the WHO/Argentinian threshold (10 µg/L) with internal blank/standard normalization and open, locally manufacturable hardware; it is not intended to replace confirmatory laboratory quantification.

In summary, the SensAr biosensor offers a balanced solution for communities requiring on-site, low-cost monitoring at relevant regulatory limits. The open-access nature further enables local manufacturing and adaptation to specific contexts or additional target analytes.

Policy implications: A global and Argentinian perspective

Global policies

Arsenic governance aligns with the WHO 10 µg/L guideline[35] and UN SDG 6[35]. While many low- and middle-income countries pursue these targets[2,5,36] routine monitoring remains limited by cost and infrastructure constraints[42]. In this context, SensAr is best positioned as a low-cost screening and decision-support tool, enabling decentralized classification of water samples relative to the regulatory threshold and prioritization for confirmatory laboratory analysis. The platform's open documentation and optional smartphone-based data capture, including geotagging, provide a technical basis for future aggregation of screening data, contingent on responsible deployment and dedicated field programs[42,43].

Argentinian programs

Groundwater arsenic is high in Argentina, especially in the Chaco-Pampean region[13,14]. Ministry of Health and utility programs emphasize treatment and public campaigns[15] but often rely on sporadic lab tests that miss temporal and spatial variability. In this context, SensAr is best positioned as a low-cost screening and decision-support tool, enabling decentralized classification of water samples relative to the regulatory threshold and prioritization for confirmatory laboratory analysis. The platform's open documentation and optional smartphone-based data capture, including geotagging, provide a technical basis for future aggregation of screening data, contingent on responsible deployment and dedicated field programs. Given its limit of detection and agreement with AAS in field samples, SensAr is primarily suited for screening and prioritization, informing targeted confirmatory testing and mitigation rather than replacing regulatory analyses.

Open-Access model: Ethical, Practical, and scientific benefits

Ethical rationale

Open-access dissemination of technology and knowledge is especially critical for addressing public health challenges in underserved regions[44]. By freely sharing device schematics, plasmid sequences, and protocols, we

promote equitable access to essential tools that can save lives. This democratizes innovation, ensuring that patent barriers or licensing fees do not hinder communities from adapting or producing the biosensor locally[44–46].

Practical advantages

Cost-Effectiveness: With the bacterial modules grown in basic lab conditions and device parts 3D-printed from inexpensive PLA filament, production costs remain < $1 per test (excluding labor and smartphone), supporting affordable community screening. **Local Adaptation**: Open designs permit iterative improvements based on local materials, cultural practices, or environmental factors (e.g., water hardness). **Community Engagement**: Shared protocols enable universities, NGOs, and grassroots organizations to build capacity, train local users, and maintain a distributed network of arsenic monitoring sites.

Scientific Benefits.

Collaboration and Transparency: Open-access fosters cross-institutional collaborations, spurring new ideas and accelerating iterative design improvements[44,45]. **Reproducibility**: Publicly available genetic constructs and device designs reduce ambiguity and facilitate validation by independent groups, building a broader consensus on performance and reliability.

In the case of the SensAr device, we have released our plasmid maps, paper-cutting patterns, and 3D-printing files to ensure any research lab or community-based science initiative can replicate or improve upon our work. This strategy helps overcome traditional limitations in technology transfer to remote settings and aligns with the ethos of open science by lowering entry barriers for others who wish to address arsenic contamination. However, it does not address certain 'contextual' limitations discussed elsewhere[47]. Additionally, the plasmid architecture used in this work is inherently modular, enabling potential adaptation to other contaminants by replacing the promoter/regulatory element while preserving the reporter framework. Such an approach could, in principle, allow the development of biosensors targeting other elements, such as lead[46]. However, potential cross-reactivity would need to be carefully evaluated on a case-by-case basis, as metal-responsive regulatory proteins may exhibit overlapping responses depending on their regulatory family. Accordingly, extending this platform to additional contaminants represents an important direction for future work rather than a demonstrated capability of the present study.

While open access lowers cost and accelerates adaptation, deployment with GMOs may face site-specific regulatory approvals, variable biosafety literacy, and inconsistent cold-chain-free logistics. Our BSL-1 disposal (10% bleach, 30 min) and sealed module design mitigate risk, but local governance and training remain critical for responsible use.

Replication in Low-Resource settings

Designing the biosensor with a focus on low-resource environments was integral to this project. Key considerations included:

Room-Temperature Shipping and Storage: The bacterial modules remain viable for ~30 days without refrigeration (Supplementary Figure S4), simplifying last-mile delivery. **Minimal Equipment**: Assays only require a pipette or syringe and minimal reagents, eliminating the need for advanced laboratory tools.

Ease of disposal Post-assay disposal is straightforward; the bacterial strips can be inactivated with mild bleach solution or incineration, complying with biosafety guidelines[1].

By alleviating common logistical hurdles (cost, refrigeration, specialized training), our biosensor can be implemented by local health workers, NGOs, or even directly by residents. Coupled with the open-access model, these features ensure the device is not only affordable but also culturally and infrastructurally adaptable across diverse settings.

Limitations (i) Shelf-life of dehydrated modules at room temperature is ~30 days (Supplementary Figure S4), suggesting periodic replenishment for field programs; (ii) Time-to-result is 8–16 h at 16–25 °C (2–4 h at ~30 °C), which suits overnight screening but not rapid triage; extreme temperatures should require retest/confirmation; (iii) A requirement of the current implementation is the inclusion of an in-frame blank and a 10 µg/L reference standard in each assay to enable proper normalization and reliable decision-making around the regulatory threshold; (iv) Users must inactivate modules with 10% bleach before disposal; (v) Matrix effects beyond those tested in this work (e.g., very high salinity, oxidants antibiotic presence, strongly colored or high turbidity waters) should be considered, with confirmatory AAS/ICP-MS recommended for regulatory decisions; and (vi) In water samples with elevated levels of aerobic mesophilic bacteria, background β-galactosidase activity from environmental microorganisms may contribute to the colorimetric signal and potentially result in false-positive responses.

Conclusion

We developed a low-cost, open-access arsenic biosensor through an interdisciplinary effort uniting synthetic biology and industrial design. The resulting tool demonstrates high sensitivity and specificity, meets WHO guidelines (10 µg/L), and can be easily mass-produced and deployed in low-resource environments. By integrating user-friendly design with freely available blueprints and protocols, we aim to empower communities with real-time water quality information, ultimately reducing chronic arsenic exposure and improving public health outcomes.

Looking ahead, scaling this open-access model can foster collaborative innovation, allowing global communities to customize and expand biosensor technologies. Such grassroots-driven surveillance supports policymaking at the local, national, and international levels, aligning with SDG 6 and other global health

initiatives. In Argentina, the biosensor offers a valuable complement to existing arsenic mitigation policies, particularly in rural or marginalized populations. More broadly, our approach highlights how open science and cost-efficient biotechnology can jointly advance the human right to safe drinking water.

Data availability

All relevant data supporting the findings of this study are provided within the manuscript and its Supplementary Information files. Additional raw data (images, colorimetric outputs, Python scripts, and 3D design files) are openly available at GitHub SensAr-Biosensor under license CC-BY 4.0.

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Declarations

Competing interests

The authors declare no competing interests.

Open hardware documentation

STL files, CAD designs, Plasmid sequence, and instructions for printing/assembly are available at GitHub SensAr-Biosensor. Physical plasmid can be requested in Addgene 240494.

Additional information

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