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A Multiplexed Electrochemical Dip-Probe Concept (Hydro-Core) for On-Site Drinking-Water Screening in India: A Critical Concept Review and Evidence Audit

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ABSTRACT

Chemical and microbial contamination of drinking water remains a major public-health problem in South Asia, yet routine multi-parameter testing in India still depends largely on centralized laboratories. A recent design-patent-oriented technical document proposes "Hydro-Core", a hand-held dip-probe that combines seven analyte channels (arsenic, lead, cadmium, pH, nitrate, total coliforms, and E. coli) on a screen-printed carbon electrode (SPCE) array with an IoT back-end. This paper audits that concept. It (i) summarises the proposal, (ii) tests each sensing mechanism against peer-reviewed literature that could be independently located, (iii) separates ornamental design features from functional sensing architecture, and (iv) identifies what must be demonstrated before any performance claim can be made.

The audit finds that the individual sensing principles are established and plausible, but that several headline performance figures in the source are not supported by the located literature. In particular, a 1 CFU/mL limit of detection after a 20-minute incubation is not consistent with published enzymatic-electrochemical coliform assays, which report hours of incubation to reach tens of CFU/mL; and published screen-printed arsenic sensors report limits near 1–3 µg/L, usually in acidic or strongly alkaline electrolytes, not 0.5 µg/L in natural water. No experimental data exist for the integrated device. This is a concept review, not a results report. Because the sandbox used to prepare it could verify only a limited set of sources, the bibliography contains 20 verified in-window references plus 4 flagged pre-window sources, not the 50 requested; the shortfall is documented in the accompanying reference-verification report.

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KEYWORDS: *drinking water; anodic stripping voltammetry; screen-printed electrodes; β-galactosidase; multiplexed sensing; design patent; India.*

1. Introduction and scope

India monitors safe drinking water using a combination of laboratory testing, field test kits, and, increasingly, sensor-based surveillance. Laboratory methods such as inductively coupled plasma mass spectrometry (ICP-MS) and culture-based microbiology are accurate, but they require sample transport, trained staff, and day-long turnaround times. A low-cost, multi-parameter, in-situ device is therefore attractive, and electrochemical sensing on screen-printed electrodes is a natural candidate technology because the same potentiostat can interrogate metals (by stripping voltammetry), pH (by potentiometry), and enzyme activity (by amperometry) [4,5,7].

The uploaded source document describes one such concept, named Hydro-Core, in the framing of a *design* patent. Design patents protect the ornamental

appearance of an article, not its function; the document nevertheless carries extensive functional claims (limits of detection, response times, fouling resistance, power budgets). This review treats those functional statements as hypotheses.

The review has four aims: to represent the source accurately, to benchmark its sensing claims against verifiable literature, to clearly state which statements are established, proposed, modeled, or unvalidated, and to outline a credible validation route. It follows an evidence policy described in Section 2, and its limits are stated in Section 9.

2. Method and evidence policy

We read the complete source document and converted it to text. Its numerical claims, equations, references, and device description were extracted. Literature was then searched through a web search tool; a reference was classed as **verified** only if a bibliographic record (publisher, repository or indexing page) showing title, venue and year was actually retrieved in the preparation session. The sandbox had no direct network access for resolving DOIs, so a DOI is reported only when it appeared in a retrieved record or in a retrieved publisher URL.

Four evidence classes are used throughout:

- **Inherited:** a statement made by the source document, not independently confirmed.
- **Verified literature:** a statement supported by a retrieved record that is cited here.
- **Proposed/modelled:** a design target or a calculation based on stated assumptions.
- **Requires validation:** a claim that only experiment can settle.

Peer-reviewed sources published before 2015 are cited only when they provide the best available evidence on a specific point; they are labeled "P" and placed in a separate list. Official drinking water limits (World Health Organization and Bureau of Indian Standards) are cited from general knowledge and flagged for confirmation against current editions, because the edition cited by the source ("IS 10500:2021") could not be matched to a retrievable document.

3. The water-quality problem relevant to India

3.1. Disease burden

Global assessments attribute a large share of diarrhoeal disease to unsafe water, sanitation and hygiene (WASH). A 2023 analysis estimated that, in 2019, the proportion of diarrhea attributable to unsafe WASH was 0.69 (95% interval 0.65–0.72), acute respiratory infections 0.14 (0.13–0.17), and undernutrition 0.10 (0.09–0.10) [3]. An earlier analysis of the burden from inadequate WASH in low- and middle-income settings covers a wider set of outcomes than waterborne microbial disease alone [2]. Two cautions are needed when applying such figures to a probe. First, these estimates cover *domestic WASH as a whole*, including sanitation and hygiene, so they cannot be read as the share of disease that drinking-water *testing* could prevent. Second, a field sensor can only contribute to health outcomes if its readings trigger remediation; the estimates say nothing about that step. The source's own burden statistics (for example, case counts attributed to specific Indian studies) could not be located and are therefore not reproduced here.

3.2. Geogenic arsenic and other chemical hazards

A global statistical model of groundwater arsenic estimated that roughly 94 to 220 million people may be exposed to groundwater with arsenic above the 10 µg/L guideline [1]. That figure is a model-based hazard estimate rather than a count of measured exposures, and the authors present it with substantial uncertainty. South Asia is a region of high predicted hazard in the wider literature, but India-specific counts were not extracted in this session and are not asserted. Lead, cadmium, and nitrate are also guideline-regulated parameters; commonly applied guideline values are 10 µg/L (arsenic, lead), 3 µg/L (cadmium), and 50 mg/L for nitrate (WHO), with the Indian standard broadly similar but expressed differently for nitrate (45 mg/L). Nitrate is regulated chiefly to prevent infant methemoglobinemia, but a 2018 review concluded that the strongest evidence for other outcomes (colorectal cancer, thyroid disease, neural tube defects) comes from studies, several of which observed increased risk at concentrations below regulatory limits [13]. For monitoring, this means that accurate nitrate readings well below the guideline value may be useful, not only readings near it.

3.3. What a screening device needs to do

Guideline values define the required *decision-level* performance. A screening device must reliably discriminate around 10 µg/L for arsenic and lead and around 3 µg/L for cadmium; a limit of detection far below those values is useful only if matrix effects, drift, and calibration uncertainty are also small. For microbial safety, the guideline is the absence of E. coli in a 100 mL sample, which implies a limit of detection far below 1 CFU/mL unless a concentration step is used (Section 5.5).

3.4. Microbial detection technologies: state of the field

Electrochemical detection of pathogens is an active field. A review published in Analyst classified

voltammetric, impedimetric, and amperometric approaches for waterborne and foodborne pathogens and highlighted microfluidics, immunomagnetic separation, and multiplexing as routes to better performance [19]. More recent reviews cover biorecognition elements, disposable and reusable formats and multiplexed pathogen detection [17], and place biosensors for water quality alongside optical and piezoelectric formats and microfluidic integration [18]. A review of foodborne-pathogen sensors notes that *E. coli* is among the most frequently targeted organisms and that DNA, immuno, and enzymatic formats are all used [20]. Two points from this literature matter here. First, the reviews present sensitivity and speed as *advantages in principle*; they do not by themselves establish that an enzymatic assay can reach a single colony-forming unit in minutes. Second, most reported formats are single-analyte devices; integrating a microbial assay with a metals-and-pH array in one chamber is an unsolved engineering problem rather than an established practice.

4. The Hydro-Core concept as specified in the source

The source describes a cylindrical, fluted, polycarbonate dip-probe about a hand-span long, with a ribbed cable collar, a tapered ogive nose cone, four external intake vanes, and two staggered tiers of rectangular electrode windows (Figure 1). Tier 1 carries electrodes for arsenic (gold-nanoparticle SPCE), lead and cadmium (bismuth-film SPCE), pH (iridium-oxide), and nitrate (copper-decorated SPCE); Tier 2 carries a β-galactosidase substrate electrode (total coliforms) and a β-glucuronidase substrate electrode (*E. coli*). The nose-cone carries the Ag/AgCl reference electrode, a platinum counter electrode, and a temperature sensor. A passive pre-filter with an approximately 50 µm cut-off feeds a chamber of about 0.5 mL, and the electrodes are said to be protected by a Nafion/cellulose-acetate bilayer. The ARM Cortex-M4 microcontroller processes the data and transmits it via BLE/LoRaWAN to a gateway and cloud dashboard (Figure 5).

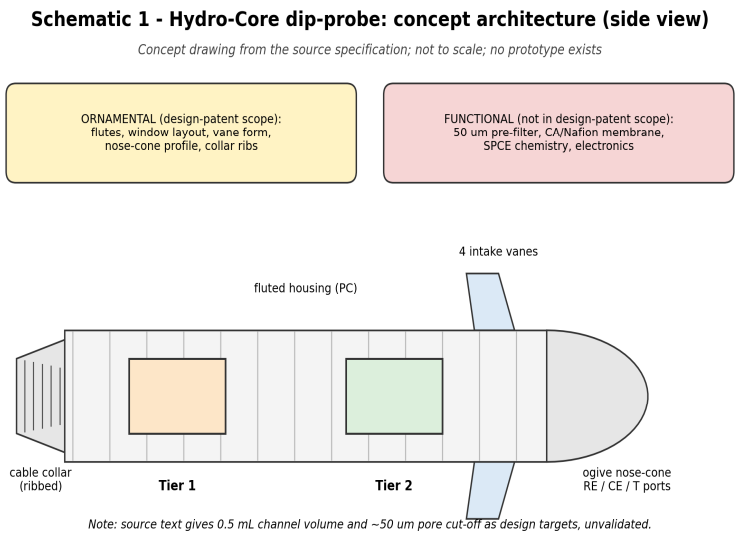


Figure 1 - Probe architecture with the ornamental/functional distinction. Concept drawing based on the source description; not to scale.

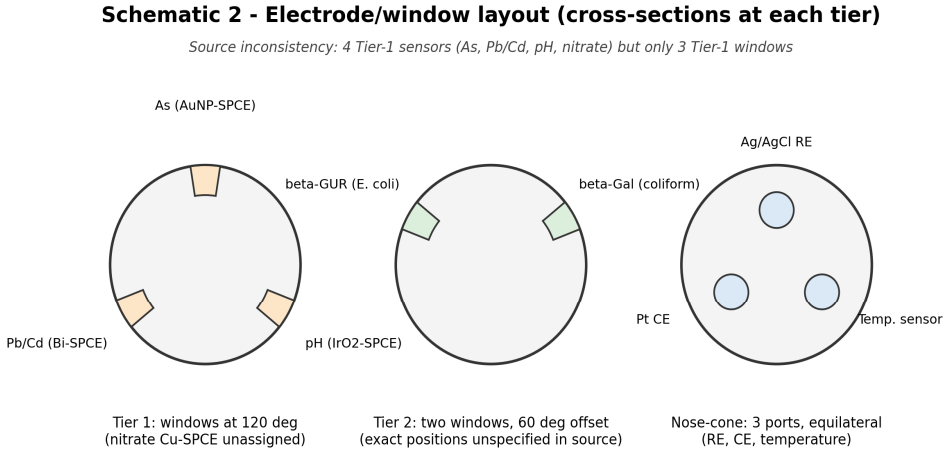


Figure 2 - Electrode/window layout at each tier. The source assigns four Tier-1 analytes (As, Pb/Cd, pH, nitrate) to three Tier-1 SPCEs, so the layout cannot be drawn without an assumption.

4.1. Inconsistencies found in the source

The audit found the following internal inconsistencies, each of which would need correction before any specification is relied on:

1. **Electrode count.** "Seven individual SPCEs" are described, split as three in Tier 1, two in Tier 2, one reference, and one counter electrode. Four Tier-1 analytes (As, Pb/Cd, pH, nitrate) cannot be assigned one-to-one to three Tier-1 SPCEs. Seven *analyte channels* (As, Pb, Cd, pH, nitrate, total coliforms, *E. coli*) do not match seven *electrodes*.
2. **Comparison table label.** The comparative table labels the proposed device "Proposed HMDE Probe." HMDE normally means hanging-mercury-drop electrode, which the device does not use.
3. **Equations.** The peak-current equation is written with the coefficient 0.4958, which belongs to the Randles–Ševčík expression for an irreversible diffusion-controlled voltammetric wave, and is not the relation for the stripping of a pre-concentrated metal film. The given amperometric equation is the Cottrell equation, which describes a decaying current and does not yield a steady-state signal. These are treated in Section 5.
4. **Standard edition.** "IS 10500:2021" could not be matched to a retrievable standard.
5. **Placement of tier windows.** Three Tier-1 windows at 120° and two Tier-2 windows "offset by 60°" cannot be uniformly offset from one another; the exact angular positions are unspecified.

5. Sensing mechanisms and critical appraisal

5.1. Arsenic(III) by stripping voltammetry on gold

Arsenic(III) is determined on gold or gold-nanostructured electrodes by cathodic preconcentration followed by an anodic stripping scan, commonly square-wave (SWASV) or linear-sweep (LSASV) [4,5]. The accumulated amount in a stirred or flowing sample under diffusion-limited deposition can be approximated by

$$\Gamma = \frac{D\,C\,t_d}{\delta}$$

where Γ is the surface excess (mol cm^{-2}), D the diffusion coefficient, C the bulk concentration, t_d the deposition time, and δ the diffusion-layer thickness. The stripping peak current then scales approximately with $nFA\Gamma$, which is why sensitivity can be raised simply by lengthening deposition. The same relation shows why a *20-minute total test* trades directly against deposition time and why unstirred dipping increases δ and lowers sensitivity.

Published SPCE arsenic sensors give an informative benchmark. A gold-nanoparticle/L-cysteine SPCE reached a limit of 0.91 µg/L with a 1–200 µg/L linear range, a 5.3% inter-assay coefficient of variation, 93.8–105.4% recovery in tap water, and agreement with ICP-MS; however, that work used a specific in-situ deposition and electrolyte protocol in water and tea samples [5]. A gold–platinum/polyaniline SPCE was characterized by SWASV for in-situ As(III) analysis [4]. Gold-nanostar-modified SPCEs achieved 2.9 µg/L for As(III) in a pH 9.5 buffer, with copper(II) codetection because Cu(II) produces an overlapping oxidation peak; mean recoveries were 87.7% (river water) and 83.2% (tap water) [6]. Two lessons follow. First, a 0.5 µg/L limit (the source target) is roughly a factor of two below the best retrieved SPCE value and about six times lower than the 2.9 µg/L value, so it is an *ambitious* target and not an established result. Second, arsenic stripping on gold typically requires an acidic or otherwise controlled electrolyte; the source does not explain how a bare dip into natural water would provide it. Copper interference is a documented problem [6], and India's groundwater matrices can contain iron, chloride and organic matter that foul gold surfaces. The arsenic channel should therefore be assumed to need on-board electrolyte conditioning (Figure 3; Flowchart 1) and a validated interference study.

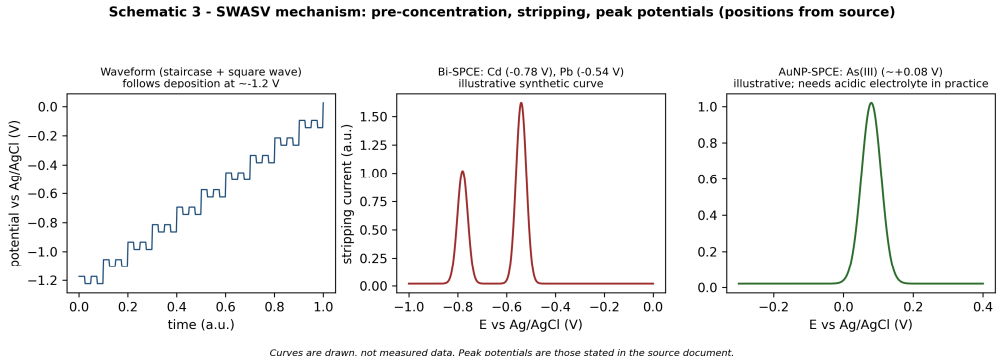


Figure 3 - SWASV principle: waveform and illustrative stripping peaks at the potentials stated in the source. The curves are synthetic illustrations, not measured data.

5.2. Lead and cadmium on bismuth-film electrodes

Bismuth films are the standard non-mercury alternative for Pb and Cd stripping. Published values vary widely and depend strongly on the electrolyte and deposition time. In situ bismuth/mercury films on SPCEs gave limits of 0.082 µg/L (Pb), 0.16 µg/L (Cd), 0.64 µg/L (Cu), and 0.97 µg/L (Zn) and agreed with ICP-MS, but that design includes a mercury component [7]. A bismuth/hydroxyapatite SPCE at pH 7.6 (close to natural-water conditions) had a Pb limit of 16.8 µg/L with 240 s deposition [8]. A Nafion–bismuth film on a screen-printed gold electrode, designed specifically to improve stability and reduce interference, achieved limits of 3 µg/L (Pb) and 4 µg/L (Cd) with linear ranges of 20–300 µg/L (Pb) and 50–300 µg/L (Cd) [9]. The spread (0.08 to ~17 µg/L for Pb) shows that near-neutral operation and polymer coatings tend to cost sensitivity.

The source claims 0.1 µg/L (Pb) and 0.05 µg/L (Cd) with a bismuth film *plus* a protective bilayer. The located evidence suggests that these values are achievable only in optimized, acidic-buffer, mercury-assisted, or long-deposition settings, and that the cadmium limit would need to be below the 3 µg/L guideline with a comfortable margin to be useful: the 4 µg/L Cd limit in [9] would not even meet the guideline, whereas the 0.16 µg/L limit in [7] would. Note also that bismuth films are typically deposited in situ from a Bi(III) solution, which requires a reagent source on the probe or a pre-plated, stability-limited film.

5.3. pH by iridium oxide

An iridium-oxide electrode responds to pH with a potential change that, for an ideal Nernstian electrode, is

$$E = E^0 - \frac{2.303\,RT}{F}\,\mathrm{pH} \approx E^0 - 59.16\ \mathrm{mV} \times \mathrm{pH} \quad (25\,^\circ\mathrm{C})$$

Hydrous iridium oxide films frequently show *super-Nernstian* or temperature-, oxidation-state-, and history-dependent slopes, and drift over days; this is general electrochemical knowledge not re-verified in this session. The source's "−59 mV/pH" is therefore an idealization. Because pH determines Pb/Cd/As stripping behavior and enzyme activity, an on-board temperature sensor and a calibration protocol are not optional, and the pH electrode shares a reference with the voltammetric channels, which raises the cross-talk question below.

5.4. Nitrate on copper

Copper and copper-modified electrodes reduce nitrate at low overpotential, which is why they dominate recent screen-printed nitrate sensors. The reported figures of merit are far below the guideline. An electrodeposited-copper sensor on a printed silver electrode reported a calculated limit of detection of 0.012 µg/L (0.207 nM) with a linear range of 0.05–5 mM, and negligible response to NO_2^-, Cl^-, SO_4^{2-}, HCO_3^-, Fe, Mn and Cu^{2+} at the concentrations tested, with tap and river water analyzed by standard addition [14]. A copper-nanowire array showed negligible interference except from chloride, which the authors removed by precipitation before measurement [15]. A carbon-black/poly(1,5-diaminonaphthalene)/copper-dendrite SPE gave a 0.28 µM limit over 1–175 µM, and its authors identify electrode stability and lengthy preparation as remaining challenges [16].

Three conclusions follow. (i) The source's 0.5 mg/L target corresponds to about 8 µM nitrate, which is *above* the sub-micromolar limits reported in the laboratory, so the sensitivity target itself is credible. (ii) The two retrieved studies that tested chloride disagree on its effect [14,15], so chloride must be checked in the actual probe geometry, particularly because Indian groundwater can be saline in some regions (a general-knowledge statement, not verified here). (iii) Stability and fabrication reproducibility, not detection limit, are the reported weak points [16]. The nitrate channel is therefore best classed as *plausible and requires validation of stability and chloride tolerance*. The source's use of the same SPCE chemistry alongside an Ag/AgCl reference also exposes copper electrodes to chloride-induced fouling, a risk that needs direct testing.

5.5. Enzymatic coliform and *E. coli* channels

The coliform channel relies on β-galactosidase (lacZ), which hydrolyses the substrate 4-aminophenyl-β-D-galactopyranoside (PAPG) to electroactive p-aminophenol (PAP); PAP is then oxidized at the carbon electrode (Figure 4), and the current is proportional to enzyme activity. This chemistry is well established, but published assays involve *incubation*: a river-water assay using gold interdigitated arrays detected 5×10^4 CFU/mL after 2 h and as little as 10 CFU/mL after 7 h of incubation, and reached 6×10^5 CFU/mL in 2 h when phage were used for enzyme release [P1]. A platinum-nanoparticle electrode reported a 20 CFU/mL limit in under 4 h [P3], and a MWNT/Nafion electrode detected 10–10^4 CFU/mL within 5 h [P2]. A conference abstract on an engineered phage with a β-gal gene reported about 10^5 CFU/mL at 3 h and 10^2 CFU/mL at 7 h in drinking water [12]. None of the retrieved sources report reaching 1 CFU/mL in 20 minutes.

The source's 1 CFU/mL / 20 min claim can be tested with a simple order-of-magnitude model. Assume a single coliform cell carrying about 3×10^3 active β-galactosidase tetramers (assumption A1) with a turnover number of about 100 s^{-1} (assumption A2) in a 0.5 mL chamber. Product formed in t seconds is

$$[\mathrm{PAP}](t) \approx \frac{N_{\mathrm{cells}}\, n_E\, k_{\mathrm{cat}}\, t}{N_A\, V}$$

which gives about 1.2×10^{-12} mol L^{-1} after 1200 s. A carbon-electrode amperometric PAP measurement is typically limited to the order of 10^{-7} mol L^{-1} or higher (assumption A3), five orders of magnitude greater. Detection therefore requires population growth: with a doubling time of around 20–30 min, it takes about 17 doublings (roughly 6–8 h) to reach roughly 10^5 cells, consistent with the 7 h in [P1]. A1–A3 are order-of-magnitude assumptions, not measurements; the conclusion (several orders of magnitude of amplification are needed) is robust to reasonable changes in them.

The regulatory indicator is also volumetric. Absence of *E. coli* in 100 mL corresponds to less than 0.01 CFU/mL, so even a true 1 CFU/mL detector would not meet the standard unless a concentration step (membrane filtration) is added, along with sampling statistics and time-to-detection. Two further calculations bear on the microbial claim. First, a chamber of volume V drawn from water with true concentration c (CFU/mL) contains no cell with probability.

$$P_0 = e^{-cV}$$

so at $c = 1$ CFU/mL and $V = 0.5$ mL, $P_0 \approx 0.61$: in about three of every five tests the chamber would hold no organism at all, however good the electrode. Second, if growth is required, the time to reach a detectable population N_d from N_0 organisms with doubling time t_d (ignoring lag) is

$$t = t_d \log_2\left(\frac{N_d}{N_0}\right)$$

Table 4 evaluates this for $N_d = 10^5$ cells (assumption A4, consistent with the 10^5 CFU/mL detected after about 3 h in [12]).

Table 4 - Illustrative incubation time (hours) to reach 10^5 cells, no lag phase. A modeling assumption, not a measurement.

Initial cells in chamber	t_d = 20 min	t_d = 30 min
1	5.5	8.3
10	4.4	6.6
100	3.3	5.0
1,000	2.2	3.3

Real assays include a lag phase and slower growth in nutrient-poor water, so these are lower bounds. They explain why a threshold-level contaminant (1 organism in 100 mL) cannot be reported in under 30 minutes by a growth-based enzymatic assay in any chamber of 0.5 mL: the expected cell count in the chamber is 0.005, and a concentration step such as membrane filtration of 100 mL would be needed before any incubation. The source's *E. coli* channel is described with a "MUGB" substrate; 4-methylumbelliferone is a fluorogenic reporter rather than a classical amperometric one, so the electrochemical read-out for the β-glucuronidase channel must be defined, for example using a PAP-type glucuronide analog.

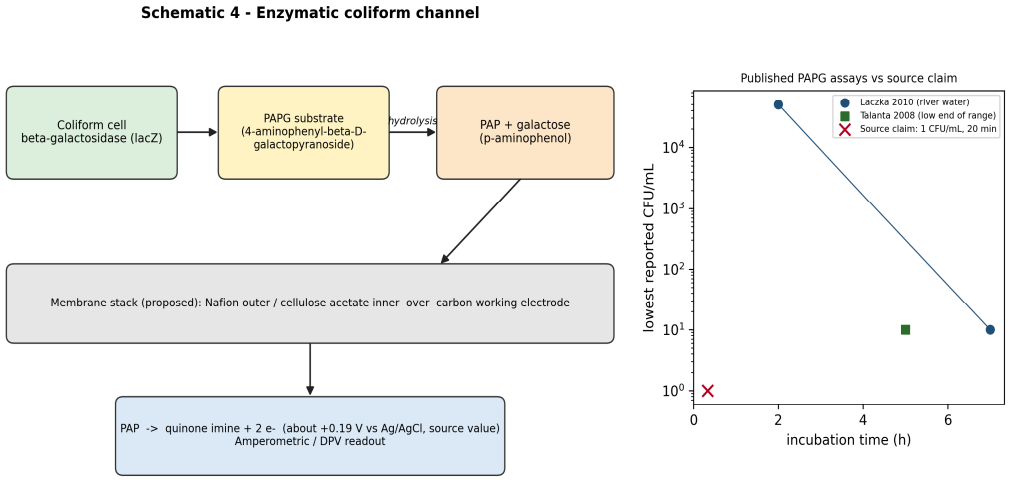


Figure 4 - Enzymatic coliform channel (left) and published time/limit data compared with the source claim (right). P1 and P2/P3 data predate 2015 and are flagged; the "source claim" marker is inherited and unsupported.

5.6. Multiplexing and cross-talk

Placing seven channels in one 0.5 mL volume introduces several risks that the source does not address: (i) metal deposition on one electrode depletes sample for neighbours; (ii) the Bi(III) used to plate bismuth films and Cu(II) released or present in nitrate chemistry interfere with arsenic stripping [6]; (iii) PAPG and its hydrolysis products can contaminate the stripping electrolyte; (iv) a shared reference and counter electrode couples all channels electrically; and (v) the incubation required for the microbial channel is incompatible with a 30-minute single-chamber workflow unless the channels are time-multiplexed or physically separated. Multiplexed electrochemical paper-based devices for heavy metals exist [10,11], but they address several *metals*, not metals, pH, and microbes together. The integrated design has not been demonstrated in the retrieved literature.

5.7. Fouling and membranes

Nafion (cation-exchange) and cellulose acetate (size exclusion) layers are widely used to reduce fouling by anionic species and large organics. The source claims they extend electrode lifetime "from hours to weeks". However, the retrieved evidence shows a *sensitivity cost* for polymer-coated stripping electrodes [9], and Nafion's cation-exchange behavior would favor transport of cationic metal ions but would hinder anionic nitrate. The source's description of PAPG as a cationic substrate favored by Nafion is not obviously correct, since PAPG is largely neutral at neutral pH. These should be tested, not assumed.

5.8. Electronics and IoT

The source proposes a power budget below 12 mW active and below 0.8 mW sleeping, a 5 W photovoltaic panel and a 2,500 mAh $LiFePO_4$ cell. A potentiostat running a multi-minute stripping sequence, a heater or pump (if any), and radio transmission rarely fit within a 12 mW envelope when duty cycle and radio transmission are included, so the budget must be recomputed from datasheet currents. No component datasheets were retrieved in the session, so the budget is "proposed, unvalidated" (Figure 5).

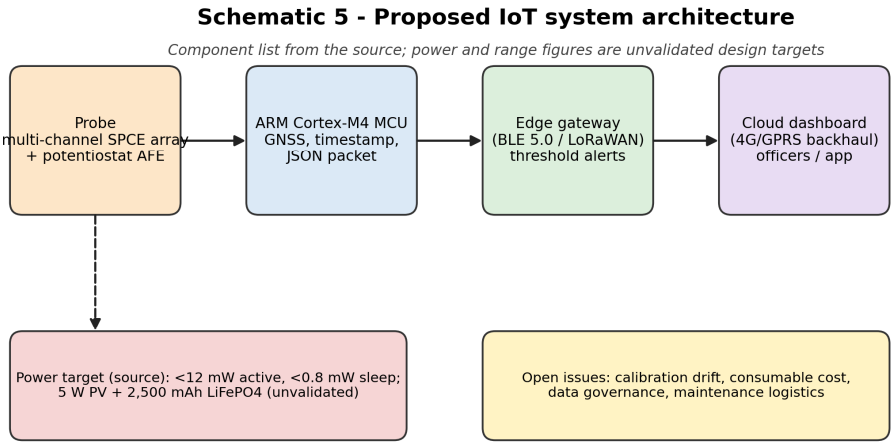
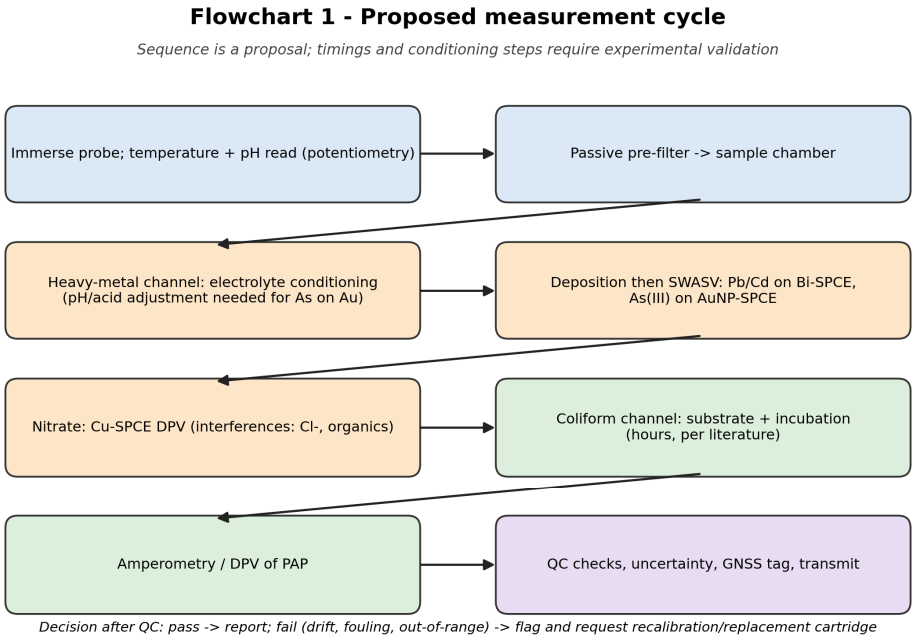


Figure 5 - Proposed system architecture; power and range figures are unvalidated design targets.

5.9. Measurement workflow

Flowchart 1 shows a measurement cycle consistent with the literature: conditioning before arsenic stripping, a separate incubation phase for the microbial channel, and a quality-control gate before transmission.



Flowchart 1 - Proposed measurement cycle (a proposal; each step requires validation).

5.10. Limit of detection and uncertainty

All performance numbers should be reported with a consistent definition of limit of detection,

$$\mathrm{LOD} = \frac{3.3\,\sigma_b}{S}$$

where σ_b is the standard deviation of the blank (or of the low-concentration response) and S the calibration slope; the source does not state which definition was used. Report limits in real matrices alongside recovery against an independent method such as ICP-MS, as in [5,7].

5.11. Decision rules and measurement uncertainty

A screening device is ultimately used to make a binary decision (above or below a guideline value L). With a combined standard uncertainty u on the reading, a guard-banded rule flags a sample as *non-compliant* when the reading exceeds $L - k\,u$ and as *compliant* only when it is below $L - k\,u$ by a stated margin, where k is a coverage factor (commonly 2 for roughly 95% coverage). Two consequences follow. First, a sensor whose limit of detection is far below L but whose uncertainty at L is, say, 30% will still produce frequent wrong decisions near the guideline, so uncertainty at the decision level should be reported alongside the limit of detection. Second, the reported recoveries in the retrieved studies (93.8–105.4% in tap water [5]; 83.2–87.7% in river and tap water [6]) are the kind of evidence that should accompany any device specification, because a systematic recovery of 83% would bias a decision at the guideline by 17% before any random error is considered.

5.12. Calibration, drift and quality control

Screen-printed electrodes are single-use or limited-life devices whose batch-to-batch variability and drift are the main practical barriers to field use. A realistic protocol would combine a factory batch calibration, an on-board standard-addition or internal-standard step for the voltammetric channels, a two-point pH calibration for the iridium-oxide electrode with temperature compensation, and a blank check before each test. Several retrieved studies use standard addition [14,7], which is time-consuming and adds directly to the test duration, conflicting with the source's 30-minute target. Quality-control logic (reject on abnormal blank, abnormal pH slope, saturated current, or reference-electrode drift) should be defined before software is written, since it determines which readings are ever transmitted.

5.13. Data, governance and cost framework

The source envisages probes across more than 600,000 villages feeding predictive epidemiological models. No evidence for the feasibility, accuracy, or health effect of such a network was retrieved, and the claim should be

read as an aspiration. Practical prerequisites include: a data-ownership and access policy for readings tied to named villages and GNSS positions; a rule for who is notified and what remediation follows an exceedance; calibration traceability so that readings are accepted by regulators; and consumable logistics for replacement cartridges. A cost assessment should be built bottom-up (cartridge materials, reagents, electronics, calibration, maintenance, data and personnel) and compared with the *cost per valid result* of existing field kits and laboratory tests; no such figures are available for this concept, and none are asserted here. Equally, no health benefit can be claimed until an intervention study links measurements to remediation and to outcomes.

5.14. Validation and standards pathway

Performance claims should be tested against accepted reference methods: ICP-MS or atomic absorption for metals (as done in [5,7,9]), laboratory pH and ion-selective or ion-chromatographic nitrate measurement, and standardized culture or enzyme-substrate methods for coliforms and *E. coli*. Studies should use certified reference materials; spiked and unspiked real waters from several hydro-chemical regimes; and report recovery, repeatability, reproducibility, limit of detection (with its definition), limit of quantification, linear range, selectivity, and robustness. Standards for laboratory competence (ISO/IEC 17025) and method validation apply if results are used for regulatory purposes; these are cited from general knowledge and should be checked.

6. Comparative analysis

Table 1 and Table 2 give the two core tables: the source specification mapped to evidence status, and the source's performance targets benchmarked against retrieved literature. Table 3 compares established methods with the proposed concept. Only qualitative statements are made about methods for which no source was retrieved.

Table 1 - Source specification and evidence status.

Item	Source statement	Evidence class	Comment
Probe form	Fluted polycarbonate cylinder, four vanes, ogive nose-cone	Inherited (ornamental)	Design-patent subject matter
Tier 1 windows	Three at 120°	Inherited	Four analytes assigned to three SPCEs
Tier 2 windows	Two, offset 60°	Inherited	Positions unspecified
Pre-filter	~50 µm passive	Proposed	Clogging and bypass not analyzed
Chamber volume	~0.5 mL	Proposed	Too small for 100 mL standard
Membrane	Nafion/CA bilayer	Proposed	Sensitivity cost expected [9]
Power	<12 mW active; 5 W PV; 2,500 mAh	Proposed	Unvalidated
Radio	BLE 5.0 / LoRaWAN	Proposed	Range not tested
Test time	<30 min	Requires validation	Conflicts with incubation [P1,P2,P3,12]

Table 2 - Source performance targets versus retrieved benchmarks.

Channel	Source target	Retrieved benchmark	Assessment
As(III)	0.5 µg/L	0.91 µg/L [5]; 2.9 µg/L [6]	Ambitious; protocol-dependent
Pb	0.1 µg/L	0.082 [7]; 3 [9]; 16.8 µg/L [8]	Depends on film, pH, deposition
Cd	0.05 µg/L	0.16 [7]; 4 µg/L [9]	Ambitious; guideline is 3 µg/L
pH	−59 mV/pH	Not retrieved	Idealised; calibrate
Nitrate	0.5 mg/L (~8 µM)	0.28 µM [16]; 0.207 nM (calculated) [14]	Sensitivity is credible; chloride and stability need testing.
Coliforms	1 CFU/mL, 20 min	10 CFU/mL in 7 h [P1]; 20 CFU/mL <4 h [P3]; 10^2–10^5 CFU/mL at 3–7 h [12]	Not supported by retrieved evidence
E. coli	1 CFU/mL	Same as above	Read-out chemistry undefined
Total time	<30 min	Hours for microbial channel	Not supported

Table 3 - Established methods versus the proposed concept (qualitative).

Method	Analytes	Strength	Main limitation	Field use	Evidence status
ICP-MS	Metals, As	Very low limits, multi-element	Cost, lab, turnaround	No	General knowledge
Atomic absorption	Pb, Cd, As (hydride)	Established, moderate cost	Lab, sample prep	Limited	General knowledge; used as reference in [9]
Laboratory ASV	Pb, Cd, Zn, Cu, As	Low limits, low-cost hardware	Needs electrolyte and skill	Partial	[5,7,9]
Colorimetric test kits (As)	As	Very simple	Semi-quantitative	Yes	General knowledge
Culture/membrane filtration	Coliforms, *E. coli*	Regulatory acceptance	18–48 h incubation	Partial	General knowledge
Enzymatic-electrochemical	Coliforms, *E. coli*	Electronic read-out	Hours of incubation	Possible	[P1–P3,12]
Paper-based multiplexed electrochemical	Several metals	Low cost, disposable	Not integrated with microbes	Yes	[10,11]
Copper-modified SPE nitrate sensors	Nitrate	Sub-micromolar lab limits	Stability, chloride [15,16]	Possible	[14,15,16]
Hydro-Core (concept)	7 channels	Integrated concept	No experimental data	Not shown	Inherited/proposed

No method is claimed to be superior; the concept's advantage, if any, would be integration and cost, which remain unquantified.

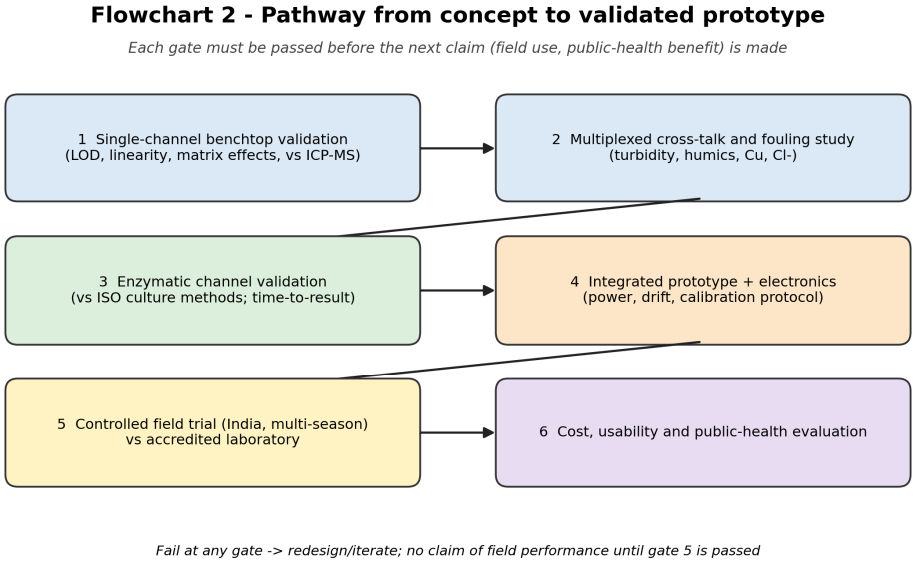
7. Design-patent scope: ornamental versus functional

A design patent protects the ornamental design of an article of manufacture as shown in its drawings, and it does not protect structural or functional features. In the Hydro-Core document, the ornamental candidates are the fluted housing, the ribbed collar, the shape of the vanes, the outline of the nose cone, and the visual arrangement of the windows. The *functional* aspects include the sensing chemistry, pre-filter, membrane stack, electronics, and data pipeline. This paper does not assess patentability, novelty, or infringement; those require a qualified patent attorney and a prior-art search. A practical consequence is that figures showing sensing internals (Figures 3–5) illustrate the *concept* and are not part of any design claim.

8. Research gaps and a pathway to a validated prototype

The principal gaps are: (i) no integrated experimental data; (ii) no demonstration of the arsenic channel in unconditioned natural water; (iii) no demonstrated time-to-result for the microbial channel below several hours; (iv) no interference or cross-talk study for seven channels in one chamber; (v) no calibration and drift strategy for the pH and nitrate electrodes; (vi) no cost model; (vii) no field protocol in Indian matrices.

Flowchart 2 sets out a gated pathway. Gate 1 validates each channel on the bench against ICP-MS and ISO culture methods. Gate 2 studies cross-talk and fouling in realistic matrices. Gate 3 isolates the enzymatic channel and honestly defines its time-to-result. Gate 4 integrates electronics. Gate 5 is a controlled field trial against an accredited laboratory; only after that should cost, usability, and public-health outcomes be evaluated.



Flowchart 2 - Validation pathway from concept to prototype.

9. Conclusions

The Hydro-Core concept combines established sensing principles, each individually plausible on screen-printed electrodes. The audit nonetheless shows that several of its headline numbers (0.5 µg/L arsenic in natural water, 1 CFU/mL in 20 minutes, weeks of membrane-protected lifetime, a 12 mW power budget) are not supported by the literature that could be retrieved, and that the integrated multi-channel architecture has not been demonstrated. The most credible next step is a staged validation (Flowchart 2) beginning with single-channel benchtop work, with the microbial channel redefined as a hours-scale assay or a filtration-plus-incubation module. Until that evidence exists, the concept should be described as a proposal.

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