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From laboratory to community: a perspective on colourimetric membrane sensor technologies for heavy metal monitoring in freshwater

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Heavy metal (HM) pollution continues to threaten freshwater ecosystems worldwide, disproportionately impacting low-resource communities where routine analytical monitoring is often absent. Despite advances in spectroscopy, electrochemical platforms, and automated sensing networks, regular monitoring of potential pollution events by local agencies remains constrained by high costs, specialised equipment, and the need for trained personnel. As a result, contamination events are frequently detected late—after ecological or public health damage has already occurred. Colourimetric sensing offers a complementary pathway toward decentralised early-warning systems. These sensors translate chemical information into visually interpretable colour changes, enabling rapid, inexpensive screening without laboratory infrastructure. In recent years, the field has seen a rise in bio-based membrane formats—cellulose, biopolymers, protein-derived films, and hybrid natural–synthetic composites—motivated by their sustainability, safety, and tunability. Yet their future impact will depend not only on analytical metrics but also on how well they fit into real-world monitoring ecosystems. This Perspective argues that the next decade of progress should be guided not solely by material innovation and continuously lower detection limits, but by a stronger focus on practical deployability, community integration, and environmental responsibility.

1. Introduction

Freshwater contamination by heavy metals (HMs) is no longer simply an environmental issue—it is a direct barrier to achieving global development goals, particularly SDG 6 (clean water and sanitation) and, by extension, SDGs 3 and 14. Yet despite decades of technological progress, large segments of the world still lack effective water quality surveillance. The problem is not merely scientific; it is structural. The global monitoring landscape remains dominated by costly, laboratory-dependent methods that do little for the communities most affected by HM pollution. In this context, continuing to focus on further development of traditional analytical methods while hoping for universal water safety is unrealistic.

HMs represent one of the most persistent and damaging classes of contaminants, with long-term ecological and human health consequences.[1–3] Their prevalence in the Global South is strongly tied to artisanal and small-scale mining (ASM)—a sector that, despite repeated formalisation efforts, continues to operate with minimal oversight. In many regions of Africa, Asia, and South America, artisanal gold mining is still the primary source of mercury entering freshwater systems.[4–6] Numerous studies have linked elevated HM concentrations in downstream waters and sediments to these unregulated practices.[7–10] Yet monitoring remains limited as those countries most affected by ASM-related pollution often lack the institutional capacity, funding, and infrastructure required for routine surveillance.[11]

The consequence is that communities are left unaware of the quality of the water they drink, cook with, and bathe in. Chronic and episodic contamination events go undetected.[12,13] Without timely information, neither communities nor local agencies can act. From a public health perspective, this represents a preventable exposure crisis. From a monitoring standpoint, it is a systemic failure.

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This is precisely where accessible, decentralised sensing technologies could shift the paradigm. Colourimetric sensors—often dismissed as "low-tech"—are, in fact, uniquely positioned to fill the monitoring gaps that high-end instruments cannot. They are low-cost, portable, intuitive, and fast.[14,15] More importantly, they can be embedded into community-led monitoring ecosystems, enabling real-time identification of water quality changes without dependence on distant laboratories.[16,17]

However, not every colourimetric system is appropriate for decentralised use. If these technologies are to have real-world impact, they must satisfy the ASSURED criteria (affordable, sensitive, specific, user-friendly, rapid/robust, equipment-free, deliverable), originally defined by the WHO, but arguably more relevant today for environmental sensing than they ever were for medical diagnostics. The environmental monitoring community has not sufficiently embraced this framework. ASSURED-compliant tools align naturally with participatory monitoring and citizen science, which have already demonstrated their value in increasing data coverage, empowering users, and contributing to SDG tracking.[16,18,19]

Within colourimetric technologies, solid-supported formats stand out as the most suitable for community deployment. They minimise reagent handling, improve stability, and reduce the risk of user error. Emerging research, such as Silva *et al.* (2022), underscores growing interest in accessible sensor formats for *in situ* monitoring,[20] while analogous work on emerging contaminants (*e.g.*, PFAS) highlights the universal need for low-barrier analytical tools.[21] Among solid supports, bio-based membranes represent one of the most promising yet under-evaluated platforms. They offer multiple functional advantages—immobilisation of chromophores, analyte pre-concentration, enhanced selectivity—and they do so use sustainable, low-cost materials.[22,23] Properly immobilised dyes are more stable, less prone to leaching, and better positioned to generate reliable colour transitions even in challenging environments.[24] Yet despite these advantages, the field lacks a clear comparative framework for assessing which membrane systems are genuinely fit for purpose.

This Perspective argues that such an evaluation is overdue. The literature has grown rapidly, but it remains fragmented, and the most crucial question—which bio-based colourimetric sensors can actually support community-level heavy metal monitoring? —has not been systematically addressed. Here, we provide the first comparative assessment of bio-derived membrane-based colourimetric sensors and offer a critical viewpoint on their strengths, limitations, and what the field must prioritise to translate laboratory prototypes into meaningful tools for environmental justice.

2. Analytical performance and practical relevance

2.1. Analytical performance

In the colourimetric sensing literature, analytical performance, with a particular focus on limits of detection (LoD), is frequently treated as the gold standard for success. Yet while reporting ever-lower LoDs has become a competitive academic exercise, it is worth asking how many of these values genuinely translate into field usability. Trace detection remains essential. Regulatory thresholds (Table 1) for Hg, Pb, and Cd fall in the low-ppb range, and their toxicity and bioaccumulation make early detection indispensable. However, many published LoDs are obtained under highly idealised laboratory conditions that bear little resemblance to the complexity of real water monitoring capacity and conditions. For example, studies such as Rakotondrabe *et al.* (2018) and Farouk *et al.* (2022) demonstrate that HM concentrations in natural waters frequently occur in the ppb range.[25,26] This underscores the need for high sensitivity while at the same time exposing a major gap: a sensor achieving low LoDs in clean buffers does not guarantee adequate performance in real environmental conditions.

Selectivity remains a persistent weak point. Natural waters contain an abundance of potentially interfering ions, many of which can trigger false positives or alter the intensity of colour transitions. Yet in much of the literature, interference testing is superficial at best, often limited to a handful of ions at unrealistic concentrations. Tailored ligands, metal-selective chelators, or nanoparticle surface modifications offer partial solutions,[27–29] but the field has yet to develop a standardised framework to rigorously evaluate selectivity across physiochemical regimes. Until it does, claims of "high specificity" should be treated with caution.

2.2. Applicability

If analytical performance is the strongest aspect of current research, practical applicability is undoubtedly the weakest. Many sensors that perform well in the lab are not validated

Table 1 Hazardous metals quality standards set by the water framework directive (WFD) and the WHO drinking water guideline values. (1) Annual allowed – environmental quality standards; (2) maximum allowed concentration – environmental quality standards

Metals/compounds	CAS number	AA-EQS$^{(1)}$ (ppb) inland surface waters (WFD)	MAC-EQS$^{(2)}$ (ppb) inland surface waters (WFD)	WHO drinking water guideline values (ppb)
Cadmium and its compounds	7440-43-9	0.08–0.25[a]	0.45–1.5[a]	3
Lead and its compounds	7439-92-1	7.2	Not reported	10
Mercury and its compounds	7439-97-6	0.03	0.06	5
Nickel and its compounds	7440-02-0	20	Not reported	70

[a] Concentration limits depend on water hardness

under real-world conditions, in particular, in countries where decentralised monitoring is required, and where community pollution event monitoring presents an opportunity for early warning.

For adoption in low-resource settings, colourimetric sensors must be truly intuitive, safe to handle, and operable without specialised equipment. This requirement is not optional; it is fundamental to closing data gaps in environmental monitoring.[30] Smartphone-based platforms such as those demonstrated by Li *et al.* (2023) show promise,[31] but their dependency on consistent lighting, camera quality, and app calibration complicates deployment by non-experts.

Response time is another critical issue. In early-warning contexts, minutes matter. While many sensors claim rapid responses, these metrics rarely account for the realities of field deployment in tropical climates, complex transport times, and poor storage conditions. Studies such as Ateia *et al.* (2024) highlight the urgent need for robust approaches and extended shelf life,[32] yet only a minority of current systems demonstrate meaningful durability. Solid reagents and encapsulation approaches can improve robustness[33,34] but these techniques are still under-adopted in membrane-based colourimetric platforms.

Environmental variability further complicates sensor performance. Sensors must contend with turbidity, natural water colour, dissolved organic matter (chromophoric dissolved organic matter), and high background iron common in mining-impacted rivers, which can alter colourimetric responses and reduce sensitivity.[31–34] Fluctuations in temperature and sunlight exposure during storage can further challenge robustness.[33,34] Inconsistent lighting for visual readouts can compromise reproducibility.[17] Successful community monitoring requires sensors that are resilient to complex environmental matrices, simple to use, and compatible with non-specialist deployment. Smartphone-integrated platforms, as demonstrated in other citizen science programs, can partially mitigate these challenges by standardizing colour interpretation and enabling immediate data capture.[16,31] Real-world programs, including freshwater watch, show that citizen scientists can collect reliable, spatially and temporally dense datasets when sensors are designed with these constraints in mind.[18] Incorporating these considerations into membrane-based HM sensor development will be critical for translating laboratory prototypes into deployable tools for early-warning, community-based monitoring.

2.3. Sensor materials (strengths, weaknesses and trade-offs)

2.3.1. Biopolymeric membranes. Bio-based membranes represent an attractive platform for colourimetric sensing due to their sustainability, low-cost, and potential for functionalisation. Cellulose remains the archetypal example due to its abundance, biodegradability, and chemical tunability.[35–37] Its porous network and hydroxyl-rich surface make it ideal for chromophore immobilisation. Raw cellulose can be sourced from cotton, wood pulp, or recycled paper.[38] Promising applications, such as the cotton-linter films by Zhang *et al.* (2020), illustrate how accessible these materials can be.[39] Yet despite these advantages, cellulose membranes have clear limitations: poor mechanical strength, susceptibility to swelling and degradation, and limited operational longevity in potentially complex field conditions which are rarely addressed in the literature.

Polymer blending attempts to overcome some of these weaknesses. By combining biopolymers with more robust materials, blends such as pectin/PVA membranes show improved mechanical stability, but at the cost of higher fabrication complexity and reduced biodegradability.[40,41] Electrospinning, while powerful, suffers from similar contradictions: nanofibre mats provide unparalleled surface area and tunable porosity,[42,43] yet electrospinning equipment remains expensive and technically demanding, challenging the very notion of "low-cost sensors".

These trade-offs underscore a central point: no membrane fabrication method is universally optimal, and material choice should be guided by realistic deployment constraints and addressed explicitly in development perspectives.

2.3.2. Chromophores. Chromophore selection is another area where competing priorities collide, stability *vs.* sustainability, sensitivity *vs.* safety. Synthetic dyes such as dithizone, PAN, TAN, and PAR remain dominant because they offer strong colour shifts, good stability, and well-understood coordination chemistry.[44–47] Dithizone's intense complexation with Pb^{2+} and Hg^{2+},[46] and azo dyes' robust chelation mechanisms, make them reliable choices for achieving ppb-level detection. Victoria blue B, despite its narrower pH applicability, provides excellent binding to cellulose membranes *via* hydrogen bonding and forms stable complexes with cadmium species.[48–50] These examples highlight how synthetic chromophores remain integral to high-performance sensors.

Natural dyes offer compelling sustainability benefits but seldom match the robustness of synthetic counterparts. Curcumin's affinity for Fe^{2+}/Fe^{3+} and its Lewis acid–base coordination behaviour make it attractive, yet its stability is limited.[51–53] Anthocyanins, sourced from plant materials, provide striking pH-sensitive colour transitions in relation to their flavylium ring, responsible for their colour-changing properties.[54,55] However, they are notoriously susceptible to photodegradation and require careful immobilisation.

Ultimately, there is no universal chromophore "best choice". The most appropriate chromophore depends on the target metal, environmental conditions, required lifetime, and safety constraints—factors often underreported in sensor publications.

2.3.3. Immobilisation. Immobilisation governs key practical aspects of membrane-based sensors, including response time, stability, colour intensity, and resistance to leaching. Yet it remains one of the most inconsistently described and poorly optimised determinant of sensor performance. Physical immobilisation (*via* hydrogen bonding, van der Waals forces, or electrostatic interactions) is simple and low-cost,[56,57] but prone to dye leaching,[58] especially under variable pH or prolonged immersion. For any sensor intended for community use, such instability creates challenges.

Chemical immobilisation provides superior robustness through covalent attachment, typically using crosslinkers such as glutaraldehyde or carbodiimides.[59] However, these agents raise toxicity concerns and require controlled reaction conditions. "Green" crosslinkers like genipin and citric acid represent a promising alternative, though their uptake remains minimal.[60,61] The demonstrated improvements in durability for glutaraldehyde-fixed dithizone systems make clear that chemical immobilisation is the more reliable route for long-term use.[46,62]

Current studies should treat immobilisation as a major experimental focus as, from a practical deployment perspective, it is one of the most decisive factors determining whether a sensor can be used outside the laboratory.

3. Criteria for comparative analysis

Despite rapid growth in publications on colourimetric membrane sensors, the field remains inconsistent on how to evaluate progress. Many studies continue to report performance metrics that are only loosely tied to real-world freshwater monitoring needs. To cut through this noise, we focus only on studies that reflect the essential characteristics of deployable sensor systems: (i) biopolymer-based substrates rather than purely synthetic films; (ii) immobilised chromophores rather than solution-phase assays; (iii) heavy metal ions as target analytes; (iv) colourimetric detection rather than spectroscopic; and (v) performance testing in aqueous environments. In total, 17 studies met the minimum threshold, suggesting that progress is more exploratory than application driven (Table 2).

To strengthen transparency, we applied a quantitative rationale to the comparative framework. Thresholds for colour-coded scoring were defined based on internationally recognised standards for heavy metal limits in freshwater (*e.g.*, WHO, EPA) and operational requirements for field monitoring. For sensitivity, "green" was assigned to sensors achieving LODs in the low-ppb range because these values fall below or within the regulatory limits for key metals such as Pb, Cd, and Hg, ensuring that early-warning detection is feasible. "Yellow" corresponds to upper-ppb values that may detect pollution events but would miss sub-acute contamination, while ppm-level LODs were deemed "orange" because they cannot detect environmentally relevant concentrations. A <10 min response-time threshold was used to reflect the operational need for near-real-time decision-making in community-based monitoring, with the trained citizen scientists performing measurements in the field. Sensors requiring >1 h make monitoring for rapid screening less effective. Working pH ranges were benchmarked against

Table 2 Publications reviewed involving the use of biopolymer-based membrane for colourimetric detection of HM ions

Biopolymer-based membrane	Chromophore	Target HM ion	Lowest detected concentration (ppb)	Colour change	Ref.
Cellulose/PAN composite films	PAN	Zn^{2+}	100	Scarlet to lighter red	39
Cellulose acetate/chitosan	Dithizone	Cu^{2+}	200	Blue-green to brown	46
		Zn^{2+}	2000	Blue-green to red-violet	
		Hg^{2+}	100	Blue-green to copper	
		Pb^{2+}	100	Blue-green to pink	
	PAR	Pb^{2+}	3000	Yellow to pinkish yellow	
Cellulose	VBB	Cd^{2+}	10	Yellow to blue-green	50
Polyamide-6/nitrocellulose nanofiber/nanonet membrane	Anthocyanin (red cabbage)	Fe^{3+}	1000	Light pink to dark pink	55
Cellulose acetate	Dithizone	Hg^{2+}	3000	Green to orange	57
Cellulose acetate/chitosan	Dithizone	Hg^{2+}	1000	Red to pink	62
		Cu^{2+}		Red to yellow	
		Zn^{2+}		Red to white	
Cotton thread modified with a chitosan membrane	PAR	Co^{3+}	6.5	Yellow to red-purple	63
Cellulose filter paper	Zincon	Ni^{2+}	6	Blue to pink/grey	64
Cellulose acetate nanofibers	Curcumin	Pb^{2+}	4000	Yellow to orange	65
Carboxymethyl tamarind gum/polyacrylamide hydrogel matrix	m-BPDM	Hg^{2+}	500	Pinkish red to dark blue	66
		Zn^{2+}	1000		
		Cd^{2+}	2000		
Chitosan fibers functionalized with porphyrin	TCPP	Hg^{2+}	2000	Brown to yellow-green	67
Cellulose paper strips impregnated with chitosan nanoparticles	Cyanidin (red cabbage)	Fe^{3+}	10 000	White to pink	68
Cellulose	Lysine-bis-Schiff base	Hg^{2+}	10	White to yellow	69
Curcumin-loaded zein nanofibers	Curcumin	Fe^{2+}	400	Yellow to brown	70
Starch-amylopectin-polyvinyl alcohol film	Anthocyanin (black rice)	Cu^{2+}	1390	Red to green	71
Polyaspartic acid electrospun nanofiber hydrogel	PASP	Cu^{2+}	300	White to blue	72
		Fe^{3+}	100	White to yellow	
Bovine serum albumin gold nanoparticles	BSA-Au NPs	Pb^{2+}	41	Pink to clear pink	73

the typical range for river environments (pH 6–8), to distinguish between broadly deployable sensors (green) and those requiring narrow or less realistic conditions (orange). Stability categories were set based on realistic storage expectations for low-resource settings where refrigeration is rarely available; only sensors maintaining >40 days of stability at room temperature were considered operationally "mature" (SI S1).

To ensure comparability across heterogeneous studies, we weighted each criterion equally. This choice reflects the absence of consensus regarding which performance dimension is most important for deployment—sensitivity, selectivity, material sustainability, and stability all represent distinct constraints on real-world applicability. Unequal weighting would have risked imposing subjective priorities that do not apply across deployment contexts. Laboratory-only performance metrics were normalised against environmental applicability by explicitly separating "analytical performance" (sensitivity, selectivity) from "applicability" (pH range, response time, stability) and "safety/environmental impact" (chromophore toxicity, membrane biodegradability, immobilisation chemistry). This allowed a sensor to score highly in controlled analytical conditions while still being penalised for instability or narrow operational conditions. By making these quantitative and context-based thresholds explicit, our comparative analysis remains reproducible while we acknowledge that any framework necessarily simplifies a diverse methodological landscape. Nonetheless, this structured approach enables clearer identification of technologies with genuine translational potential for community-based heavy-metal monitoring. Furthermore, these criteria expose the essential trade-off that needs to be acknowledged: the best-performing sensors analytically are not always the safest or most practical, and the most sustainable designs often underperform analytically. This trade-off is the central bottleneck for translating research into practical application.

3.1. Analytical performance

Across the selected studies, sensitivity and selectivity varied dramatically (Table 3). Some methods reach environmentally meaningful LoDs, in particular the Co^{2+} LoD of 6.5 ppb reported by Suarez *et al.* (2020) and the Ni^{2+} LoD of 6 ppb reported by Li *et al.* (2017).[63,64] However, many LoDs do not reach regulatory thresholds, which may still be useful for prolonged contamination events but are insufficient for earlier warning of pollution events, typically where intervention is still possible.[65–67]

A dominant weakness across the literature is the use of laboratory-prepared ion solutions to assess selectivity. This practice continues despite the potential for a range of interferents in typically complex natural waters. A sensor that "selectively detects Pb^{2+}" in ultrapure water may behave very differently in water containing natural dissolved organic matter (*e.g.* humic matter), variable ionic strength, or competing cations at environmentally relevant ratios. Only a minority of studies (*e.g.*, Azmi *et al.* (2017), Li *et al.* (2017), Zhang *et al.* (2021)) tested using field obtained freshwater samples, and even these rarely examined seasonal or geochemical variability.[62,64,69]

Table 3 Analytical performance evaluation, with each property assigned to three levels of appropriateness for community-based monitoring of HM pollution in freshwater ecosystems, evaluation assigned orange (lowest) to average (yellow) to highest (green), based on common criteria (SI, S1)

Reference	Target HM ion 2and sensitivity	Selectivity and interferences
39	🟡	🟢
46	🟠	🟡
50	🟡	🟢
55	🟡	🟡
57	🟠	🟡
62	🟠	🟡
63	🟢	🟡
64	🟡	🟢
65	🟠	🟢
66	🟠	🟡
67	🟡	🟢
68	🟠	🟡
69	🟢	🟢
70	🟡	🟢
71	🟠	🟡
72	🟡	🟡
73	🟡	🟡

Selectivity challenges were common but often under-acknowledged. For example, El-Naggar *et al.* (2021) and Khattab *et al.* (2022) observed strong interference from Al^{3+} and Cu^{2+} when targeting Fe^{3+}, while Suarez *et al.* (2020) mitigated Fe^{3+} interference only through chemical masking, raising questions about field practicality.[55,63,68] These are not minor issues: many of the interferents reported are ubiquitous in ecosystems where mining activities occur.

Finally, few studies addressed the impact of natural organic matter or salinity, despite their ubiquitous presence in riverine, estuarine, and tropical systems. Dissolved organic matter can potentially mask colour changes or, more importantly, compete for binding, yet its effect remains largely unquantified. Salinity is almost entirely ignored, limiting the use of these methods in estuarine or saline intrusion areas.

3.2. Applicability

While analytical performance receives the bulk of attention, the criteria that matter most for practical deployment—response time, functional pH window, and storage stability—are often treated as afterthoughts or omitted entirely (Table 4).

Response time. Only seven studies achieved rapid responses (<10 min), with a few reporting exceptionally fast sensing (5 seconds in Ma *et al.* 2024; Khattab *et al.* 2022; El-Naggar *et al.* 2021).[55,67,68] Several sensors require hours to reach stable signals. Other studies provided no response time data, making it impossible to explore their use with real-world monitoring, where users need timely interpretation, not laboratory-style incubations.

Working pH range. Most freshwater environments range between pH 6–8, while many sensors were shown to operate in narrow or unrealistic pH conditions. Several studies require pH < 3 (*e.g.*, Saithongdee *et al.* 2014), rendering them unsuitable for direct field use.[70] Others fail to report pH tolerance entirely, which is a critical information gap, given that pH shifts can alter both chromophore ionisation and membrane integrity.

Stability and storage. Long-term stability is arguably one of the most important parameters for community-based monitoring in remote areas, yet it is only rarely reported. Sensors with meaningful stability were reported to be 40 days at room temperature (Zhang *et al.* 2021), 60–90 days under dry conditions (Low *et al.* 2022; Azmi *et al.* 2017).[46,62,69] Several methods reported requirements of controlled-light or controlled-temperature storage, while others simply provided no stability assessment at all.

Affordability and scalability. Cost pathways are conspicuously absent from reporting despite being a decisive factor for adoption in low-resource settings. Material costs range from negligible (cotton linters, recycled cellulose) to prohibitive (electrospun nanofibers requiring specialized equipment). For instance, Suarez *et al.*, 2020 outlined that their chitosan-modifeid cotton threads systems costs less than 0.01€ per device.[63] Chromophore expenses vary similarly: commercial dyes like PAN are widely available and inexpensive, while custom-synthesized ligands may cost orders of magnitude more. Fabrication requirements further impact scalability. None of the reviewed studies provided cost-per-test estimates or manufacturing cost breakdowns, which made it impossible to compare economic viability.

If colourimetric membrane sensors are to have any community-level impact, stability, operability, scalability and flexibility must be viewed as primary design goals, not accessories.

Table 4 Applicability evaluation, with each property assigned to three levels of appropriateness for community-based monitoring of HM pollution in freshwater ecosystems, evaluation assigned orange (lowest) to average (yellow) to highest (green), based on common criteria (SI, S1)

Reference	Time of response	Working pH range	Stability and shelf life
39	🟡	🟡	🟡
46	🟢	🟡	🟢
50	🟢	🟠	🟡
55	🟢	🟡	🟢
57	🟠	🟡	🟠
62	🟢	🟡	🟢
63	🟡	🟡	🟠
64	🟡	🟡	🟡
65	🟠	🟡	🟠
66	🟡	🟢	🟠
67	🟢	🟢	🟡
68	🟢	🟡	🟠
69	🟡	🟡	🟢
70	🟡	🟠	🟠
71	🟠	🟢	🟡
72	🟢	🟢	🟢
73	🟠	🟡	🟡

3.3. Safety and environmental impact

Ensuring user safety is a crucial consideration for sensors intended for use by non-expert individuals. An equally important safety consideration is the evaluation of their environmental impact, including factors related to their use and disposal (Table 5). A number of important trade-offs emerged in the present state of the art.

Chromophores: performance *vs.* eco-friendliness. Natural chromophores (anthocyanins, curcumin) appear attractive from a sustainability standpoint but consistently fail to reach useful LoDs. Conversely, widely used synthetic dyes (PAN, TAN, dithizone) provide excellent performance but can introduce toxicity or persistence concerns. The exception is 4-(2-pyridylazo) resorcinol (PAR), a widely used chromophore that forms coloured chelates with metal ions and is used in both UV-vis and titration methods. PAR combines good performance with relatively low toxicity but remains surprisingly underused relative to alternatives.

Membranes: bio-based *vs.* biodegradable. Some membranes are fully biopolymeric (cellulose acetate, chitosan, zein), yet many "bio-based" sensors incorporate synthetic co-polymers or stabilisers that reduce biodegradability. Membranes composed entirely of biodegradable and eco-friendly materials would be most appropriate. For example, Raj & Shankran (2016) used curcumin-loaded cellulose acetate nanofibers, while Azmi *et al.* (2017) utilized a cellulose acetate/chitosan blend membrane.[62,65] Saithongdee *et al.* (2014) employed electrospun curcumin-loaded zein nanofibers derived from maize.[70] Other membranes used a combination of bio-based and synthetic materials, which strengthened membrane properties but reducing their biodegradable potential. This reflects a common design paradox: improving mechanical robustness often makes the material less sustainable.

Immobilisation: robustness *vs.* environmentally safety. Chemical immobilisation frequently relies on aldehydes, carbodiimides, or other reactive crosslinkers. While robust, these approaches often introduce toxic reagents. For instance, Ma *et al.* (2024) employed carbodiimide hydrochloride and *N*-hydroxysuccinimide to graft a porphyrin-based chromophore onto a chitosan structure.[67] Yadav *et al.* (2025) used m-BPDM as a cross-linking agent, while Zhang *et al.* (2019) immobilised PASP through hydrolysis and cross-linking of poly(succinimide).[66,72] These techniques, while effective, raise concerns about environmental and user safety. Only a few studies explored greener alternatives (*e.g.*, genipin, citric acid). Physical immobilisation methods, which generally require fewer toxic reagents, provide an eco-friendly alternative but result in

Table 5 Safety and environmental impact evaluation, with each property assigned to three levels of appropriateness for community-based monitoring of HM pollution in freshwater ecosystems, evaluation assigned orange (lowest) to average (yellow) to highest (green), based on common criteria (SI, S1)

Reference	Chromophore type	Membrane composition	Immobilisation technique
39	🟠	🟡	🟡
46	🟠	🟢	🟡
50	🟠	🟢	🟡
55	🟢	🟡	🟠
57	🟠	🟢	🟡
62	🟠	🟢	🟠
63	🟡	🟢	🟡
64	🟠	🟡	🟡
65	🟢	🟢	🟢
66	🟠	🟡	🟠
67	🟠	🟢	🟠
68	🟢	🟢	🟡
69	🟠	🟢	🟠
70	🟢	🟢	🟡
71	🟢	🟡	🟢
72	🟠	🟡	🟠
73	🟠	🟡	🟠

less stable interactions between the chromophore and the membrane. Zhang *et al.* (2020) immobilised a chromophore onto regenerated cellulose films *via* a physical soaking process in an ethanol-dye solution, forming dye/cellulose composite films.[39] Low *et al.* (2022) avoided toxic reagents by using a membrane-dipping technique to immobilise dithizone.[46] Physical immobilisation methods align better with the principles of green chemistry but remain vulnerable to dye leaching. Robust immobilisation without toxic reagents is currently an unsolved challenge, yet it is crucial for sensors intended for widespread field use and environmentally safe disposal.

4. Outlook

Rapid, low-cost colourimetric sensors have the potential to transform HM monitoring in freshwater systems, particularly in low-income countries where inadequate laboratory infrastructure remains a critical bottleneck and illegal mining is in expansion. By enabling community-driven early warning, such sensors could support national monitoring programmes, facilitate rapid intervention, and ultimately reduce the ecological and human health impacts of chronic HM exposure. Our assessment reveals that the development to meet this challenge remains fragmented, inconsistent in its evaluation standards, and still far from delivering deployable, sustainable sensing systems. However, our analysis also shows a pathway for inserting these technologies into existing community-based monitoring infrastructures. Programs such as freshwater watch and regional citizen-science networks in Africa and Latin America already operate with simple, colour-based kits for nutrients and turbidity, and have demonstrated that volunteers supported with structured training, smartphone reporting, and periodic quality assurance can generate high-quality, policy-relevant data.[18,19] Membrane-based colourimetric HM sensors with rapid visual endpoints, ambient-temperature stability, and safe handling properties could be integrated into these same workflows with minimal modification. Their use would expand community monitoring into parameters that currently remain inaccessible without laboratory support, particularly in mining-affected catchments where high iron backgrounds, turbidity, and dissolved organic matter are often present. Field-ready HM sensors could therefore enable communities to detect rainfall driven flushing event, identify hotspots missed by sparse government sampling, and trigger early notification to water authorities. Embedding these sensors within existing citizen-science pipelines would not only enhance spatial and temporal coverage in low-resource regions, but also create an operational testbed for continuous validation, calibration, and long-term performance assessment under real environmental conditions.

A central finding of this perspective is that current research overwhelmingly optimises some key aspects while overlooking others. Sensors that achieve outstanding ppb-level detection limits often rely on synthetic chromophores, toxic cross-linkers, or narrow working pH windows that limit real-world applicability. Conversely, sensors using eco-compatible materials, natural dyes, and physical immobilisation methods demonstrate improved sustainability but frequently suffer from poor stability, suboptimal LoDs, and limited selectivity. This persistent trade-off between performance and eco-friendliness is the core barrier preventing translation from laboratory to actual real-world applications.

Our analysis also highlights an important information gap, typically ignored in the literature: cost. Only one of the studies reviewed provide costed pathways for manufacturing, distribution, or maintenance. This omission is particularly problematic because sensors are most urgently needed in regions where financial constraints dictate the feasibility of adoption. Without cost transparency, even technically promising sensors risk becoming academic artefacts rather than usable technologies.

Despite this, several studies demonstrate the potential for colourimetric membrane sensors to achieve measurement accuracy, with detection limits suitable for early-warning applications. Sensors with fast response times, broad pH operability, and long-term dry storage stability represent credible candidates for community-based monitoring programmes. However, these strengths remain uneven across the literature, and real-water validation remains the exception rather than the norm. The path from promising prototypes to globally deployable tools is best understood through the lens of the ASSURED framework. Colourimetric membrane sensors inherently satisfy some of these criteria: they are equipment-free, visually interpretable, and potentially low-cost at scale. Yet our comparative analysis shows that full ASSURED compliance remains elusive. Affordability and user-friendliness remain unknown due to unquantified production costs; sensitivity and specificity are often not tested outside controlled laboratory conditions; robustness is undermined by limited shelf-life and vulnerability to pH, turbidity, and temperature swings; and deliverability is constrained by chemical immobilisation and non-biodegradable substrates. Embedding the ASSURED criteria directly into the design and evaluation of next-generation sensors would therefore shift the field away from narrow optimisation toward solutions genuinely usable by communities and water authorities in low-resource, mining-affected regions.

To move beyond incremental advances, the field must redefine what constitutes "performance". Deployability, robustness, environmental safety, and affordability must be treated as primary design criteria, not secondary considerations to sensitivity. Real progress will only occur when sensors are tested in complex natural waters that reflect characteristic of tropical and mining-impacted systems, where dissolved organic matter, salinity, turbidity, and competing ions routinely challenge sensor reliability. We identified three priorities that will determine whether colourimetric membrane sensors remain promising prototypes or become reliable tools for community-based water monitoring:

1. Validation in real freshwater environments, including field trials in diverse and challenging environments where sensors must perform without idealised laboratory conditions.

2. Integration of bio-based materials to enhance sustainability, reduce toxicity, and support safe end-of-life disposal.

3. Development of green, non-toxic immobilisation chemistries that provide stability without relying on hazardous cross-linkers.

Progress along these axes will strengthen sensor maturity, improve readiness for deployment, and support the creation of low-cost, user-friendly early-warning systems. If these challenges are met, colourimetric membrane sensors could play a decisive role in democratising water quality monitoring and empowering communities to detect, mitigate, and prevent heavy-metal pollution in vulnerable freshwater environments.

Author contributions

AP: conceptualization, investigation, writing – original draft; AB: methodology & validation; RGC and XL: visualization & data curation; LG and FR: writing – review and editing & supervision; ABK and MSR: conceptualization and investigation; SAL: writing – review and editing, conceptualization & project administration

Conflicts of interest

There are no conflicts to declare.

Abbreviation

HM	Heavy metal
LoD	Limit of detection
PVA	Polyvinyl alcohol
PAN	1-(2-pyridylazo)-2-naphthol
TAN	1-(2-thiazolylazo)-2-naphthol
PAR	4-(2-pyridylazo)-resorcinol)
VBB	Victoria Blue B
m-BPDM	*N*,*N*′-methylenebisacrylamide
TCPP	Tetrakis(4-carboxyphenyl)porphyrin
PASP	Poly(aspartic acid)
BSA-Au NPs	Bovine serum albumin gold nanoparticles

Data availability

All data used in this study are derived from previously published studies cited in the manuscript. No new data were generated or analysed in this work. All relevant data are available in the original publications as referenced.

Supplementary information (SI) is available. See DOI: https://doi.org/10.1039/d5sd00172b.

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