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Unlocking the global benefits of Earth Observation to address the SDG 6 *in situ* water quality monitoring gap

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Achieving Sustainable Development Goal 6 requires innovative and often disruptive approaches to address critical gaps in global water quality monitoring. The most recent SDG Indicator 6.3.2 *(Proportion of bodies of water with good ambient water quality)* progress report highlights a critical water quality *in situ* data gap, with an urgent need for countries to strengthen their monitoring capacity and commence state water quality assessments and trend analysis. Earth Observation (EO) technologies hold immense potential to close that gap for SDG Indicator 6.3.2. However, limited awareness, lack of skills and resource inequalities are some of the barriers which hinder widespread adoption of EO. We present insights from a unique workshop held at the University of Stirling in 2024, which convened diverse participants from academia, industry, NGOs, and international agencies and across disciplines, geographies, and sectors. Through creative and collective thinking approaches, they developed four actionable concepts: (1) Space Buzz: a media campaign to raise awareness of EO value; (2) centralised EO access hubs to empower users and improve equality; (3) scalable education strategies for capacity building; and (4) an Intergovernmental Panel for Water Quality to enhance global coordination. Each concept derived from a synoptic creative process, demonstrating the uniqueness of thinking within the teams. To unlock the potential of EO for global water quality monitoring, we invite EO networks, funders, water resource managers and individuals to champion these concepts, and incorporate them into funding calls and proposals.

KEYWORDS

water quality remote sensing, hackathon, water quality monitoring, innovation, Sustainable Development Goal

1 Introduction

Good ambient water quality is vital to human and ecological health. Poor quality water adversely impacts public health, agricultural yield, food security, biodiversity and economic stability, exacerbating inequalities and limiting efforts to address climate change (Fuller et al., 2022; Plessis, 2022; WMO, 2024). Ensuring adequate and accessible means to monitor environmental change is critical to tracking progress towards the United Nations 2030 Agenda for Sustainable Development. This is inherently reflected in the United Nations Sustainable Development Goal (SDG) Target 6.3: by 2030, to halve the proportion of untreated wastewater and substantially increase recycling and safe water reuse globally.

The latest progress report on the SDG Indicator 6.3.2, which measures progress in ambient water quality (UNEP, 2024), highlighted stark trends. More countries now report on this indicator compared to previous years, but just 3% of *in situ* data came from the lower income half of the world. Consequently, an estimated 4.4 billion people currently rely on unmonitored water bodies, underscoring a need for alternative water quality monitoring approaches complementary to *in situ* measurements and which enable more country-level participation and reporting globally.

Remote sensing technologies, particularly optical sensors onboard satellites, have significant capacity to support water quality monitoring, management, and addressing data gaps (Tyler et al., 2022). Moreover, EO data has been adopted as a potential data source for SDG Indicator 6.3.2 (UNEP, 2024). Despite this, Earth Observation (EO) data remains under-utilised by counties and communities with the most to gain (European Union Agency for the Space Programme, 2024; Kutser et al., 2022). As an emergent technology, stakeholder engagement is critical to realising more benefits of EO within the water sector (Politi et al., 2024; Bennett et al., 2024). Hackathons bring an impactful time-condensed collective intelligence to a shared problem, while encouraging relationship-building, levelling out hierarchies and facilitating knowledge-sharing (Chernov et al., 2024; López-Maldonado et al., 2024). Such events are a rare and valuable opportunity to innovate for cleaner water and better management.

Here we present the perspective of a community of global stakeholders on how to unlock the benefits of satellite EO data for national water quality. Critical insight and inspiration for funders, researchers, satellite data providers, and water managers is offered.

2 Collective and creative thinking approach

A 3-day workshop was held in August 2024 at the University of Stirling to innovate solutions "*Unlocking the Global Benefits of Water Quality Monitoring through Earth Observation*". It was a follow-on to the *Innovation Workshop on Water Quality Monitoring and Assessment* (Chernov et al., 2024).

2.1 Workshop participants

Participants included 34 individuals coming from 21 countries including Europe, Africa, Asia, Latin America and North America. Over 300 applications across 90 countries were received. Optimising for innovation, our selection criteria ensured gender balance and diverse, multidisciplinary perspectives and roles within the environmental monitoring domain were represented. Half of attendees were from academia (senior and early career), and half from private companies, NGOs, governments and international agencies (including individuals directly supporting SDG Indicator 6.3.2 reporting). Travel grants supported some attendees and seven team members joined a separate virtual hackathon, enabling flexibility and inclusivity for those facing illness or visa challenges.

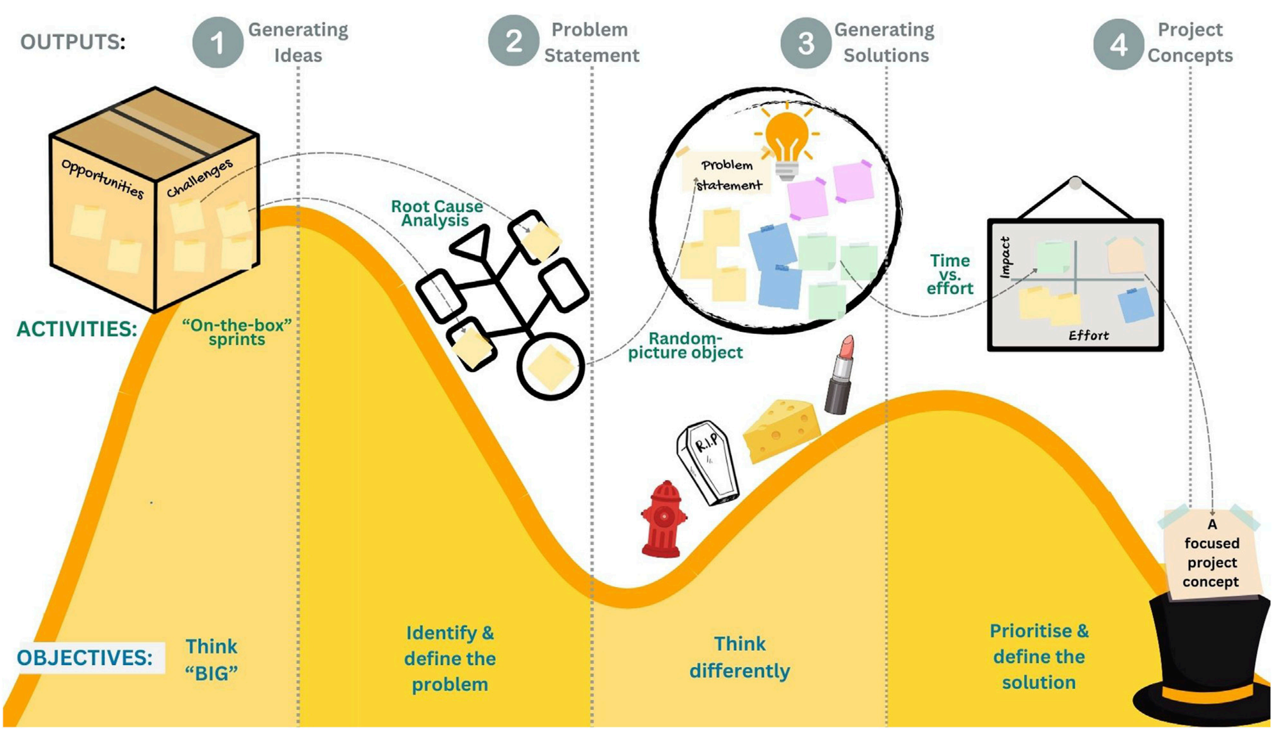

FIGURE 1
Participants (1) individually brainstormed benefits and challenges of EO for water quality monitoring on different sides of a cardboard box in short "sprints", then (2) identified root causes using Ishikawa fishbone diagrams, to arrive at a problem statement. Participants then generated ideas through (3) random object ideation using other point-of-view and random object techniques for creative thinking, (4) clustered them into themes, and prioritised these by impact and feasibility, to (5) finally, develop a single concept statement which was evaluated through the Six Thinking Hats technique (de Bono, 1985) (Image: created by the authors using Canva and adapted from the HDC process by IDEO).

2.2 Hackathon process

Attendees, many of whom were meeting for the first time, were arranged into teams of 5–6. Inspired by Edward de Bono's "mental valley" model (de Bono, 2014) participants were instructed through lateral thinking techniques to solve problems. The hackathon process was structured with iterative cycles of divergent and convergent thinking (Figure 1). Key steps included: 1) "On-the-box" sprints to explore the many benefits and barriers of EO for water quality monitoring, 2) root cause analysis and the formulation of problem statements, 3) idea generation using other point-of-view and random object techniques, 4) clustering and prioritisation, and 5) concept development employing the Six Thinking Hats technique (de Bono, 1985) (Full process in Supplementary Annex 1).

2.3 Analysis of workshop content

Consecutive hackathon stages led to idea prioritisation, followed by a thematic analysis of workshop content (Braun and Clarke, 2006). Workshop content was analysed to document each team's individual process and identify cross-team themes. Post-workshop, all participants were invited to contribute to this publication and materials were shared in open-access databases.

3 Perspectives from the hackathon

3.1 Challenges and root causes

Root cause analysis can often "open-up" thinking and ease problem solving (Pereira et al., 2021). Several common challenges and root causes arose suggesting why EO has not been more widely used for water quality monitoring. We explain these in detail below, using some direct quotes from participants, and highlight the paradoxes where challenges also present as opportunities in Figure 2 and highlight the paradoxes where challenges also present as opportunities in Figure 2.

3.1.1 Dependency on *in situ* data

Participants highlighted reliance on *in situ* data for satellite product calibration and validation, together with national data inaccessibility as a major barrier, especially in remote regions and the Global South. *In situ* data scarcity limits the validation of EO data, which increases EO data uncertainty, prohibits reliable application and undermines user trust. Both EO and *in situ* data have their own limitations and some conflicting perspectives were revealed on the relationship between them. One participant noted it would be "difficult to convince decision-makers about benefits of EO over *in situ* observations", while another expressed concern over "perception that *in situ* data are no longer needed for water quality and that investment in *in situ* data collection can be reduced". While

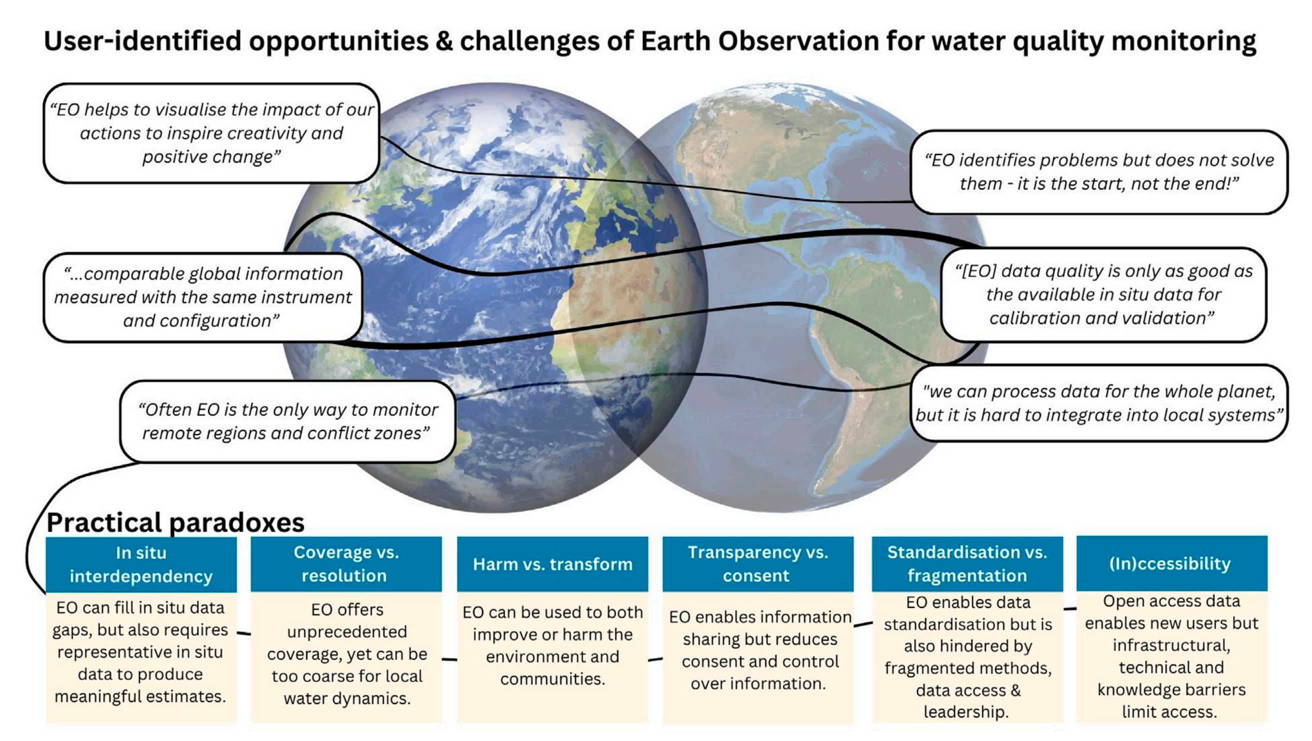

FIGURE 2
User stories from around the world contributed to the identification of opportunities and challenges demonstrated through a few select quotations. These in turn resulted in the paradoxes presented in the boxes at the bottom of the figure. These emerged in discussions across the 3 days throughout the activities represented in Figure 1. The opportunities, challenges and the practical paradoxes between the two were considered as the project concepts were developed, as outlined in Section 4. (Image: created by the authors using Canva).

EO can fill *in situ* data gaps in low-income countries, those same existing gaps limit EO data quality.

3.1.2 Technical limitations

It was widely agreed that inherent technical capabilities remain a barrier for EO's application in water quality monitoring, affirming EO as complementary to *in situ* monitoring rather than a standalone solution. Participants noted that satellite technology is limited to near-surface waters, precluding deep-water and groundwater EO assessment. Frequently mentioned was EO's inability to monitor "small water bodies" or dynamic systems because it is sometimes too coarse in resolution and infrequent in availability. Because water bodies are complex in composition and optical properties change over time and across regions, quantifying and reducing uncertainties of regional EO water quality products were major concerns. Participants also highlighted that optical satellites cannot directly detect aqueous fractions of non-visible pollutants like nitrogen, phosphorus, or microplastics and the challenges posed by cloud cover and atmospheric correction. Development timescales were also identified as a challenge, since "satellites take 10+ years to develop, by which time the challenge has evolved."

3.1.3 Awareness and interest

A key root cause was lack of stakeholder awareness of EO's potential for water quality monitoring and downstream benefits. Participants noted "satellite capabilities to monitor water resources are not well known to most stakeholders". Stakeholders overlook EO's value, with one participant stating the "need to decide who it is useful for" and better communicate its applications. This extended to decision-makers who were discussed as particularly important in driving uptake and investment, with comments such as "politicians seem disinterested in applying this technology" and "lack of acceptance and use by environmental decision-makers." Mistrust also hinders adoption, as EO is associated with "overly ambitious promises."

3.1.4 Skills and capacity gaps

Participants highlighted a "lack of qualified personnel to work with EO data for water quality" compounded by the "need [for] specific training with a steep learning curve." Complexity of EO technology was regarded as potentially overwhelming as "huge amounts of EO databases make it difficult to choose the right one for water management." Limited educational opportunities exacerbate this issue, contributing to "careless use of EO data and products without proper understanding."

3.1.5 Resource inequalities and infrastructure

The realised benefits of EO are largely limited to limited to regions with adequate resources (i.e., internet infrastructure, computational capacity, reliable networks, and the ability to handle data processing and storage costs), revealing a global inequality. Participants highlighted unequal access in low-to middle-income economies as a root cause, where EO may be perceived as a "different" technology. Even with openly accessible data, these barriers prevent effective utilisation, reflecting a global divide in EO capacity, often described as a "southern hemisphere" challenge. Disparity was also identified in terms of the lack of realised benefit at the local scale, compared to regional and global.

3.1.6 Fragmented leadership and policy gaps

Lack of integrated, evidence-based policy hinders the implementation of EO for water quality monitoring. Participants highlighted a root cause in the absence of "umbrella" organisations to coordinate efforts, and gaps in industry and policy standards for gathering, storing, and sharing data. One participant observed there is currently "no common protocol to process or EO data to enable comparisons across the globe," while others questioned, "How do we standardise data without losing its integrity?" Lack of coordinated policies and strategic government agendas were linked to a reduction in EO's credibility and its ability to support local communities.

3.1.7 Ethics and governance

Consent and potential misuse present challenges. EO "records data globally to be made public—no consent [is given] to data acquisition," raising concerns about data sovereignty and privacy. Participants discussed at length the loss of data sovereignty as a consequence of open data principles, and the cultural consequences to Indigenous Peoples of sharing data about their land and territories. Participants warned that EO data is "prone to exploitation" and can be used to harm rather than empower. Such concerns demand careful consideration of data accessibility and the role of regulations and governance to protect vulnerable communities.

3.2 Opportunities to create benefits from EO for water quality monitoring

Common opportunities from EO for water quality monitoring were identified and demonstrate the tools which can overcome challenges.

3.2.1 A synoptic view of our planet

The global spatial coverage of EO emerged as the most significant benefit for water quality monitoring, offering a "synoptic" or holistic view of the Earth. Participants emphasised EO's ability to monitor across scales—national, regional, and transboundary. Participants noted this enabled monitoring of "whole water bodies, as opposed to a single sampling point," and across the "land-water interface". Data consistency and standardisation across regions provide opportunities for global comparisons and tracking changes. Additionally, EO supports long-term analysis through regular temporal observations, enabling the study of natural change and anthropogenic impacts. The availability of near-real-time data was frequently cited as a key advantage, described as delivering "fast" and actionable insights.

3.2.2 Monitoring the un-monitorable

EO's ability to measure inaccessible areas, such as conflict zones, remote regions, and protected areas, was widely emphasised. Participants highlighted its "remote" and "non-invasive" nature critical to providing information where conventional *in situ* observation is impossible. Participants mentioned nuances where *in situ* monitoring may be possible and even preferable to EO based solutions, but is blocked by social, political and economic barriers. EO data provides a unique opportunity for water quality monitoring in resource-limited low-income countries. In such cases, participants argued that useful water quality information can be derived, even without local validation. Links were made to increased reporting on SDG Indicator 6.3.2, enabling countries to understand the state of their water bodies and evaluate the progress of interventions.

3.2.3 Complementary and cross-disciplinary

EO was seen as a tool connecting diverse knowledge systems, including Indigenous Knowledge, with one participant describing its ability to "complement and confirm the subject matter from other sources." The flexibility of EO allows it to "bridge disciplines" and "enable international collaboration." Some noted its potential in applications such as early warning systems, forecasting, and addressing broader health and social challenges. Participants also appreciated that EO data can complement or integrate with other data types, such as long-term monitoring programmes, numerical modelling, and citizen science, to enhance water quality knowledge. EO can enable upscaling of existing monitoring programs and ingrain the validity of *in situ* programmes. Participants emphasised that cost-benefits of EO, per observation and in terms of coverage, allows the reallocation of funds toward *in situ* sampling.

3.2.4 Transparency and accountability

Available open-access EO data was linked to greater transparency of water quality and accountability of polluters. EO overcomes many barriers to data sharing, enabling monitoring regardless of political or geographic restrictions. One participant described EO's impact as ensuring that "the truth is always out—there's no way of altering information." EO's role in tracking pollution and identifying sources of environmental crimes was highlighted as a critical benefit, supporting environmental and social justice initiatives.

3.2.5 Visualising impact for positive action

EO was frequently described as "visually captivating" and "intuitive," particularly for its ability to raise awareness and inspire action. Participants emphasised its value as a "communication tool" for engaging policymakers and the public. By making complex issues more accessible, EO has the potential to increase water quality awareness, inspire creative solutions, and promote meaningful change.

3.3 Hackathon Outcomes: Prioritising Impact and Feasibility

Each hackathon team developed unique concepts in response to the same challenge, prioritising them based on an impact-versus-effort assessment. A key consideration for all proposals is securing funding and ensuring long-term continuity. Evaluating feasibility requires assessing adaptability to shifting political landscapes and evolving water quality challenges. Some concepts may need to be refined into smaller, more manageable initiatives to gain broader support.

3.3.1 Space Buzz: enhancing awareness through media campaigns

The "Space Buzz" concept is a low-cost, impactful, media-driven campaign to generate excitement and awareness of the value of EO among potential users and decision makers. While communication is not a traditional focus of scientific funding, it is critical for engaging local communities and policymakers who influence funding and regulatory frameworks.

This concept integrates ideas from multiple teams, proposing multimedia campaigns that engage diverse audiences and foster an emotional connection to EO applications. These campaigns leverage visually compelling content, success stories, and testimonials to build trust in EO technologies and highlight their practical benefits. A bottom-up communication strategy ensures EO awareness extends beyond technical communities, influencing policy decisions, increasing investment, and accelerating adoption.

3.3.2 EO Access Hubs: Advancing Equity in Earth Observation

Centralised EO Access Hubs address disparities in resources, skills, and community empowerment. These hubs serve as repositories for EO tools and data, providing a single access point for skill development, knowledge-sharing, and product innovation. By reducing infrastructure requirements, they lower barriers to EO utilisation, particularly in under-resourced communities.

Recognising diverse regional challenges, concept developers emphasised the importance of including non-Western perspectives to foster locally relevant EO applications. EO Access Hubs empower communities to develop tailored solutions, overcoming accessibility and training limitations. Additionally, these hubs improve *in situ* data collection, reduce technical barriers, and promote EO awareness.

3.3.3 Education Strategy: Building EO Expertise

A scalable, accessible and affordable EO education framework was proposed to address workforce shortages, the absence of government strategies, and inadequate funding. This framework advocates for training programs tailored to national needs, equipping countries with the expertise to develop autonomous EO applications aligned with their specific objectives.

The strategy spans all levels of the information chain, from school children to policymakers and industry leaders. To counter "parachute science," it emphasises co-designed curricula that integrate traditional and local knowledge systems. Modern educational tools—such as online courses and twinning programs—facilitate resource-sharing and sustainable capacity building, particularly in the Global South. The expected outcome is a skilled workforce capable of advancing EO science.

3.3.4 IPWQ: Establishing an Intergovernmental Panel for Water Quality

To address policy fragmentation and the lack of global coordination in EO-based water quality monitoring, the Intergovernmental Panel for Water Quality (IPWQ) is proposed, modeled after the Intergovernmental Panel on Climate Change (IPCC). The IPWQ would provide a platform for experts to collaborate on EO standardisation, data processing advancements, and next-generation satellite development.

A key function of the IPWQ would be the production of Global Water Quality Assessment Reports, translating EO data into actionable policy recommendations (Challenges G & C). These reports, based on peer-reviewed research, would track water quality trends at global, regional, and national levels. The IPWQ could build on UNEP's World Water Quality Alliance (WWQA) and leverage existing initiatives, such as the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), which includes efforts in the Lake (Golub, et al., 2022) and Water Quality (van Vliet et al., 2019) sectors.

By integrating modeling and in situ data, the IPWQ would enhance trust in EO-based water quality assessments, promoting broader EO data adoption in decision-making (Challenges A & B). Ultimately, this initiative fosters a globally coordinated expert community dedicated to advancing water quality monitoring and policy development.

4 Conclusion and future outlook

This unique workshop enabled valuable cross-disciplinary engagement and international participatory collaboration to address the root causes hindering the uptake of EO for water quality monitoring in support of SDG 6 (Pahlevan, et al., 2022; United Nations, 2023). The community perspective confirmed that achieving SDG 6 will require a balanced approach that combines innovative EO solutions with strengthened *in situ* monitoring (Agnoli et al., 2023; Kutser et al., 2022). The need for water quality data to improve management of water resources will remain beyond the end of the UN's Agenda 2030 for Sustainable Development. Embedding an EO approach into national management processes offers an opportunity for further future development of products and services to help fill the data gap at local, regional and global scales.

Groups, despite following the same process, created distinct concepts, highlighting the role of group dynamics in shaping outcomes and the fundamental importances of representative participation for addressing global water challenges (Marques et al., 2023; Chernov et al., 2024). Feedback demonstrated strong engagement, accelerated equitable knowledge-sharing and relationship-building, and a desire to increase inclusivity by replicating in other regions or online. The concepts offer actionable pathways to increase the number of people, countries and communities benefiting from EO-derived water quality monitoring. We invite EO networks, funders and individuals to champion these concepts, develop and incorporate them into funding calls, and proposals, and unlock the benefits of EO for water quality monitoring.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

HW: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Visualization, Writing–original draft, Writing–review and editing. NR: Conceptualization, Funding acquisition, Project administration, Supervision, Writing–review and editing. ES: Conceptualization, Funding acquisition, Project administration, Supervision, Writing–review and editing. MD: Methodology, Resources, Writing–review and editing. MN: Conceptualization, Project administration, Resources, Writing–review and editing. AS: Conceptualization, Funding acquisition, Project administration, Writing–review and editing. SP: Methodology, Project administration, Visualization, Writing–original draft, Writing–review and editing. IC: Conceptualization, Writing–review and editing. SA: Writing–review and editing. AA: Writing–review and editing. AB: Writing–review and editing. CC: Writing–review and editing. DeM: Writing - review and editing. FM. Writing - review and editing. AF: Writing–original draft, Writing–review and editing. JH: Writing–review and editing. DJ: Writing–review and editing. TM: Writing–review and editing. SL: Writing–review and editing. LL: Writing–review and editing. FL: Writing–review and editing. JM: Writing–review and editing. AN: Writing–review and editing. JO: Writing–review and editing. IO: Writing–review and editing. IR: Writing–review and editing. AR: Writing–original draft. SuS: Writing–review and editing. KS: Writing–original draft, Writing–review and editing. StS: Writing–review and editing. ShW: Writing–review and editing. StW: Writing–review and editing. TA: Conceptualization, Writing–review and editing.

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Conflict of interest

Author MN was employed by Global Science and Technology. Author DeM was employed by FinSat Inc. Author CC was employed by 3edata. Ingeniería Ambiental.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsen.2025.1549286/full#supplementary-material

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