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Citizen analytical chemistry: building a participatory and shared science through global data generation

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This work presents citizen analytical chemistry (ZAC) as a framework that unites analytical science with the participatory nature of citizen science, enabling professionals and especially non-professionals to collect, interpret, and share chemical data using simplified, low-cost, and portable tools. Through smartphones, open-source platforms, and do-it-yourself devices, ZAC democratizes access not only to chemical measurement but also to chemical information and knowledge, creating opportunities for environmental monitoring, public health protection, and food safety assessment on a global scale. It encourages large-scale data generation while promoting education, transparency, and scientific literacy. At the same time, it raises new challenges related to data quality, privacy, ethics, and public engagement that must be addressed to ensure reliability and trust. This article highlights ten pillars of ZAC, presents key enabling technologies, and explores future directions where community-driven sensor networks, mobile platforms, and AI-assisted analysis could transform analytical chemistry into a shared societal practice. ZAC proposes a more inclusive, participatory, and sustainable model of science, one in which analytical chemistry becomes a bridge connecting people, data, and the environment.

Sustainability spotlight

Citizen analytical chemistry (ZAC) expands analytical science toward inclusivity, accessibility, and sustainability. It allows citizens to gather and interpret chemical data using portable, affordable, and open-source tools, turning measurement into a collaborative social practice with tangible environmental and educational value. This concept connects analytical chemistry with the United Nations Sustainable Development Goals by advancing good health and well-being (SDG 3), quality education (SDG 4), responsible consumption and production (SDG 12), and partnerships for the goals (SDG 17). ZAC strengthens scientific literacy, reduces resource consumption and waste, and builds global data networks that link chemistry with society, encouraging transparent, participatory, and sustainable scientific engagement across communities.

1. Introduction

Analytical chemistry has traditionally developed within laboratories, research institutes, and industrial environments. However, many of the societal challenges that analytical chemists aim to address, such as environmental pollution, food safety, and public health, extend far beyond these controlled boundaries and directly affect citizens in their everyday lives. In this context, closer and more structured engagement between chemists and society is increasingly necessary. One established approach to enable this interaction is citizen science, which the European Union defines as "the voluntary participation of non-professional scientists in research and innovation at different stages of the process and at different levels of engagement, from shaping research agendas and policies, to gathering, processing and analyzing data, and assessing the outcomes of research".[1] Such collaboration relies on a bidirectional flow of knowledge between scientists and citizens, allowing analytical expertise and societal insight to reinforce each other.[2,3]

Citizen science opens research to the public by providing access to measurement and observation tools, promoting a shift in perspective.[4] Its relevance becomes especially evident when tackling air quality challenges in urban environments worldwide. For instance, in Mexico City, one of the most polluted megacities in Latin America, citizens have long relied on traditional indicators such as the visibility of surrounding mountains or the smell of smog to assess air quality. When these community-based observations are combined with modern analytical approaches (such as portable electrochemical sensors, spectroscopic monitoring, or chromatographic determination of volatile pollutants), solutions arise that are both scientifically robust and socially meaningful. This combination of local knowledge and analytical rigor validates

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Table 1 Comparison between different concepts used in analytical chemistry

Concept	Main focus	Key principles	Technological dimension	Societal aspect	Ref.
Green analytical chemistry (GAC)	Environmental sustainability	Minimization of reagents, waste, and energy; safer solvents	Greener solvents, miniaturized sample prep, waste prevention	Limited; focus on environmental impact rather than citizen involvement	9
White analytical chemistry (WAC)	Balance of performance, sustainability, and practicality	Integration of red (analytical performance), green (sustainability), and blue (applicability) dimensions	Smart method design, cost-effectiveness, operational simplicity	Implicit; encourages accessibility through practical dimension	10
Click analytical chemistry (CAC)	Efficiency and modularity	Simplicity, reliability, and reusability inspired by click chemistry	Modular and easily adaptable analytical setups	Indirect; focus on reproducibility and robustness	11
Smart analytical chemistry (SAC)	Digital transformation	Integration of AI, automation, and data analytics with sustainability	Intelligent sensors, robotics, real-time analytics	Indirect; focus on data-driven automation rather than participation	12
Disposable analytical chemistry (DAC)	Rapid, low-cost, on-site analysis with single-use devices	Simplicity, contamination control, minimal sample/reagent use, eco-designed/biodegradable materials	Paper/polymer microfluidics, lateral-flow and screen-printed electrodes, integrated reagents, smartphone readout, roll-to-roll/3D printing	High accessibility in low-resource settings; faster decisions at point-of-care, with sustainability trade-offs due to single-use waste	13
Citizen analytical chemistry (ZAC)	Democratization and participation based on a critical approach	Accessibility, inclusiveness, transparency, co-creation and emancipation	Low-cost, portable, open-source analytical tools	Direct citizen critical engagement in sampling, measurement, and data interpretation	This work

community perceptions and promotes collective action, increasing the societal impact of chemical measurements.[5]

Beyond specific case studies, citizen science enables collaboration between professional scientists and society, combining scientific expertise with widespread public participation to support large-scale data generation. When coordinated measurement campaigns are carried out jointly, this collaborative approach can expand the spatial and temporal coverage of data collection, beyond what either group could achieve independently. In environmental monitoring, for instance, volunteers can track biodiversity loss, deforestation patterns, or local pollution events.[6] In the field of food science, citizen-driven initiatives have a direct impact in ensuring the authenticity and traceability of locally produced foods. In this regard, IsoPROTECT project, focuses on protecting regional food production in Austria through isotopic and multielemental fingerprinting. It invites local producers, schools, and interested citizens to become citizen scientists by registering on an online platform and contributing to the collection of food samples and related data through a crowdsourcing approach. Such participation not only broadens data collection capacity but also raises awareness, reinforces shared responsibility for health and environment, and can place pressure on industries or policymakers to adopt more sustainable practice.[7] In the United States, for example, growing public concern over per- and polyfluoroalkyl substances has prompted the Environmental Protection Agency to issue new guidelines, reflecting how citizen awareness can trigger regulatory responses.[8] In Europe, a notable example of a multi-actor participatory framework is the COST Action BeSafeBeeHoney, which adopts a coordinated approach to address the complex threats faced by honeybees. This initiative brings together expertise from chemistry, biology, ecology, veterinary science, beekeeping, agrarian engineering, nutrition, economy, and policy to jointly address issues ranging from pesticide contamination in hive products to the nutritional and medicinal value of honey. Through shared monitoring activities, data exchange, and stakeholder dialogue, the action illustrates how citizen involvement and participatory research practices can inform discussions on food safety, environmental sustainability, and agricultural policy.

At the same time, it is worth emphasizing that the very challenges analytical chemistry seeks to address, require not only advanced instrumentation, but also new ways of broadening data collection. Techniques such as gas chromatography (GC)-mass spectrometry for monitoring volatile organic compounds, inductively coupled plasma mass spectrometry or atomic absorption spectroscopy for assessing heavy metals, are indispensable for generating accurate and actionable results. Yet, their implementation at large scale is often constrained by high costs, limited infrastructure, skilled personnel, or the difficulty of achieving extensive spatial and temporal coverage. This gap highlights the need for complementary approaches that can expand reach, accelerate data acquisition, and make chemical insights more directly relevant to society.[5]

Since 2013, analytical chemistry has not only advanced through methodological innovation, but also through the creation of conceptual paradigms that frame how the discipline contributes to sustainability and societal needs. Gałuszka *et al.*[9] introduced green analytical chemistry (GAC), emphasizing the minimization of hazardous reagents, energy, and waste. Later, Nowak *et al.*[10] proposed white analytical chemistry (WAC), conceptualized as the integration of three dimensions: red (performance), green (sustainability), and blue (practicality). More recently, Mansour *et al.*[11] presented click analytical chemistry (CAC) as an approach inspired by click chemistry, highlighting simplicity, efficiency, and reliability. Hussain *et al.*[12] formulated smart analytical chemistry (SAC), which integrates advanced technologies such as artificial intelligence (AI), automation, and data analytics with sustainable principles in chemical analysis. Finally, disposable analytical chemistry (DAC) was included to address rapid, low-cost and on-site chemical analysis using disposable devices.[13] Yet, despite the proliferation of these terms (see Table 1), one crucial aspect truly remains absent: the role of citizens. Citizen analytical chemistry (ZAC) is a pillar that has been largely overlooked and underrepresented.[14] Whilst it is evident that there are already numerous successful large-scale citizen science projects, such as iNaturalist, Wildbook, and Coral Watch,[15] its "sister field", ZAC, has not. To the best of our knowledge, this is the first time that the concept is formally introduced, discussed, and framed within analytical chemistry. This article aims to highlight how ZAC can inform decision-making processes, support evidence-based policies, and engage diverse stakeholders, including citizens, educators, scientists, and policymakers, across different socio-economic and geographical contexts. In doing so, we discuss its foundations, opportunities, and implications for building a participatory and shared science through global data generation and use.

2. The meaning of citizen analytical chemistry

ZAC can be defined as a framework that integrates the principles and practices of analytical chemistry with the participatory philosophy of citizen science. The term "citizen analytical chemistry" is hereafter referred to as "ZAC" to avoid misunderstands with the already established concept of "click analytical chemistry (CAC)".

After conducting a critical analysis of publications from the last ten years, based on searches in the ERIC and Web of Science databases in the last 10 years, we did not identify any study that formally defines ZAC or establishes a structured framework or set of pillars in the field of analytical chemistry. While related concepts such as analytical science, citizen science projects, and citizen science have been discussed, the explicit intersection between citizen participation and analytical chemistry remains unexplored. To date, two recent studies[16,17] have mentioned this intersection. However, these works mainly adopt a review-oriented perspective, providing examples of how recent technological advances have made analytical tools simpler and more affordable for citizens, rather than proposing a clear definition, conceptual foundation, opportunities, challenges, risks, or a global perspective. This gap in the literature highlights the need for a structured framework that situates ZAC within the discipline.

In this context, ZAC involves the active engagement of non-professional individuals (students, enthusiasts, and community members) in the generation, collection, and interpretation of analytical data related to real-world problems. Through simplified, miniaturized, and low-cost analytical tools, ZAC aims at democratizing access to chemical measurements, enabling citizens to perform analyses of air, water, soil, food, or biological samples outside traditional laboratory settings. ZAC can offer a way of connecting analytical chemistry to society, taking chemical measurement beyond universities and research centers, allowing people from different backgrounds to participate in meaningful scientific inquiry. Using open-source tools, smartphones, and simple or homemade instruments, anyone can measure and understand what is happening around them.[7] ZAC also carries an important educational and social dimension. It helps people recognize how chemistry shapes their daily lives, increases awareness of environmental and health issues, and empowers them to make informed decisions based on evidence. In this sense, ZAC can be both a scientific practice and a collective movement that seeks to make science opener, more inclusive, and relevant to society. Some typical ZAC applications that illustrate the variety of challenges, citizen roles, and analytical values are summarized in Table 2.

This growing connection between analytical science and society also aligns with the environmental goals of modern chemistry. As Koel highlighted,[18] "there are simple sensors and analytical devices available on the market, and enthusiastic individuals are developing ways to monitor the environment without the need for expensive laboratory instruments". From this perspective, ZAC can be regarded as the "green cousin" of analytical chemistry, one that operates with minimal resources and generates very little waste.[18]

Here, we present the ten main pillars in which ZAC stands on that describe how this approach can connect analytical science with people and society globally (see Fig. 1 and Table 3). These statements reinforce not just what ZAC is, but what it aspires to be: a way of doing analytical chemistry that is open, inclusive, and meaningful for everyone, so that solutions to problems can be found and collective decisions made for the common good, based on scientific data.

In this context, collaboration between analytical scientists and the local communities affected is critical to find solutions. Modern citizen science has shown that communities effectively contribute to identifying problems when they are given access to monitoring tools and the knowledge to use them.[16,19] Advances in portable sensors, simplified test kits, and digital platforms now make it possible for non-specialists to measure pollutants directly in their surroundings, but the availability of instruments alone is not sufficient.[20] Training and education to promote scientific literacy are essential to ensure that

Table 2 Examples of challenges, citizen roles, and analytical value of ZAC initiatives

Challenge	Citizen role	Analytical value
Air pollution in urban areas	Use portable sensors to measure particulate matter and NO_2	Validation of sensor data with GC-MS or reference stations; calibration support
Pesticide residues in fruits and vegetables	Collect samples from local markets for screening	Confirmation of residues with LC-MS; public workshops on safe consumption
Heavy metals in drinking water	Test tap water with simple colorimetric kits	Laboratory ICP-MS analysis to verify and quantify results
Microplastics in rivers and beaches	Gather water or sand samples and perform visual sorting	Scientists apply FTIR or Raman spectroscopy to identify polymer types
Antibiotic residues in milk	Farmers or consumers provide milk samples for rapid testing	Confirmation through HPLC-MS and data sharing with food safety agencies
Soil contamination near industrial areas	Residents collect soil samples at different distances	Elemental analysis (AAS, ICP-MS) to map contamination gradients
Allergen presence in processed foods	Citizens check labels and provide suspect samples	ELISA and LC-MS validation of undeclared allergens
Noise and air quality around schools	Students record noise levels and basic air metrics	Integration with analytical monitoring of VOCs and particulates
Authenticity of honey	Beekeepers submit local honey samples	Isotope ratio MS or LC-MS to detect adulteration
PFAS contamination in communities	Residents collect water samples for screening kits	Confirmation of PFAS by LC-MS/MS; trend mapping
Loss of biodiversity in rural areas	Citizens track plant and insect diversity	Correlation with pesticide residues measured by chromatography
Pharmaceutical waste in rivers	Anglers or residents collect water samples downstream from treatment plants	LC-QTOF-MS screening of pharmaceuticals and metabolites
Indoor air pollution	Families measure CO_2 and VOCs with portable devices	Analytical validation of VOC profiles *via* GC-MS
Lead in old housing infrastructure	Residents test paint or dust with DIY kits	ICP-MS quantification to support health risk assessment
Food fraud in spices or oils	Citizens purchase and submit suspect products	NMR or MS fingerprinting to confirm adulteration
Nitrate contamination in groundwater	Farmers and households use nitrate strips	Ion chromatography or spectrophotometry to confirm results
UV exposure in cities	Citizens use wearable badges to track daily exposure	Correlation with spectroscopic monitoring of UV radiation
Plastic additives leaching from containers	Citizens donate used food containers for testing	GC-MS determination of phthalates or BPA migration
Air quality in public transport	Commuters record $PM_{2.5}$ and CO levels	Validation through portable GC or reference instruments
Health risks near waste disposal sites	Communities report odors, water color, or plant die-off	Laboratory analysis of VOCs, metals, and pesticides to assess risks

individuals can use these tools correctly and generate data of acceptable quality. Empowering communities in this way enables them to detect hazards early and to engage in decision-making processes based on real evidence. The consequences of not doing so have been illustrated in historical cases such as the Love Canal disaster in New York in the 1970s, where toxic waste buried beneath a residential area caused widespread chromosomal damage and birth defects.[21] Had robust community-based monitoring been available earlier, the contamination could have been recognized before it reached such critical levels. For analytical scientists, working directly with communities strengthens trust and ensures that studies are not only technically sound but also directly relevant to the needs and concerns of local populations. Today, user-friendly tools such as accessible and portable sensors, simple experiment kits, mobile applications, AI-powered reporting systems, and open-access platforms provide new ways for communities to submit data and receive feedback, turning monitoring into a shared responsibility rather than an isolated scientific task.

Beyond the provision of tools, training and science education in different degrees and levels, building long-term partnerships between scientists and communities is crucial for the success of initiatives in ZAC. These collaborations should not be limited to short-term projects but instead aim to establish networks that can respond flexibly to emerging challenges. For instance, schools, universities, local associations, NGOs, and health organizations can serve as bridges to involve broader groups of citizens, creating a culture of vigilance and scientific literacy.[7] Moreover, ensuring that data collected by communities is validated and integrated into national or regional monitoring systems increases its credibility and policy impact. Ethical considerations are equally important.[22] Communities must retain ownership of their data and be able to influence how results are communicated and used. In this sense, ZAC has the potential not only to multiply the amount of available data but also to democratize scientific practice by giving citizens a real voice in how environmental and health challenges are addressed.

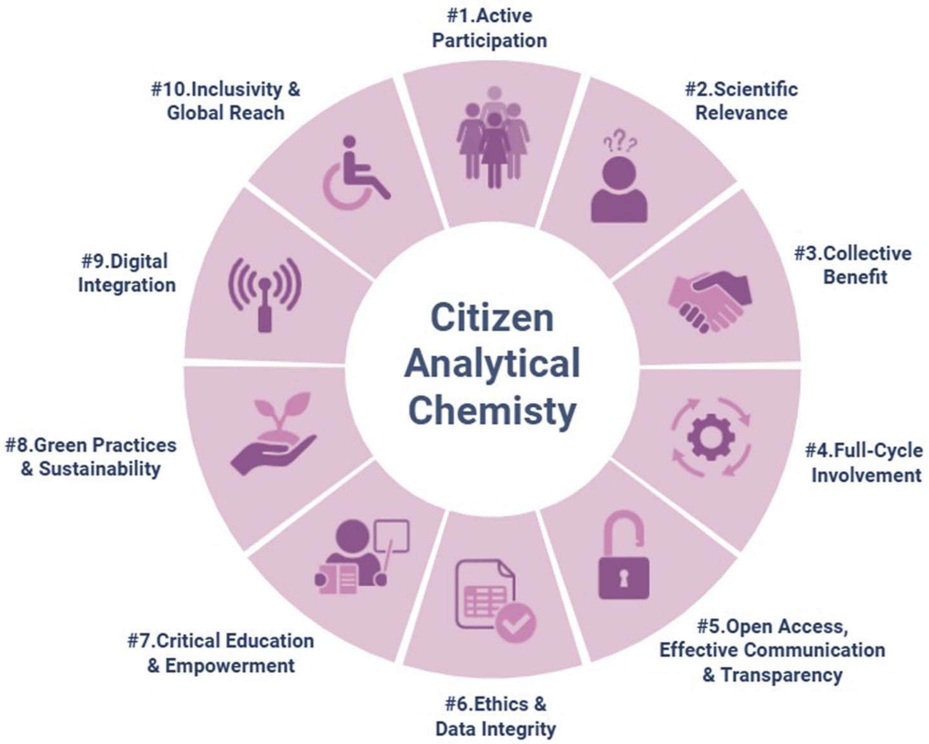

Fig. 1 Core pillars defining the framework of citizen analytical chemistry.

3. A brief snapshot of technologies

Recent advances in analytical chemistry reveal a clear trend toward miniaturization, simplification, and digital integration of analytical instruments. Over the past decade, technologies that once required large laboratory setups have moved into compact, user-friendly, and highly portable devices. These innovations mark the beginning of a new era in analytical science, characterized by the decentralization of chemical measurement and the democratization of data collection.[17] Their value for ZAC lies in four main features: (i) simplicity of construction, which enables do-it-yourself (DIY) assembly and repair; (ii) ease of operation, allowing non-specialists to perform reliable measurements; (iii) portability and digital integration, which brings analysis directly to the field; and (iv) automation, which ensures consistency and efficiency even outside laboratory settings. Furthermore, these miniature instruments inherently align with the principles of GAC,[23] as they require smaller reagent volumes, lower energy consumption, and generate minimal waste. Miniaturization and digitalization have led to the development of new technologies, some of which are summarized below (see Table 4).

3.1. Do-it-yourself devices

The design and fabrication of low-cost, portable analytical devices that can be easily assembled and transported have been key drivers steering scientific research toward small-scale, self-built projects. The DIY approach has gained increasing popularity as it not only empowers the public to develop zero-coding systems but also promotes more robust and streamlined device architectures.[24] DIY analytical instruments have become valuable educational tools, allowing people to understand the function and assembly of each component while gaining a hands-on appreciation of analytical chemistry principles. In recent years, an increasing number of DIY analytical instruments have been reported in the literature, including educational potentiostats[25,26] and a low-cost GC system designed for teaching analytical chemistry.[27] Among these, UV-vis spectrophotometers have become particularly popular within the DIY community, as they are a core component of undergraduate chemical education and a versatile tool for chemical research. Several recent publications describe innovative designs for such instruments. For example, Grasse *et al.* developed a 3D-printable smartphone spectrophotometer,[28] Pap *et al.* created an inexpensive 3D-printable visible spectrophotometer suitable for online, hybrid, and classroom-based learning,[29] and Del-Monache *et al.* designed a low-cost (<$100) DIY spectrophotometer system adaptable for different applications.[30]

3.2. Portable instruments and smartphones

In recent years, portable analytical instruments and smartphones have established themselves as key drivers of innovation. Combining multiple sensors, cameras, connectivity, and user-friendly interfaces, they transform everyday devices into accessible analytical tools for data collection and interpretation outside traditional laboratories (see Fig. 2). These platforms allow non-specialists to perform chemical measurements in real time, bridging the gap between laboratory-based analysis

Table 3 The ten pillars of ZAC

#	Core concept	Description	Added value for analytical chemistry
1	Active participation	Citizens actively engage in the generation of analytical data using portable instruments, open-source tools, and simplified methods. They move from passive observers to active data producers	Expands sampling capacity and data diversity, allowing broader monitoring
2	Scientific relevance	ZAC projects target questions of both scientific and societal importance such as air pollution, water contamination, or food authenticity	Aligns research with real-world needs and promotes socially responsive analytical science
3	Collective benefit	Scientists gain access to large datasets, while citizens gain scientific literacy, awareness, and empowerment to make informed decisions	Strengthens the link between academia and society, reinforcing public trust in science
4	Full-cycle involvement	Citizen participation extends beyond sampling to include hypothesis definition, data interpretation, and dissemination of results	Enhances data ownership, motivation, and scientific understanding among participants
5	Open access, effective communication & transparency	ZAC promotes open data repositories, transparent reporting, and reproducible workflows that the public can access and verify	Improves data traceability, reproducibility, and collaboration across analytical networks
6	Ethics & data integrity	Projects must ensure data reliability, informed consent, anonymity, and proper credit to contributors	Guarantees credibility of results while building trust between professionals and citizens
7	Critical education & empowerment	ZAC promotes chemical literacy through hands-on experimentation, training workshops, and collaborative learning towards emancipation	Cultivates a new generation of scientifically aware citizens and supports lifelong STEM education
8	Green practices & sustainability	Inspired by green and white analytical chemistry, ZAC emphasizes low-cost, low-waste, and energy-efficient analytical practices	Encourages environmentally responsible experimentation and sustainable analytical methods
9	Digital integration	Combines IoT, AI, and mobile applications for real-time data collection, visualization, and quality control	Increases precision and scalability of citizen-generated analytical data
10	Inclusivity & global reach	ZAC welcomes diverse participants regardless of background or location, promoting equitable access to analytical knowledge	Democratizes science globally, reducing geographic and socioeconomic barriers to participation

and field applications. Sample collection often remains a major bottleneck in analytical workflows, as samples must be taken at a specific site and transported to the laboratory for analysis. However, if we change our perspective, we can envision a scenario where key stakeholders, such as farmers, food inspectors, and even citizens themselves, could perform preliminary analyses directly on-site. This is the idea behind the FoodSmartphone project, one of whose strategic lines focuses on the development of a 3D-printed surface plasmon resonance biosensor integrated into a smartphone, designed for the detection of biomarkers in milk. The device offers rapid response times and costs less than $100, aligning with the blue dimension of WAC.[31] Another example in this field is the development of a microfluidic paper-based analytical device integrated with solid-phase extraction for fat removal and nitrite separation in high-fat food samples.[32] The authors highlighted that this laboratory-free, point-of-care testing approach, specifically designed for non-specialist users, offers new perspectives on citizen science as a valuable resource for researchers, policymakers, and the general public interested in understanding and tackling challenges in food chemistry.

A similar direction is being pursued through the creation of portable analytical kits that use mobile phone sensors. Wang *et al.*[33] designed a low-cost smartphone-based field detection

Table 4 Representative technologies for ZAC

Technology	Example	Analytical target	Advantages for ZAC	Ref.
Smartphone-based colorimetry	Nitrite and ammonium detection *via* WeChat mini-program	Water quality parameters	Intuitive interface, real-time analysis, global accessibility	4
DIY UV-Vis spectrophotometers	3D-printable smartphone spectrophotometer	Absorbance-based assays	Educational, open design, reproducible results	67
Portable GC systems	Arduino-based low-cost GC for VOC monitoring	Volatile organic compounds	Field deployment, real sample compatibility	34
Microfluidic paper-based devices	On-site nitrite separation in high-fat foods	Food additives and contaminants	Reagent-free operation, rapid screening	32
Fast-flow microfluidic device	Monitoring in surface water	Phosphate	User-friendly operation	38

platform for analyzing antibiotic contaminants in water and aquatic products. This approach not only allows citizen scientists to evaluate antibiotic residue levels in their surroundings but also raises public awareness about environmental exposure and encourages proactive risk reduction. Collectively, these innovations illustrate how mobile technology and participatory science can converge to decentralize analytical chemistry, transforming data generation into an accessible and socially driven process.

In the context of portable instrumentation, two separation techniques are particularly promising: sensor GC and capillary electrophoresis (CE).[17] In the first case, Hinterberger *et al.* designed a low-cost Arduino-based GC system suitable for teaching analytical chemistry in undergraduate laboratories.[27] Similarly, Kaljurand *et al.* developed a low-cost, portable, and robust GC system for the analysis of volatile organic compounds emitted from gasoline stations and oil extraction sites (see Fig. 3).[34] This instrument is well suited for use in citizen science projects focused on environmental monitoring. Secondly, CE stands out for its ongoing transition from traditional bench-top instruments to compact, portable systems that enable on-site and real-time analysis, a trend that is becoming increasingly evident in recent studies.[35] Furthermore, it is important to highlight how open-source hardware and software significantly contribute to ZAC by facilitating access to affordable, modular, and customizable analytical tools that can be built, modified, and operated by citizens and communities without the need for complex infrastructure.[36] This approach not only reduces costs and promotes component reuse but also minimizes the environmental footprint of analytical instruments while

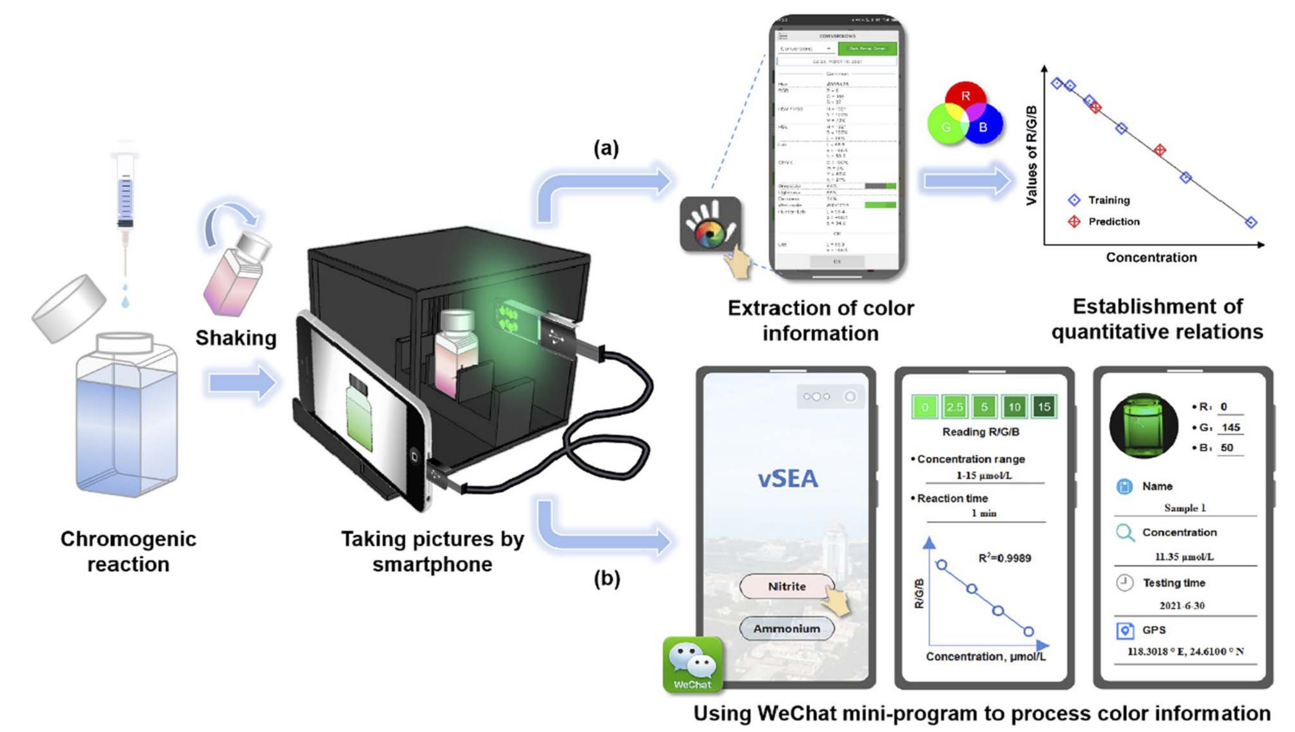

Fig. 2 Workflow of the smartphone-based method for determining nitrite and ammonium in water. After the chromogenic reaction, the colored sample is photographed with a smartphone placed in a homemade device. Image data are processed either (a) by extracting RGB values with a built-in app to build calibration curves or (b) through a WeChat program that automatically converts color information into concentration using pre-stored calibration data. Reproduced from ref. 4 with permission from Elsevier, copyright 2022.

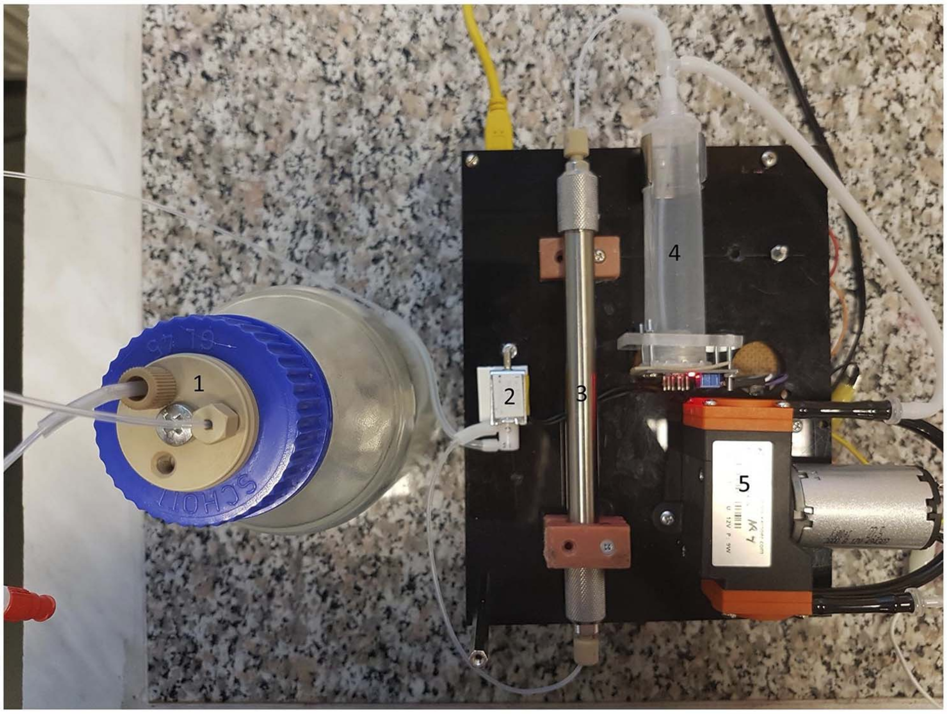

Fig. 3 Portable gas chromatograph for monitoring hydrocarbon emissions into the environment (1 – sample bottle, 2 – solenoid valve, 3 – column, 4 – gas sensor in a 20 mL plastic syringe body, 5 – vacuum pump). Reproduced from ref. 34 with permission from Elsevier, copyright 2021.

encouraging transparency, collaboration, and the exchange of knowledge. In this way, the open-source paradigm brings analytical chemistry closer to the public, reinforcing the participatory and sustainable approach that defines ZAC.[37]

As mentioned by Kaljurand *et al.*, the democratization of analytical chemistry enables motivated individuals with basic scientific knowledge to perform practical measurements aimed at understanding and monitoring their surroundings, including the quality of food, air, and water, as well as personal health indicators. To date, the most significant advances within the framework of ZAC have been achieved through the use of smartphones, which integrate multiple sensors and high-resolution cameras capable of functioning as simple yet effective spectrometers.[7] However, the absence of integrated chemical sensors in smartphones remains both a challenge and an opportunity, opening a broad horizon for technological development and innovation.[37]

4. Opportunities and advantages for analytical chemistry

The ten pillars described above provide the conceptual foundations of ZAC. Building on these principles, the following sections outline the main opportunities and advantages that arise when this framework is translated into practice.

4.1. Integrating technologies for real-time analysis

ZAC can open new opportunities for the analytical community by extending chemical measurements beyond the laboratory and enabling data generation at scales previously unattainable by conventional approaches. The integration of sensor networks connected devices, and Internet of Things (IoT) technologies allows for continuous monitoring of environmental parameters by both experts and more scientifically literate citizens. These tools facilitate the detection of hazardous substances, chemical spills, and pollutants in real time, supporting rapid responses and long-term sustainability strategies. IoT-based sensor systems embedded in irrigation networks, pipelines, reservoirs, weather stations, ocean applications, and industrial infrastructures can measure variables such as temperature, humidity, water levels, or chemical contaminants with high spatial and temporal resolution. This constant flow of environmental data contributes to building large-scale, distributed analytical datasets that enhance the capacity of governments, industries, and local communities to protect air, soil, and water quality.[24]

Image-based datasets are becoming an increasingly common tool for wildlife monitoring, largely thanks to technological advances. While innovations, such as drones and camera traps, can greatly reduce fieldwork time, the subsequent image analysis often represents a major challenge, especially for projects operating with limited funding or personnel. In this context, online initiatives where engaged individual members of the communities contribute to image analysis remotely, are proving to be an effective solution, offering clear benefits in terms of cost efficiency and data processing speed. Here, ZAC can provide a valuable solution by involving non-specialists in data interpretation and pattern recognition. An example is the study by Varela-Jaramillo *et al.*[15] which engaged volunteers to identify and count marine iguanas in aerial drone images from the Galápagos Islands. Each image was shown to several independent participants who marked all visible iguanas. These individual annotations were then aggregated to reach a consensus result, allowing accurate population estimates comparable to expert analyses.

4.2. Environmental monitoring and public health protection

The growing concern over environmental pollution has driven the development of easy-to-use yet reliable tools for citizen-based chemical measurements capable of delivering high spatial and temporal resolution, without compromising analytical accuracy. ZAC can have the potential to transform this field by enabling widespread, real-time environmental monitoring through affordable and accessible technologies.[6] A remarkable example of this progress is the low-cost, rapid, and user-friendly microfluidic sensor developed by Aryal *et al.* for citizen-led phosphate monitoring in surface waters.[38] The sensor operates through a simple "dip-and-read" approach, minimizing procedural steps while ensuring precise sample handling. Over 1000 sensors were distributed globally, allowing citizens from Thailand, Nepal, Brazil, Chile, the United States, and Germany, among others, to collect and analyze water samples. This large-scale initiative led to phosphate mapping across diverse aquatic environments and, through community participation, helped identify regional topographical patterns and local socioeconomic practices potentially contributing to eutrophication. In the same direction, Li *et al.* developed a smartphone-based environmental analyzer for the rapid determination of seawater pH.[5] The system is compatible with a variety of smartphone models, making it widely applicable and suitable for public use in citizen science initiatives. Together, these studies show how ZAC can empower communities to take an active role in public health surveillance and environmental protection by building early warning systems that detect contaminants in real time. Such initiatives democratize access to analytical tools, expand global data collection networks, and bridge the gap between scientific research and societal well-being.

4.3. Education and scientific literacy

Following the perspective proposed by Lüsse *et al.*,[39] citizen science has also been shown to be particularly valuable in formal school education. Analytical chemistry education and popularization provide students with a robust set of skills and tools that make them well prepared to contribute to, and even lead, citizen science initiatives. They can develop a strong foundation in scientific reasoning that allows them to work critically and in an independent manner with communities in defining research questions and designing strategies to tackle local challenges. Their familiarity with key analytical techniques enables them to validate and contextualize the data generated by community participants, collaborating with emancipatory learning processes. Hands-on experience with sampling and fieldwork further ensures that they can bridge laboratory expertise with real-world application.[40] In addition, chemometrics can enable students with the capacity to handle complex, large and often noisy datasets, a common feature of citizen science projects. Exposure to case studies that span environmental monitoring, food safety and public health issues strengthens their ability to connect laboratory results with broader societal implications.[41] This integration of technical proficiency, critical thinking and applied problem-solving aligns with the sustainability and community-oriented goals of citizen science, positioning analytical chemistry graduates and technicians as catalysts for collaborative and evidence-based action.[42] Some studies have shown that citizens who participate in citizen science projects tend to develop more positive attitudes.[15] Therefore, involving the public not only benefits the project and the scientific community, but also promotes critical education and social interest in different fields, including good scientific communication.[43] In this educational context, hands-on resources such as home experiment kits have been shown to further support engagement, reflection, and discussion around scientific topics.[44]

Evidence from youth-focused community and citizen science programs also suggests that educational benefits increase when young participants move beyond short, one-off data collection activities and take responsibility for key parts of the scientific process. For example, Ballard *et al.*[45] highlight that strong learning outcomes are linked to the development of environmental science agency, which combines scientific understanding with young people's identification with scientific practices and their belief that they can act on environmental systems. In practice, this agency is supported when students are encouraged to ensure rigorous data collection, communicate findings to authentic external audiences such as communities, managers, or scientists, and engage with complex social-ecological problems that connect environmental change with human activities. These program features can strengthen motivation and scientific literacy, while helping learners perceive citizen science as relevant through links between analytical work, real-world conservation actions, and decision-making contexts.

4.4. An open door to everyone

One of the defining strengths of ZAC lies in its inclusivity: anyone, regardless of *e.g.*, age, background, region, gender, or scientific expertise can contribute to data collection and analysis.[14] From school children to retirees, ZAC can create pathways for all members of society, globally, to engage in meaningful scientific inquiry. The ultimate goal is that any individual, regardless of their prior training or resources, can perform an analytical measurement, whether to assess air quality, test drinking water, or check the authenticity of food products, interpret and/or use such scientific data. When inviting non-specialists to participate in research projects, tests and analytical targets must be simple, intuitive, and safe to use. A key part of this simplification process involves identifying a single analyte or parameter that can provide useful information about a broader issue. For example, instead of analyzing hundreds of compounds across a metabolome, detecting a single metabolite representative of a metabolic pathway related to a disease may suffice. Time and accessibility are also decisive factors. The requirement for lengthy incubation periods, complex sample preparation steps involving centrifugation, or the use of costly materials creates barriers to public adoption. Extended waiting times can discourage participation, and realistically, not many people have access to a centrifuge at home. Hence, ZAC supports the "make it as simple as possible" approach, emphasizing usability, affordability, and engagement.[18]

However, inclusivity should not be assumed as an automatic outcome of citizen science. Recent critical work highlights that participation in many large-scale projects is influenced by social and economic barriers, and that "where" people live and "what" resources they have can directly influence "what" data are produced. For instance, spatial monitoring projects may generate uneven coverage when participation is concentrated in wealthier or more privileged areas, resulting in data gaps that can mirror existing racial and class-based inequalities and, in turn, bias the knowledge produced and the decisions informed by these datasets.[46] In addition, experiences from projects working with marginalized and Indigenous communities show that barriers such as limited infrastructure, safety concerns, unequal knowledge hierarchies, and unclear data rights can restrict participation, even when the scientific goals are socially relevant.[47] These studies converge on a key point: "citizen science can broaden participation only when project developers intentionally design for equity, accessibility, and long-term engagement, rather than relying on voluntary participation alone". At the same time, evidence shows that, when such principles are considered in project design, meaningful participation is also possible in remote or resource-limited settings. In these contexts, even students can carry out relevant scientific investigations using tools they already possess, such as smartphones, cameras, or webcams.[48,49]

5. Challenges and risks

Rather than focusing only on its benefits, it is also important to consider the challenges that may arise when applying the ten pillars of ZAC. The following sections explore the main risks, limitations, and concerns that should be addressed to support responsible and sustainable implementation.

5.1. Data quality and reproducibility

As highlighted by Fritz *et al.*[50] and Varela-Jaramillo *et al.*[51] one of the main barriers in citizen science lies in the uncertainty surrounding the quality of the data generated by non-professional participants. This remains one of the most widely debated and studied issues in the field of citizen science.[52] So here one of the solutions would be to create complementary methods for triangulating data collected by different individuals involved in the same project (*e.g.*, greater number of replicates, diversity of methodologies for analyzing parameters of interest, among others). Kosmala *et al.*[53] demonstrated that citizens can produce scientifically valid and valuable data, comparable in quality to those obtained by professional researchers. A remarkable example is the Mosquito Alert initiative, which has provided crucial information on the spread of the Asian tiger mosquito (*Aedes albopictus*) in Spain through active citizen participation.[54] In this study, data collected by citizens were compared with those obtained using traditional surveillance methods across a large geographic area. The comparison was made based on (1) economic cost, (2) effectiveness as an early warning system, and (3) the ability to capture spatial-temporal variations in human-mosquito encounter probabilities. The authors demonstrated that citizen-collected data can be obtained faster and at lower cost, while maintaining an accuracy level comparable to traditional monitoring approaches. To achieve such reliability, several quality assurance strategies have proven effective, including: (i) volunteer training/education and continuous feedback;[55] (ii) comparison with professionally collected data; (iii) expert validation; (iv) peer review; (v) automated outlier filtering; (vi) consensus-based evaluation methods; and (vii) the use of standardized and calibrated measurement tools.[53] These approaches allow differences in participants' skill levels to be absorbed at the system level rather than determining data quality at the individual level. Furthermore, AI and data mining are playing a growing role in improving data accuracy and consistency,[50] especially when they are used critically. Consequently, the quality of citizen-generated data can and should be evaluated using the same standards applied to official datasets, as proposed by Koel.[56] However, Ali *et al.*[57] observed that the accuracy of reported results varies depending on the participant's level of experience, with trained and expert users providing more consistent and reliable measurements. This aspect emphasizes the importance of taking participant expertise into account when designing citizen science campaigns.

5.2. Ethical and privacy risks

Ethical and private concerns are among the most sensitive challenges facing ZAC. When citizens take part in generating analytical data related to air quality, food safety, or personal health, questions naturally arise about who owns the data, when and how it is used, and who can access it.[16] Measurements gathered through mobile devices or connected sensors can unintentionally reveal personal, geolocated, or health-related information, creating potential privacy risks. At the same time, the open sharing of analytical datasets must be carefully balanced with responsible data management to prevent misuse or misinterpretation. Ethical frameworks should therefore guarantee informed consent, anonymization of sensitive information, and clear communication about the purpose and limitations of data collection.[58] For ZAC projects to succeed, they must not only comply with existing legal standards such as the General Data Protection Regulation in Europe, but also promote a culture of trust, transparency, and accountability that protects participants while preserving the openness that gives citizen science its transformative power.[59,60]

To address these challenges in practice, ZAC initiatives should integrate ethical and privacy safeguards from the project design stage.[22] This includes applying data minimization principles, ensuring that only strictly necessary information is collected, as well as using spatial or temporal aggregation when geolocation data are required, in order to reduce re-identification risks. Anonymization and pseudonymization strategies, such as the removal of personal identifiers, the use of randomized participant codes, and secure hashing or encryption techniques, can further prevent the linkage of analytical results to individual participants. In addition, tiered data-access models may be adopted, whereby aggregated datasets are made openly available, while raw or high-resolution data remain accessible only to authorized users under clear ethical agreements. Transparent informed-consent procedures and participatory governance models, in which communities are involved in decisions regarding data use and dissemination, can also help ensure responsible access.

5.3. From the (technological) valley of death to life

This metaphor describes a critical stage in the innovation development process, where a technology or project fails to transition from the research and prototype phase to commercialization and self-sustainability. Some of the technologies mentioned are already available, but others will require substantial financial investment to move forward. This will involve validating methods in laboratories, conducting field trials, and scaling up device production. To overcome this challenge, it will be essential for technology providers to work closely with academic specialists in order to develop tailored, innovative solutions.

5.4. Social and psychological challenges

When considering the adoption of ZAC-based initiatives by individuals and general public globally, it is important to acknowledge the social and psychological challenges involved. Not everyone will be interested in learning or performing scientific tests, and this reality must be addressed. However, inviting and providing users with a direct personal benefit could help shift this perception. When individuals perform analyses related to health monitoring, food quality verification, or environmental exposure, they may feel more motivated to participate actively, as they can perceive a tangible and immediate impact on their well-being and surroundings.[61] This sense of personal commitment can transform initial curiosity into long-term engagement, strengthening public participation in data generation and reinforcing the critical and system thinking connection between science and society that defines the ZAC approach. Participation could also become more appealing when linked to causes with which people feel emotionally connected.

Likewise, good and effective communication challenges must be anticipated. The results of citizen-led analyses will be questioned, particularly on social media, as often occurs with scientific information in general, potentially giving rise to skepticism, misinformation, or the spread of oversimplified interpretations.[62] For this reason, effective and proactive communication strategies are important to properly inform participants, communities, and broader audiences, and to counteract misinformation at its source. When used strategically, social media can become a key ally rather than a barrier in this process. Platforms such as X, Instagram, YouTube, TikTok, or community-based forums can be used to provide explanations of methodologies, clarify uncertainties and limitations, and communicate results using accessible yet scientifically accurate language. The involvement of recognized scientific institutions, universities, and professional analytical chemists in social media communication further strengthens trust and helps distinguish evidence-based information from speculation. Moreover, visual formats such as short videos can improve understanding of how measurements are performed and how results should (and should not) be interpreted.[63] Also, active moderation, rapid responses to emerging misinformation, and two-way dialogue with communities are ways to build trust, address doubts in real time, and prevent the amplification of false narratives. Moreover, beyond the choice of communication platforms, the way information is shared should be considered. Using clear and simple language helps nonspecialists understand the results, while openly explaining uncertainties, limitations, and possible sources of error supports realistic expectations and builds trust.[64]

6. Looking ahead

The future of analytical chemistry faces both exciting opportunities and significant challenges. As global concerns about climate change, environmental degradation, and food security continue to grow, analytical science will need to advance toward greater accessibility, sustainability, and social relevance. ZAC is positioned to respond to these needs by extending the reach of analytical measurement beyond specialized laboratories and into the hands of individuals and communities around the world.

Community-driven air quality monitoring networks, citizen initiatives to detect food fraud, and grassroots efforts to track pollutants in water, soil, and consumer products are already widespread and actively contributing to environmental and public health knowledge. Rather than emerging anew, a key opportunity lies in strengthening collaboration between analytical chemists and these existing initiatives, by sharing instrumentation, methodological expertise, and analytical frameworks. When such local actions are connected and supported, they can generate large-scale datasets that complement academic research and inform public policy. Through this collaborative engagement, analytical chemistry can act as a bridge between science, society, and decision-making, providing reliable and actionable data on issues that directly affect everyday life.

Some of these advances are already becoming reality. For example, the integration of sensors with mobile phones and deep learning algorithms demonstrates how cutting-edge technology can be adapted for public use.[65] With current and future smartphones, additional features such as geolocation and time stamping could be harnessed to create real-time spatiotemporal maps of collected data.[66] Similarly, machine learning can be applied to analyze drone imagery, train AI for pattern recognition to reduce computer training time and assist in data filtering. This approach is expected to enhance volunteer participation and decrease the overall duration of online projects.[15]

Looking ahead, ZAC also holds the power to make analytical science more inclusive. By lowering technical and financial barriers, it opens the door for underrepresented groups to take part in scientific discovery, decisions and communication, whether through schools, community labs, or online platforms. Encouraging diverse participation not only enriches the scientific process, but also ensures that the benefits of analytical innovation reach all segments of society.

Through the adoption of the ZAC perspective, it is expected that both researchers and citizens will be inspired to embrace a shared and democratic vision of science, empowering communities, nurturing curiosity, and reaffirming that analytical science is for everyone.[7]

7. Conclusions

ZAC describes an approach in which chemical measurements are not limited to specialized laboratories but are increasingly connected to society. It builds on existing practices in citizen science and community-based monitoring, and highlights collaboration between professional analytical chemists and citizens. Through simple, affordable, and open tools, people can study the chemistry of their surroundings, for example by testing air, water, or food, and contribute data related to everyday concerns. This approach does not replace established analytical methods. Instead, it complements them by increasing the geographic and temporal reach of data collection and by linking scientific questions to real social and environmental needs, contributing to science popularization. Individuals and communities with different backgrounds can take part in meaningful scientific activities, while analytical chemists provide methodological guidance, data validation, and interpretation. In this way, analytical chemistry connects scientific knowledge with society and decision-making, supporting socio-environmental actions, public health protection, and transparent policy processes. At the same time, this participatory approach shows that inclusivity cannot be assumed automatically. Issues such as data quality, ethics, privacy, and long-term participation require careful attention. Training, clear communication, and sustained collaboration are necessary to ensure reliable results and mutual trust. When these aspects are considered, ZAC can help people to understand the role of chemistry in daily life and encourage informed participation in scientific and societal discussions.

Author contributions

A. Fuente-Ballesteros, conceptualization, formal analysis, investigation, methodology, visualization, writing original draft, writing review & editing; V. Samanidou, writing review & editing; V. G. Zuin Zeidler, supervision, writing review & editing.

Conflicts of interest

There are no conflicts to declare.

Abbreviations

AI	Artificial intelligence
CAC	Click analytical chemistry
CE	Capillary electrophoresis
DAC	Disposable analytical chemistry
DIY	Do-it-yourself
GAC	Green analytical chemistry
GC	Gas chromatography
IoT	Internet of things
SAC	Smart analytical chemistry
WAC	White analytical chemistry
ZAC	Citizen analytical chemistry

Data availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this perspective article.

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