Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 22 May 2026
Revised 26 June 2026
Accepted 18 July 2026

Natural Resources for Human Health 2026, Vol. 6 (8s): 451–456

KEYWORDS:
Green chemistry, Contamination, Microextraction, Biosensors, Clean water, Sustainable analysis, Aquatic monitoring, Environmental monitoring.

Analyzing Aquatic Systems: The Integration of Green Chemistry Principles in Water Quality Testing

[1]Gowtham Raj A, [2]Sowmya C, [3]Hemnath S, [4]Sujatha K*

[1]Department of pharmaceutical chemistry, Sri Ramachandra Faculty of Pharmacy, Sri Ramachandra Institute of Higher Education and Research (DU), Porur, Chennai-16
Mail: gowthamraj12403@ gmail.com
[2]Department of Pharmaceutics, Sri Ramachandra Faculty of Pharmacy, Sri Ramachandra Institute of Higher Education and Research (DU), Porur, Chennai-16
Mail: drcsowmya@sriramachandra.edu.in
[3]Department of pharmaceutical chemistry, Sri Ramachandra Faculty of Pharmacy, Sri Ramachandra Institute of Higher Education and Research (DU), Porur, Chennai-16
Mail: hemuhemnath870@gmail.com
[4]*Department of pharmaceutical chemistry, Sri Ramachandra Faculty of Pharmacy, Sri Ramachandra Institute of Higher Education and Research (DU), Porur, Chennai-16,
Mail: sujatha.k@sriramachandra.edu.in

ABSTRACT: Industrialization and the ongoing human activities that continue to add environmental pollutants mandate that the monitoring of the quality of water be sustainable, dependable and timely. In general, prior technologies, though highly sensitive, continue to use of hazardous reagents, frequent organic solvent extractions and large amounts of energy for instruments, and many generate toxic residues in the overall scheme. The green chemistry guidelines thus, prescribe directions toward water quality monitoring which is less toxic, safer, efficient, sustainable for clean water, and is able to protect under-water natural habitats. This review highlights how the necessity of reducing the pollution of water, lowering toxicity and the real-life conditions prompt us towards rapid water quality tests. Various approaches including microextraction techniques, paper-based devices, microfluidic platforms, biosensors, greener and gentler oxidants and reduction in the handling of solvent are covered. New strategies like solid-phase microextraction (SPME), dispersive liquid-liquid microextraction (DLME) and hollow-fiber microextraction (HFME) could reduce the use of organic solvent in an efficient and sensitive manner. A good amount of research interest is focused on portable, low-power, hand-held and rechargeable biosensor systems and microfabricated devices that allow in situ analysis of the samples. The green methods also are applied to foods and plants as well as waters. For example, for the applications of water in analysis of nutrients and heavy metals, there is the in-situ estimations of some harmful pollutants into the water media by reduced matrix effects and it may also apply to pollution remediation of those substances. However, matrix effect, scalable operation and other practical considerations of such green technologies must be discussed at length. Incorporating green chemistry into water testing is a vital step toward sustainable environmental monitoring for promoting the resilience of healthier aquatic ecosystems.

INTRODUCTION

Water quality analysis is a key component of sustainable public health, resource management and environmental protection, and. The growth rate of urbanization, industrialization, and agricultural activities is a major factor in the rising level of nutrients, heavy metals, pesticides, pharmaceuticals, endocrine-disrupting compounds, and microplastics in water bodies around the world. Water pollution can range from ecological imbalances to serious health impacts. The traditional analysis of these water pollutants, such as acid digestion, Soxhlet extraction, and dichromate-based COD analysis, requires dangerous chemicals, produces hazardous waste, and requires energy-intensive analytical equipment [1,2]. Although these analysis methods provide quantitative data with high accuracy, their environmental impact is not aligned with the principles of sustainable analytical chemistry.

The 12 principles of green chemistry proposed by Anastas and Warner are a helpful starting point when developing a new chemical process aiming to prevent the generation of hazardous substances and to use less hazardous chemicals. Water analysis is known as a good application for this strategy for reducing our environmental footprint while ensuring no deterioration in analytical quality. This concept has been extended to green analytical chemistry as a thread in the aim of establishing less toxic, highly selective and green measurement procedures. When green chemistry is applied in aquatic environment, favoured techniques usually consist of methodologies requiring very little, zero or even negative consumption of any hazardous substances; they often utilize reduced energy and amount of waste, and offer the possibility for in situ direct analyses. This review discusses about low energy instrumentation, biosensor technology, microfluidic systems, miniaturized analytical instruments, sustainable sample preparation, and greener reagents, along with critical comments concerning the application of green chemistry in water quality monitoring. However, practical implementations of greener analytical techniques showed convincing success, so it seems that green chemistry is promising in this area, and after having a clear overview of the current state of the field, the current work proposes an outlook on new research directions for a green analytical method for water quality monitoring.

WATER QUALITY TESTING AND LIMITATIONS OF CONVENTIONAL METHODS

Water quality assessment typically requires scanning a host of physicochemical variables including but not limited to the following: pH, Conductivity, Dissolved oxygen DO, Turbidity, Chemical oxygen demand COD, Biological oxygen demand BOD, Nutrients, Toxic metals, Organic substances and also Microbiological Parameters. [5]. All these things are typically tested with conventional techniques, where for example COD is taken care of via dichromate oxidation, DO via Winkler titration, nitrogen using Kjeldahl digestion, organics through Soxhlet extraction, and metals are evaluated with atomic absorption spectroscopy. Even though these methods are conventional and pretty widely trusted, they still bring serious environmental risks into the picture.

In particular, the use of potassium dichromate, a hexavalent chromium compound that is a known carcinogen, in dichromate oxidation COD analysis in the presence of concentrated sulfuric acid poses significant environmental hazards due to the production of hazardous waste containing Cr(VI) [6]. The use of nitric or perchloric acid, which may be required at high temperatures in various metal digestion analysis, increases energy consumption and reagent requirements [7]. The analysis of traditional organic pollutants may require the use of several hundred millilitres of chlorinated solvents, such as dichloromethane or chloroform, which are environmentally persistent and toxic [8]. These methods are therefore inconsistent with the strategy of reducing the formulation of hazards and minimizing waste generation.

Moreover, the high energy consumption by some spectrometric instruments like gas chromatography-mass spectrometry (GC-MS) and inductively coupled plasma-mass spectrometry (ICP-MS) goes against the aim of Sustainability. Sample to analysis times and laboratory infrastructure support requirements restricts the possibility of in-situ analysis and has driven the research for greener analytical methods which requires minimal energy, pose less threat to the environment with comparable or higher levels of sensitivity.

GREEN CHEMISTRY PRINCIPLES IN WATER ANALYSIS

A number of principles of green chemistry can be combined with the basic method outlined for water quality monitoring. In particular, the reduction of sample preparation size reduces waste by minimizing solvent consumption, and the replacement of dangerous oxidants and metal ions with less hazardous reagents is preferred in colorimetric analysis [3]. The technique also favors low-temperature reactions, solar-powered sensors and hand-held analysis tools, so as to save energy. Other green principles include real-time analysis, as exemplified by in-situ sensors or lab-on-a-chip systems that consume few resources and cause little degradation of samples by providing immediate results without prolonged storage and transport [9].

Furthermore, from a chromatographic point of view regarding the analysis of organic pollutants, the number of derivatization reactions should be kept to a minimum to avoid over modification and reagent consumption. Green feedstocks are represented by the development of biosensors and biomaterials, such as cellulose-based microfluidic devices. In conclusion, the above considerations define the conceptual framework for sustainable water analysis.

Table 1. Application of Green Chemistry Principles in Water Quality Testing

Green Chemistry Principle	Application in Water Testing	Example Method
Waste Prevention	Minimizing reagent and sample volumes	Solid-phase microextraction (SPME)
Safer Solvents & Auxiliaries	Use of water or bio-based solvents	Deep eutectic solvents (DES) extraction
Energy Efficiency	Low-energy or ambient-temperature analyses	Portable spectrophotometers
Design for Degradation	Biodegradable sensing materials	Paper-based microfluidic sensors
Real-Time Analysis	On-site continuous monitoring	Electrochemical biosensors

GREEN SAMPLE PREPARATION TECHNIQUES

In fact, some of the most influential journals of the time either originated or developed their characteristic features during this period, such as Lirica y Pensamiento, Cuadernos Americanos, El Combate, Antropo, and Letras de Mexico.

Sample preparation is the most time-consuming step in an analytical procedure. Green sample preparation methods often provide a dramatic reduction in solvent usage by avoiding the use of hazardous reagents and optimizing sample preparation throughput. Of these, solid-phase microextraction (SPME) is one of the most successful green extraction methods. It avoids the use of organic solvents by directly adsorbing the analytes from the sample matrix to a coated fiber, followed by thermal desorption into a GC-MS analyzer. This method has been successfully applied to the analysis of volatile organic compounds, pesticides, phenols, and pharmaceuticals in aqueous samples. SPME is a green technology that uses zero organic solvent, is highly sensitive, and can be automated.

Other successful developments include dispersive liquid-liquid microextraction, which uses only microliters of extraction solvent and provides a high enrichment factor for the determination of metals, phenolic compounds, and organic pollutants with fast phase separation; hollow-fiber liquid-phase microextraction, which uses porous fibers as a selective barrier to provide low solvent consumption and acceptable selectivity; and solvent-free methods such as pressurized hot water extraction and ultrasonic extraction, which reduce the use of hazardous chemicals and energy consumption. Collectively these methods present environmentally friendly choices that are aligned with green chemistry philosophy.

Table 2. Comparison of Green Sample Preparation Techniques

Technique	Solvent Usage	Advantages	Typical Applications
SPME	Solvent-free	Highly green, rapid, reusable fiber	Volatile organics, pesticides
DLLME	Low μL levels	Fast, high enrichment factor	Trace metals, dyes
HF-LPME	μL solvent inside fiber	High selectivity, low cost	Pharmaceutical residues
μSPE	Significantly reduced	Portable, high throughput	Drug metabolites

GREEN ANALYTICAL REAGENTS AND MEASUREMENT METHODS

In the context of water quality testing, Green Chemistry's application mostly focuses on substituted toxic conventional reagents with greener substitutes. For example, in chemical oxygen demand (COD) determination, potassium dichromate has been replaced by greener oxidizing agents such as persulfate and hydrogen peroxide. They ensure oxidation efficiency and also avoid formation of hazardous chromium contain waste [13]. Biomaterials derived reagents were widely adopted for example, enzymatic sensors of the level of phenolic pollutants has been constructed using horse radish peroxidase or laccase enzymes [14]. Furthermore, Microbial fuel cell (MFCs) could convert oxidation of organic compounds to electrical signals, serving as a green and cleaner method for biochemical oxygen demand (BOD) due to reduced reagent usage and shorter incubation time [15]. Eco-friendly colourimetric detection for heavy metal ions is developing, there were several approaches in detection for example using green chelating agents and natural plant extracts.

MINIATURIZED AND LOW-ENERGY INSTRUMENTATION

Breakthroughs in portable and microfabricated technologies have greatly improved the greener approach to monitoring water quality. Smartphone sensors, portable spectrophotometers, and electrochemical meters eliminate the need for laboratory equipment, thereby lowering energy use [16]. Lab-on-a-chip technology refers to a small device that combines microchannels, micro-pumps, and micro-detectors, which function using microliter amounts of reagents, thereby allowing complex analysis to be done in a small device [17]. This technology helps in waste reduction and allows for in-situ analysis without the need for transporting samples. Portable X-ray fluorescence (XRF) analyzers greatly lower toxic waste generation because they allow for fast metal analysis without the need for sample digestion. Other examples of conventional devices that have been made greener include inductively coupled plasma-optical emission spectrometry (ICP-OES) instruments that consume low argon, as well as water-rich mobile-phase liquid chromatography-mass spectrometry (LC-MS) [18].

BIOSENSORS AND BIOLOGICAL METHODS

Research is ongoing to create biosensors using algae, bacteria, and enzymes for the detection of trace amounts of organic pollutants, heavy metals, and nutrients with reduced environmental effects. Biosensors can be viewed as an alternative to the traditional five-day biochemical oxygen demand test, as microbial fuel cell sensors for BOD analysis can be done quickly and without reagents [19]. Biosensors are a new type of ecologically friendly analytical tool that combines low-power sensing technology with renewable biological components.

DNA biosensors and aptamer technology use a minimal amount of reagents for the detection of organic pollutants and infectious agents. Biodegradable cellulose-based paper microfluidic devices are gaining popularity for the colorimetric analysis of nutrients, heavy metals, and pharmaceuticals. These devices do not require external power, produce minimal waste, and are ideal for developing countries [20].

Table 3. Emerging Green Analytical Devices for Aquatic Monitoring

Device Type	Key Green Features	Target Analytes
Paper-based PADs	Biodegradable, no solvents, ultra-low waste	Nutrients, metals
Microfluidic Chips	µL reagent volumes, miniaturized	Pesticides, pharmaceuticals
Biosensors	Enzyme-based, renewable, low-energy	BOD, COD, heavy metals
Portable Spectrometers	Low energy, field-friendly	Organic contaminants

CASE STUDIES IN GREEN WATER QUALITY MONITORING

A range of studies shows that green chemistry principles are finding their way into established water monitoring procedures. For instance, SPME has been successfully implemented in Spain for pesticide analysis of a river system because of a combination of reasonably high sensitivity and lower demand for organic solvent [21]. In rural India, paper-based nitrate assays can act as a simple proxy indicator for agricultural run-off providing fast results without cumbersome lab procedures [22]. Portable, smartphone based colorimetric methods also hold a great promise for determination of lead and arsenic in drinking water [23]. Finally, green H_2O_2-mediated COD method appears to be performing well for analysis of wastewaters and showing excellent agreement with traditional dichromate method [24]. It is obvious from these few examples that the notion of green methods may be evolving out of the pure abstract domain.

CRITICAL ANALYSIS

However, these green technologies also pose a number of challenges, such as matrix effects that can affect microextraction procedures and may require exhaustive processing to obtain repeatable data. Although biosensors are environmentally friendly, the biological parts that are usually incorporated into these sensors also pose temporal instabilities.

The lack of standardized regulatory guidelines is also a factor that has contributed to the disparate use of green analytical methods among environmental agencies. These challenges are being quickly remedied by the rapid progress being made in materials science, nanotechnology, and microfabrication. Increasing demands for point-of-use water analysis and regulatory mandates are expected to drive the shift towards greener technologies.

FUTURE DIRECTIONS

Future research will be cantered on reagent-free detection systems, such as optical sensors that can function without chemical reagents. The combination of machine learning and artificial intelligence is expected to improve the accuracy of sensors and predictive modelling of pollutant dynamics. Solar-powered analytical instruments, biodegradable sensor platforms, and multi-analyte microfluidic systems are expected to improve accessibility. In addition, a greater degree of harmonization with existing frameworks will be necessary to increase the use of green technologies in environmental monitoring.

CONCLUSION

Thus, the application of green chemistry guidelines on water quality assessments can be referred as an innovative paradigm in sustainable development of water quality assessments. This paradigm represents substantial reduction of hazard reagents used, minimization of waste generated, energy efficiency, and move to real-time detection. Accordingly, green analytical chemistry as a practical method has emerged as effective substitute against conventional water quality method because of decrease of hazard chemical, waste generation, energy saving, and real-time detection thereby ensuring the protection of water aquatic ecosystems. So far greener oxidants, biosensors, microfluidic devices and microextraction have already been applied in determine a various aquatic contaminant. Although a series of obstacles present in its development the swift advancement of this technology as well as a growing conscious on greenness is certain to lead to increasing application of green water analysis. Indeed, such a new analytical approach would even prove to be crucial in future in maintaining our valuable natural resources and protecting natural water bodies from contaminating.

REFERENCES

[1] Bartram J, Ballance R. *Water Quality Monitoring: A Practical Guide to the Design and Implementation of Freshwater Quality Studies.* London: CRC Press; 1996.
[2] Manahan SE. *Environmental Chemistry.* 9th ed. CRC Press; 2009.
[3] Anastas PT, Warner JC. *Green Chemistry: Theory and Practice.* Oxford University Press; 1998.
[4] Gałuszka A, Migaszewski Z, Namieśnik J. The 12 principles of green analytical chemistry. *TrAC Trends Anal Chem.* 2013;50:78-84.
[5] APHA. *Standard Methods for the Examination of Water and Wastewater.* 23rd ed. American Public Health Association; 2017.
[6] Chen J, Wu W, Chen W. Replacement of dichromate in COD tests: A review. *Water Res.* 2015;80:221-232.
[7] Boss CB, Fredeen KJ. *Concepts, Instrumentation, and Techniques in Inductively Coupled Plasma Optical Emission Spectroscopy.* PerkinElmer; 2004.Płot
[8] ka-Wasylka J. Green sample preparation techniques. *Talanta.* 2018;181:204-219.
[9] Płotka-Wasylka J, Namieśnik J. Green analytical chemistry in water analysis. *Anal Chim Acta.* 2018;1025:1-16.
[10] Pawliszyn J. Solid-phase microextraction in environmental analysis. *Anal Chem.* 1991;63(24):2143-2148.
[11] Rezaee M, Assadi Y, Hosseinia MR. Dispersive liquid–liquid microextraction. *J Chromatogr A.* 2006;1116:1-9.
[12] Pedersen-Bjergaard S, Rasmussen KE. Liquid-phase microextraction. *Anal Chem.* 1999;71:2650-2656.
[13] Sanches S, Crespo MT, Pereira VJ. Persulfate oxidation for COD determination. *Water Sci Technol.* 2011;64(11):2252-2258.

[14] Rodríguez Couto S, Toca Herrera JL. Laccase applications in water treatment. *Biotechnol Adv.* 2006;24:500-513.
[15] Kumar SS, Mohan SV. Microbial fuel cell sensor for BOD. *Biosens Bioelectron.* 2012;35(1):236-241.
[16] Sun S, Zhang L, Zhu J. Portable water analysis devices. *Anal Methods.* 2018;10:2845-2858.
[17] Sackmann EK, Fulton AL, Beebe DJ. The present and future of microfluidic platforms. *Nature.* 2014;507:181-189.
[18] Płotka-Wasylka J, Frankowski M. Greener LC-MS methods. *Green Chem.* 2021;23(5):1984-2001.
[19] Di Lorenzo M, Thomson AR, Schneider K. MFC-based biosensors for water monitoring. *Biosens Bioelectron.* 2014;62:182-188.
[20] Martinez AW, Phillips ST, Whitesides GM. Paper-based microfluidics. *Anal Chem.* 2010;82:3-10.
[21] Zeng Y, Wang Z, Lentz M. SPME analysis of pesticides in river water. *J Chromatogr A.* 2013;1300:169-175.
[22] Gupta P, Verma N. μPAD nitrate detection in groundwater. *Environ Monit Assess.* 2019;191:1-12.
[23] McCracken K, Yoon J. Smartphone-based heavy metal detection. *Sens Actuators B.* 2016;231:674-680.
[24] Li X, Li Y. Evaluation of H_2O_2-based COD methods. *Environ Sci Pollut Res.* 2014;21:12354-12362.