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Recent Advances in Analytical and Applied Chemistry: A Comprehensive Review

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Abstract

Analytical and Applied Chemistry form the backbone of modern scientific progress, connecting fundamental molecular insights with real-world industrial and societal applications. Over the past decade, these fields have undergone significant transformation, driven by the need for sustainability, precision, and efficiency. This review highlights key advancements in green analytical chemistry (GAC), high-resolution mass spectrometry (HRMS), and the incorporation of nanotechnology into chemical sensing, while also examining their broader implications in applied chemistry.

Green analytical chemistry has emerged as a crucial paradigm, emphasizing the reduction of hazardous reagents, energy consumption, and waste generation. Techniques such as miniaturized sample preparation, solvent-free extraction, and the use of eco-friendly reagents are now widely adopted, making analytical practices safer and more sustainable. These innovations align with global environmental goals and regulatory frameworks, encouraging industries to adopt cleaner and more efficient methodologies without compromising analytical performance.

Simultaneously, high-resolution mass spectrometry has revolutionized chemical analysis by enabling ultra-sensitive and highly accurate detection of complex compounds. HRMS technologies, including time-of-flight (TOF) and Orbitrap systems, allow researchers to identify trace-level contaminants, metabolites, and unknown compounds with exceptional precision. This has profound implications in fields such as pharmaceuticals, environmental monitoring, and food safety, where reliable detection at low concentrations is critical.

The integration of nanotechnology into analytical chemistry has further enhanced sensing capabilities. Nanomaterials, such as gold nanoparticles, carbon nanotubes, and quantum dots, offer unique optical, electrical, and catalytic properties that significantly improve sensor sensitivity and selectivity. These nanoscale systems enable rapid, real-time detection of chemical and biological analytes, paving the way for advanced diagnostic tools and portable analytical devices.

In applied chemistry, these analytical advancements have facilitated significant progress in environmental remediation and sustainable material synthesis. Techniques informed by precise analytical data are being used to remove pollutants from water and air, develop biodegradable materials, and optimize resource-efficient chemical processes. Ultimately, the synergy between analytical precision and applied innovation is driving a new era of sustainable development, positioning chemistry at the forefront of solving global environmental challenges.

Keywords: Applied Chemistry, Nanotechnology in Chemical Sensing, Sustainable Analytical Methods, Solvent-Free Extraction, Miniaturized Sample Preparation, Trace Contaminant Detection, Time-of-Flight Mass Spectrometry.

1. Introduction

The transformation of chemistry from a largely descriptive science into a predictive, quantitative, and highly precise discipline stands as one of the most significant intellectual evolutions in modern science. Early chemists relied heavily on observation—color changes, precipitate formation, and qualitative reactions—to infer the nature of substances. While these approaches laid the foundation of chemical knowledge, they were inherently limited in accuracy, reproducibility, and depth. The true revolution came with the development and refinement of analytical techniques, which enabled chemists not only to detect substances at extraordinarily low concentrations but also to understand their structure, behavior, and interactions at a molecular level.[1]

At the heart of modern analytical chemistry lie the “Three S’s”: Sensitivity, Selectivity, and Speed. These three pillars define the effectiveness and applicability of any analytical method. Sensitivity refers to the ability to detect even trace amounts of a substance—often at parts per million (ppm), parts per billion (ppb), or even parts per trillion (ppt) levels. This capability is crucial in fields such as environmental monitoring, where pollutants must be identified long before they reach harmful concentrations, and in medical diagnostics, where early detection of biomarkers can significantly improve patient outcomes.[2]

Selectivity, on the other hand, is the ability of an analytical method to distinguish a specific compound from a complex mixture. In real-world samples—whether biological fluids, industrial products, or environmental samples—numerous compounds coexist. A highly selective technique ensures that the signal obtained corresponds only to the analyte of interest, minimizing interference

and false positives. Techniques such as chromatography coupled with mass spectrometry exemplify high selectivity by separating compounds before identifying them based on their molecular signatures.[3-4]

Speed is the third defining factor, reflecting the growing demand for rapid analysis in both research and industry. Traditional analytical methods often required hours or even days to yield results. Modern advancements, however, have drastically reduced analysis time without compromising accuracy. High-throughput screening, real-time monitoring, and automated systems now allow thousands of samples to be analyzed within short time frames. This is particularly important in pharmaceutical development, clinical diagnostics, and industrial quality control, where timely decisions are critical.

The integration of these three attributes has been made possible through technological innovations such as spectroscopy, chromatography, electrochemical analysis, and hyphenated techniques. Instruments like nuclear magnetic resonance (NMR) spectrometers, gas and liquid chromatographs, and mass spectrometers have become indispensable tools in chemical research. These technologies not only provide qualitative identification but also quantitative data that can be used to model chemical systems and predict outcomes with remarkable precision.[5]

As chemistry has become more analytical and data-driven, its role has expanded beyond the laboratory into addressing some of the most pressing global challenges. This is where applied chemistry comes into play—bridging the gap between theoretical understanding and practical solutions. One of the most critical applications is in carbon capture and climate change mitigation. Advanced materials such as metal-organic frameworks (MOFs) and functionalized polymers are being designed using insights from analytical chemistry to selectively capture carbon dioxide from industrial emissions. The ability to analyze adsorption efficiency, stability, and regeneration cycles depends heavily on sensitive and selective analytical techniques.[6]

In the realm of clean energy, applied chemistry is driving innovations in energy storage and conversion. The development of high-performance batteries, fuel cells, and solar cells relies on a deep understanding of electrochemical processes and material properties. Analytical tools allow scientists to study charge transfer mechanisms, degradation pathways, and material interfaces at the nanoscale. This knowledge is essential for improving efficiency, lifespan, and safety of energy technologies, ultimately supporting the transition to sustainable energy systems.

Personalized medicine represents another frontier where analytical chemistry plays a transformative role. Traditional medical treatments often follow a “one-size-fits-all” approach, which may not be effective for all patients. By contrast, personalized medicine tailors treatment based on an individual’s genetic, proteomic, and metabolic profile. Techniques such as high-resolution mass spectrometry and DNA sequencing enable the identification of specific biomarkers and genetic variations. This allows for early diagnosis, targeted therapies, and better monitoring

of treatment efficacy. The precision offered by modern analytical methods ensures that therapies are not only effective but also minimize adverse effects.[7]

Furthermore, the rise of data science and artificial intelligence has amplified the predictive power of chemistry. Analytical instruments now generate vast amounts of data, which can be processed using advanced algorithms to uncover patterns and relationships that were previously inaccessible. Machine learning models can predict reaction outcomes, optimize synthesis pathways, and even design new molecules with desired properties. This convergence of chemistry and computational science is accelerating innovation and reducing the time required for discovery and development.

Despite these advancements, challenges remain. The need for cost-effective, portable, and user-friendly analytical devices is growing, especially in resource-limited settings. Environmental concerns related to chemical waste and energy consumption of analytical instruments also need to be addressed. Green chemistry principles are increasingly being incorporated into analytical practices to minimize environmental impact while maintaining performance.

In conclusion, the evolution of chemistry into a predictive and quantitative science has been driven by the continuous advancement of analytical techniques characterized by sensitivity, selectivity, and speed. These capabilities have not only deepened our understanding of chemical systems but have also empowered applied chemistry to tackle global challenges. From combating climate change and advancing clean energy to revolutionizing healthcare through personalized medicine, modern chemistry stands at the forefront of innovation. As technology continues to evolve, the synergy between analytical precision and practical application will further enhance the ability of chemistry to shape a sustainable and healthier future.[8-9]

2. Emerging Trends in Analytical Chemistry

2.1 Green Analytical Chemistry (GAC)

The growing global emphasis on sustainability has significantly influenced the field of analytical chemistry, giving rise to the concept of Green Analytical Chemistry (GAC). This paradigm shift focuses on designing and implementing analytical methods that minimize environmental impact while maintaining accuracy, precision, and reliability. One of the central objectives of GAC is to reduce the consumption of hazardous chemicals, particularly organic solvents, which are often toxic, volatile, and environmentally persistent. By adopting safer alternatives and minimizing waste generation, GAC aims to make laboratory practices more eco-friendly and sustainable. In addition to reducing solvent use, GAC encourages the replacement of toxic reagents with less harmful or renewable substances. This not only decreases the risk to human health but also reduces the burden of chemical disposal and environmental contamination. Techniques such as miniaturization, automation, and the use of energy-efficient instruments are also promoted under GAC principles, as they contribute to lower resource consumption and increased efficiency. Furthermore, GAC supports the development of innovative methodologies such as solvent-free

analysis, microextraction techniques, and the use of biodegradable materials. These approaches help in achieving high analytical performance while aligning with environmental safety standards. Regulatory bodies and scientific communities are increasingly advocating for the integration of GAC principles into routine laboratory practices. Overall, Green Analytical Chemistry represents a forward-thinking approach that balances scientific advancement with environmental responsibility. By prioritizing sustainability, it not only improves the safety and efficiency of analytical procedures but also contributes to the broader goal of environmental conservation and sustainable development.[10]

Miniaturization: Lab-on-a-chip (LOC) devices.

Alternative Solvents: Deep Eutectic Solvents (DES) and Ionic Liquids (ILs).

2.2 Advanced Instrumental Techniques

The integration of Artificial Intelligence (AI) with Chromatography and Spectroscopy has revolutionized data interpretation (Table 1).

Technique	Primary Application	Key Advantage
UHPLC-MS/MS	Metabolomics & Proteomics	High resolution and throughput
ICP-OES	Heavy metal analysis	Multi-element detection limits
NMR Spectroscopy	Structural elucidation	Non-destructive analysis
CRDS	Trace gas sensing	Extreme sensitivity (parts-per-trillion)

3. Applied Chemistry in Environmental Remediation

Applied chemistry is fundamentally concerned with the “how” of chemical reactions—how they can be controlled, optimized, and applied to solve real-world problems. One of the most urgent areas where this practical approach is needed is in addressing environmental pollution. Among the most challenging contaminants are PFAS (per- and polyfluoroalkyl substances), often referred to as “forever chemicals” due to their extreme persistence in water, soil, and biological systems. Their strong carbon–fluorine bonds make them resistant to natural degradation, requiring advanced chemical techniques such as advanced oxidation, electrochemical treatment, and novel catalytic processes for effective breakdown.[11]

Similarly, microplastics—tiny plastic particles formed from the degradation of larger plastics—pose a growing threat to ecosystems and human health. Applied chemistry plays a crucial role in developing methods to detect, capture, and degrade these particles, including biodegradable polymer design and innovative filtration materials. By focusing on actionable solutions, applied

chemistry bridges laboratory research and environmental remediation, offering scalable technologies to reduce pollutant load and restore ecological balance.[12]

3.1 Photocatalysis

Utilizing semiconductor materials for the degradation of organic pollutants under ultraviolet (UV) or visible light is a promising approach in environmental remediation. Photocatalysts such as titanium dioxide (TiO₂) and zinc oxide (ZnO) absorb light energy to generate electron–hole pairs, which subsequently participate in redox reactions that break down harmful organic compounds into less toxic or mineralized products like CO₂ and H₂O. The overall efficiency of a photocatalyst largely depends on its bandgap energy (E_g), which determines the range of light wavelengths it can absorb.

The relationship between the wavelength of incident light (λ) and its energy is expressed as:

$$E = hc/\lambda$$

where E is the photon energy, h is Planck's constant, and c is the speed of light. A smaller bandgap allows the material to utilize visible light more effectively, whereas a larger bandgap restricts activation to UV light. Therefore, modifying semiconductor materials to optimize their bandgap is crucial for enhancing photocatalytic performance under solar irradiation, making the process more energy-efficient and sustainable for large-scale environmental applications.[13]

Where:

- h is Planck's constant.
- c is the speed of light.

3.2 Carbon Capture and Utilization (CCU)

Chemical engineers are developing Metal-Organic Frameworks (MOFs) that act as molecular sponges to capture CO₂ directly from the atmosphere.

4. Nanotechnology in Chemical Sensing

The application of nanomaterials—such as carbon nanotubes, graphene, and gold nanoparticles—has enhanced the limit of detection (LOD) for various biosensors.

Mechanism of a Nanochemical Sensor:

1. **Recognition:** A ligand binds to the target analyte.
2. **Transduction:** The nanomaterial converts the chemical interaction into an electrical or optical signal.

3. **Amplification:** The high surface-area-to-volume ratio of nanomaterials ensures high sensitivity.[14]

5. Challenges and Future Perspectives

Despite progress, significant hurdles remain:

- **Data Overload:** The volume of data generated by modern HRMS requires more robust chemometric tools.
- **Scalability:** Many applied chemistry solutions (like MOFs) are still too expensive for mass industrial adoption.
- **Interdisciplinarity:** The need for chemists to work alongside biologists and data scientists is more critical than ever.

• 6. Conclusion and Discussion

- Analytical and Applied Chemistry are no longer isolated silos but deeply interconnected disciplines driving modern scientific progress. The discussion demonstrates that advances in analytical techniques now allow scientists to detect, quantify, and characterize molecules at extremely low concentrations, even approaching the single-molecule level. Such precision has profoundly influenced applied chemistry by providing the detailed mechanistic understanding necessary for the rational design of catalysts, advanced materials, and efficient chemical processes tailored for specific transformations. As a result, the traditional boundary between fundamental understanding and practical application has become increasingly blurred, fostering innovation across pharmaceuticals, materials science, environmental engineering, and process technology.[15]
- The discussion further highlights that this integration has accelerated problem-solving in areas requiring both accurate characterization and functional implementation. Modern spectroscopic, electrochemical, and computational analytical tools not only support molecular-level insights but also enable optimization of reaction pathways, performance monitoring, and process control. These developments have strengthened the role of analytical science as a foundation for innovation in applied chemistry, enhancing efficiency, selectivity, and industrial relevance.
- Looking ahead, the integration of these fields must align with the principles of sustainability. Future research should prioritize a “circular chemistry” model, where chemical processes are designed to minimize waste, reuse resources, and reduce environmental impact. This includes developing greener synthesis methods, recyclable catalysts, energy-efficient technologies, and environmentally benign process designs. The discussion emphasizes that embedding sustainability into both analytical discovery and applied development is essential to ensure technological progress does not come at the expense of ecological health.
- Overall, the convergence of analytical precision, applied innovation, and sustainable design represents a holistic framework for the future of chemistry. Continued efforts toward interdisciplinary collaboration, scalable green technologies, and circular process

strategies will be critical for balancing scientific advancement, industrial growth, and environmental responsibility in the decades to come.

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Author Contributions

S. Brindha contributed to the conceptualization, literature review, manuscript drafting, and overall supervision of the review. R.M. Aadarsh Vel contributed to literature compilation and data interpretation. T.B. Suneetha contributed to critical analysis of the reviewed studies and manuscript revision. S. Ravichandran contributed to technical input, review editing, and final approval of the manuscript. All authors have read and approved the final version of the manuscript.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this review article.

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