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POINT OF VIEW

Analytical Chemistry at a Crossroads: Integrity, Reproducibility, and Societal Impact

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Over four decades at the University of São Paulo (three as professor), I have witnessed the transformation of analytical and bioanalytical chemistry from a discipline often seen as "supportive" to one that is at the center stage of some of the most critical scientific and technological advances of our time. From the development of DNA sequencing technologies in Boston during my doctoral studies[1] to my sabbatical years at Harvard working on microfluidic paper-based devices,[2] I have seen how analytical chemistry has evolved, contributing to our understanding of life, environment, health, and how it can serve society. Today, analytical chemistry faces significant opportunities and tough challenges. On one hand, our methods enable precision diagnostics, environmental monitoring, and quality control for industries in our modern society. On the other hand, we confront a crisis of reproducibility that erodes the public trust in science and widens persistent gaps in connecting academic excellence with societal benefit.

Analytical chemistry has long been the "invisible science" that guarantees reliability. As I argued previously,[3] it is time we innovate from the bottom up. The COVID-19 pandemic reminded us that diagnostics are not ancillary, but central to public health. Brazil responded with creativity, producing molecular tests and even initiating vaccine development. Yet, our dependency on imported reagents and instrumentation exposed the fragility of our system. This paradox — intellectual strength but industrial weakness — must be addressed at the governmental level if we are to transform knowledge into impact.

The societal impact of analytical chemistry goes beyond health crises. It is central in fields such as food safety, drug development, forensic science, and climate monitoring. Our discipline ensures that decisions are based on solid data, but the credibility of science rests not only on data but also on integrity. For students and colleagues alike, I often stress that analytical chemistry is about more than numbers — it is about truth. Selective reporting, inadequate validation, and neglect of uncertainty undermine not only the quality of science but also the faith in it.

As researchers and educators, we carry the responsibility of transmitting ethical practices to the younger generations. This involves rigor in data handling, transparency in reporting, and humility in acknowledging limitations. Journals, funding agencies, and universities must reinforce ethics and responsible research, but ultimately it is at the laboratory bench where integrity is practiced daily. Unfortunately, we have seen an unprecedented number of paper retractions from journals, and not only from the predatory publishers.[4]

The issue of reproducibility has emerged as a defining challenge for modern science.[5] A recent study we conducted confirmed that analytical chemistry is not immune to this crisis. We found that method validation and measurement uncertainty are frequently misapplied, leading to results that cannot be reproduced with confidence. In nearly one-third of the papers analyzed, uncertainties exceeded 100% at the lowest concentration levels, resulting in questionable conclusions.[6]

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These findings are not isolated, and concerns have been raised across disciplines regarding insufficient statistical training, inadequate replication, and a lack of data transparency. In chemistry, these deficiencies are particularly concerning because our results often serve as the basis for regulatory approval, industrial processes, and clinical decisions. The path forward requires collective efforts. First, we must integrate chemical metrology, method validation, and quality assurance into curricula from undergraduate levels to graduate school. Second, journals should enforce clearer standards for reporting validation and uncertainty, let alone the use of artificial intelligence. Third, open science practices — including data sharing — must become the norm rather than the exception.

Reversing the reproducibility crisis and reinforcing research integrity requires cultural change and education. We must teach future chemists not only how to generate data but also how to ensure that those data can withstand scrutiny and serve society. After all, what good is an analytical breakthrough if it cannot be trusted, reproduced, or applied to real-world challenges?

Analytical and bioanalytical chemistry stand at a crossroads. We have never been more central to the scientific enterprise, but we must also face the truths revealed by the reproducibility crisis. By embracing integrity, rigor, and innovation, we can restore confidence in our results and amplify our impact on society. More than that, we should be able to bring to the spotlight the reasons for unethical behavior in producing data, writing papers, and pushing the productivity numbers (and the toll it takes on the mental health of young researchers). As a professor who has trained generations of chemists at USP, I remain convinced that the way to move forward relies on education, transparency, and the pursuit of truth. Only then will our discipline live up to its promise — to provide the reliable answers upon which science, technology, and society rely.

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Disclosure: To be truthful to the point of view, I declare that artificial intelligence was used to edit, improve, and proofread the text.

Emanuel Carrilho, FRSC, is a Full Professor at the University of São Paulo (USP) with a Master's degree in Analytical Chemistry from USP (1990) with focus in instrumentation for supercritical fluid chromatography, and a Ph.D. from Northeastern University, Boston, USA (1997) in bioanalytical chemistry, helping in the development of DNA sequencing technologies that led to the sequencing of the Human Genome Project. Later, (2007-2009) he spent a sabbatical leave at Harvard University in the Whitesides Group, working on the emergence of microfluidic paper-based analytical devices (μPAD) and wax-printing. The Carrilho group, or BioMicS – Bioanalytical, Microfabrication, and Separations Group, develops new bioanalytical methods and instrumentation covering the broad aspects of genomics, proteomics, and metabolomics for human health, applied cell and microbiology in microfluidic platforms like organs-on-a-chip, searching for biomarkers for cancer, rare, and neglected diseases. Dr. Carrilho has supervised over 60 graduate students and a dozen of post-docs, has published about 200 papers with 9,000 citations, and an h index of 41. CV