Methods 242 (2025) 54–61

Contents lists available at ScienceDirect

Methods

journal homepage: www.elsevier.com/locate/ymeth

Fragile methods, fractured trust: rethinking scientific responsibility☆

Stephen A. Bustin [a,*], Carl T. Wittwer [b]

[a] Medical Technology Research Centre, Faculty of Health, Education, Medicine and Social Care, Anglia Ruskin University, Chelmsford CM1 1SQ, UK
[b] Emeritus Professor of Pathology, University of Utah School of Medicine, Salt Lake City, UT 84109, USA

ARTICLE INFO

Keywords:
qPCR
Gene expression
Molecular diagnostics
Reproducibility
MIQE
Scientific integrity

ABSTRACT

Science has a credibility problem, and it is not just the fault of politicians, journalists, or conspiracy theorists. It begins within science itself. This review examines how flawed methods and selective reporting, combined with overly polished communications that prioritise image over clarity, have normalised bad practice in molecular biology, diagnostics, and related applied sciences. The quantitative real-time polymerase chain reaction (qPCR) offers a clear example: a conceptually simple, technically mature technology that is nonetheless routinely misused, despite published standards and repeated calls for methodological rigour over the past two decades. If qPCR is so often misapplied, what does that suggest about confidence in more complex, less transparent technologies? An additional problem lies in the way scientific findings are misreported or exaggerated. Such distortions have far-reaching consequences beyond individual studies. From the MMR-autism scare to COVID-19 testing and vaccine hesitancy, they have fuelled confusion, eroded public trust, and endangered public health. Consequently, when flawed or overstated findings shape public policy or clinical decisions, the damage undermines science's role as a reliable source of knowledge and informed choice. Credibility must rest on transparent practice, ethical responsibility, and attention to both how results are produced and how they are communicated. Until scientists recognise that communication is not value-neutral, and that our public voice carries consequences far beyond the lab, public scepticism will be justified.

1. Introduction

In biology, as in all science, knowledge is built on uncertainty. Healthy scepticism of scientific claims is therefore not only acceptable, but necessary. It serves to test consensus, challenge assumptions, and refine understanding. Yet in recent years, the trust once instinctively placed in scientists, and the authority this conferred on the scientific culture and its institutions, has eroded. From climate change to vaccines, from genetically modified crops to pandemic responses, the scientific voice, once presumed to be disinterested and grounded in evidence, is increasingly regarded with suspicion or outright hostility. This loss of confidence has serious implications: for scientists themselves, for public understanding, and for public health [1].

Recent efforts at self-scrutiny have focused on communication: greater transparency, clearer messaging, more engagement. But two important caveats remain. First, scientific information is often filtered through ideologically charged or scientifically illiterate media environments. Second, efforts to educate or inform rest on the assumption that the public are listening, an assumption that may no longer hold. Consequently, in many cases, science is not only misunderstood; its legitimacy is challenged.. Entire segments of the public now operate within intellectually closed worlds where there is no longer a shared frame of understanding and accurate communication is dismissed as manipulation. In some circles, the willingness to reconsider one's opinions is not just absent, it is treated as a weakness. This condition casts a long shadow. If scientific trust no longer holds, then no amount of clarity can repair what has become a structural divide.

Yet we cannot ignore our own complicity. Scientific trust is eroded not only from without but also from within. Inconsistently applied methods, selective reporting, and routine exaggeration are sufficiently common to raise uncomfortable questions. Do our own practices, whether through neglect, pressure, or intent, contribute to the mistrust we experience? This review explores how internal scientific behaviours, external communication failures, and intellectual fragmentation have converged to undermine public trust, and draws on the quantitative polymerase chain reaction (qPCR) as a technology that exposes this

☆ This article is part of a special issue entitled: 'Editors Collection - YMETH' published in Methods.

* Corresponding author at: Medical Technology Research Centre, Bishop Hall Lane, Chelmsford, Essex CM1 1SQ, UK.
E-mail address: stephen.bustin@aru.ac.uk (S.A. Bustin).

https://doi.org/10.1016/j.ymeth.2025.07.003
Received 29 May 2025; Received in revised form 1 July 2025; Accepted 7 July 2025
Available online 7 July 2025

scientific fragility.

When compromised practices influence diagnostics, policy, or public debate, they cause real harm: to patients, to populations, and to the credibility of science itself. As we reflect on the world our children will grow up in, where the boundary between opinion and fact is increasingly blurred, we want to remind all of us that the responsibility for scientific integrity does not end with the generation of data. This obligation extends through the systems that shape how science is practiced, conveyed, and understood, and it is one we owe to future generations: our students, our children, our grandchildren.

2. Trust in science: public perception and global variation

Public trust in science reflects a complex interplay of cultural history, education, political polarisation, media framing, and live experience, with religious affiliation also emerging as a significant predictor of attitudes toward scientific claims [2]. Whilst most people still believe that scientists should engage with the public and play a larger role in policymaking [3], the depth and resilience of trust in the integrity of scientific pronouncements are increasingly under strain. This erosion of confidence is not uniform. In countries with strong civic institutions, high levels of education, and transparent governance, scientists continue to command substantial public confidence [4]. In others, however, where trust in government is low or the media landscape cultivates polarisation, scepticism toward science is far more pronounced. France, notably, has some of the lowest levels of trust in science in Western Europe, shaped by a long-standing cultural scepticism toward technocratic authority [5]. This disparity is particularly evident in attitudes toward vaccines. Whilst an already low 72 % of people in Northern America and 73 % in Northern Europe agree that vaccines are safe, confidence is only 59 % in Western Europe and 50 % in Eastern Europe. By contrast, confidence is significantly higher in low-income regions, with 95 % of respondents in South Asia and 92 % in Eastern Africa affirming vaccine safety [5]. The UK ranks 15th out of 68 countries in trust in scientists [3], although that faith is continually undermined by a tabloid media culture that amplifies fringe views [6]. A particularly damaging episode was the MMR-autism controversy, fuelled by sensationalist coverage in outlets such as the *Daily Mail*, which gave sustained attention to Andrew Wakefield's claims despite widespread scientific rejection [7]. The episode continues to have lasting global effects on vaccine uptake and public health [8].

Two decades later, the COVID-19 pandemic exposed and intensified many of the same vulnerabilities. Vaccine hesitancy revealed deep societal rifts, as widespread misinformation, politicisation, and conspiracy theories eroded confidence in one of the most significant biomedical achievements of the century [9]. In the United States, political affiliation is now a stronger predictor of trust in scientists than either scientific literacy or personal experience with science [10], an indication not only of polarisation, but of a deeper breakdown in shared epistemic norms.

This mistrust was amplified by the hesitant, confused, and often contradictory response of the scientific and medical communities to the pandemic [11]. Shifting guidelines and evident disagreements amongst experts made it harder for the public to accept this as the consequence of predictable uncertainty of evolving evidence. Instead, social media fed on this ambiguity and fuelled the rapid spread of emotionally charged misinformation, thus alienating a large section of the population [12]. Together with the politicisation of scientific roles [13] this growing scepticism toward expert consensus undermined the perceived legitimacy of science itself [14]. Remarkably, perceived inconsistency in scientific advice, e.g. shifting guidance on masks, boosters, or transmission routes, had a more corrosive effect on trust than any single falsehood or conspiracy theory [15].

While these external factors are well documented, a more troubling possibility needs exploring: what if science itself has become harder to trust not because of its enemies, but because of its own failings? If the public finds science confusing, inconsistent, or unreliable, we must consider whether the science reaching the public is at times poorly executed, selectively reported, or inadequately validated. The issue is not whether the scientific method is flawed, but whether its implementation, dissemination, and public presentation have deviated from its ideals. This connects directly to internal debates now taking place across the scientific community, most visibly in the discussions surrounding reproducibility and reliability.

3. Reliability under scrutiny: science examines itself

The scientific community itself is aware of problems affecting the reliability of research results [16] due to methodological weaknesses and low rates of reproducibility [17–19]. This internal understanding suggests that there is a valid reason for the erosion of public trust in science.

An early warning with a provocative title ("Why most published research findings are false") came from John Ioannidis, who argued that structural features of the scientific process, low statistical power, publication bias, and researcher flexibility, inevitably lead to a high rate of false-positive findings [20]. Although this stark conclusion was criticised for relying on theoretical modelling rather than empirical measurement [21], and although some of Ioannidis' later pronouncements on COVID-19 were widely regarded as ill-informed and misleading [22], his original argument catalysed a global discussion about scientific reliability [23]. This debate resulted in calls for reform: improved training, better statistical practices, and changes in incentive structures to promote reproducibility [24].

The so-called "replication crisis" is particularly apparent in biomedical research. Independent replication efforts at Amgen [25] and Bayer [26] found that only 11–25 % of landmark preclinical studies could be reproduced. Strikingly, non-reproducible studies were cited more frequently than those that were replicable, a pattern echoed in the finding that retracted publications continue to attract citations long after their retraction date [27]. But replication alone does not resolve the problem, as this pattern reflects not just individual error but structural incentives: academic reward systems tied to publication, funding, and visibility may help foster a natural selection of inadequate science. These incentive structures prioritise novelty over rigour, volume over validation, and impact over transparency, encouraging researchers, often unconsciously, to adopt practices that maximise publication potential rather than truth [28].

Crucially, the underlying issues are rarely the result of outright fraud. Instead, they reflect a continuum of questionable research practices [29]: flexible data analysis ("p-hacking"), selective reporting, failure to pre-register hypotheses, and neglect of proper statistical controls [30]. Such practices fatally undermine the reliability of the conclusions drawn, resulting in a body of literature that, while formally peer-reviewed and statistically "significant," is not reproducible and has little translational relevance or clinical impact [31]. When scientists themselves question the reliability of the literature, and replication failures become widely reported, it is unsurprising that public confidence is affected.

There is some disagreement with regards to the claims of widespread scientific unreliability, with one argument being that whilst science faces methodological challenges, fear of a systemic collapse are not supported by long-term trends in publication quality or correction rates [32]. But such arguments rest on generalised metrics and discipline-averaged data. They fail to account for method-specific fragility, where technical complexity, lack of standardisation, and entrenched practices contribute to systemic problems that may be obscured in broader analyses. Fields that work with inherently variable biological systems and rely on complex statistical modelling, small sample sizes, or poorly standardised protocols are particularly susceptible to persistent methodological weakness. They shape what is published, what informs policy, and what is taken to be true. Addressing these issues requires focused scrutiny of the specific techniques by which data are generated, and the standards by which those techniques are judged. Scientific technologies are not neutral tools; they structure what can be observed, measured, and claimed. One such technique is quantitative real-time PCR (qPCR), whose conceptual simplicity masks widespread problems in its application.

4. qPCR as an example of scientific fragility

The speed and volume of data generation in molecular science has increased dramatically over the past 40 years. Today, researchers can analyse thousands of samples using a range of techniques such as the qPCR and massively parallel sequencing targeting nucleic acids and multiplex immunohistochemistry targeting proteins. These technologies generate vast volumes of data whose accuracy and interpretation depend on rigorous quality control. Whilst this was already patchy in small-scale experiments, it becomes logistically and practically overwhelming in large-scale studies. This imbalance is the predictable outcome of a system optimised for speed, novelty, and scale, but poorly equipped to ensure that its outputs are reliable, interpretable, or meaningful.

qPCR is probably the most widely adopted molecular technology across scientific, diagnostic, and regulatory domains [33], and it played a central role in the global COVID-19 response [34]. Its outputs inform regulatory decisions [35], making its reliability not just a technical concern but a public health imperative [36–39]. Yet because its outputs are transparent enough to expose flawed practice, it also constitutes a clear example of how a widely adopted method can be consistently misapplied [40]. This is widely recognised within the qPCR community itself but rarely appreciated by its broader user base [41]. For example, even in high-profile applications such as wastewater-based surveillance of SARS-CoV-2, flawed RT-qPCR data have impaired interpretation and delayed public health response [42].

Decisions made at any of the many stages of its workflow, whether in reagent or instrument selection, assay configuration, or data analysis, can introduce substantial variation, often leading to divergent results that may appear methodologically sound but are not directly comparable [43–45]. This, in turn, invites the publication of unsupported interpretations. Frustratingly, many published qPCR studies omit key methodological details, making it difficult even for experienced readers to detect the flaws that may underlie reported results [46].

Recognising these weaknesses, the Minimum Information for Publication of Quantitative Real-Time PCR Experiments (MIQE) guidelines, published in 2009 [47] and recently revised [48], set out minimum requirements for the design, execution, and reporting of qPCR experiments. With over 17,000 citations, the original guidelines have helped shape expectations around data quality, transparency, and methodological rigour in qPCR and RT-qPCR experiments [49]. They now serve as a reference standard across molecular biology, diagnostics, agriculture, and regulatory science, have shaped journal policy, and underpin ISO 20395 [50].

And yet, MIQE is routinely ignored [51–53]. Numerous surveys of the qPCR literature have documented persistent non-compliance. Common failures include poor quality control [54–56], neglect of the reverse transcription step [57–59], and the use of unvalidated reference genes [60–63], despite clear guidance on how to characterise the most appropriate ones [64–66]. Additional problems include uncertainty around PCR efficiency measurement [67–69], inadequate reporting of Cq variation [70], and a lack of transparency regarding primer sequences or assay conditions [71–74]. Even when papers cite MIQE, many fail to meet its basic requirements. Although web-based tools now exist to guide proper qPCR analysis [75–78], uptake remains limited.

Whilst industry has the potential to standardise methods, too often commercial incentives lead to secret ingredients in buffer solutions, confidential enzyme variants, and undisclosed sequences in primers and probes. Contrary to completely defined components that are the standard in scientific literature, proprietary kits, mixtures and components seldom outlive the company that once provided them. Detailed methods are often replaced by, "…according to manufacturer instructions…" that may not be retrievable. Variation in different reagent lots are seldom disclosed. Undisclosed salt and additive concentrations in PCR buffers make it impossible to accurately predict required denaturation and primer annealing conditions [79]. The apparent certainty of temperature cycling protocols crucial to the success of PCR (e.g. 95 °C for 15 s, 60 °C for 30 s) is an illusion masked by differences between instruments and samples within an instrument. Scientists seeking to maximise their workflow too often rely on kits or promised outcomes from instruments without verification. The volume of results enabled by commercial support of scientists is extraordinary, but only if the results are valid and can be repeated.

The disconnect between acknowledged awareness and actual practice raises an awkward question: if scientists know how to perform qPCR correctly, why is it so often conducted in ways that fall short of established best practice? This persistent gap between awareness and implementation likely reflects a combination of practical constraints, such as time pressure, limited resources, or perceived publication demands, and the assumption that some deviation from best practice is inconsequential. Whatever the cause, the result is a widespread tolerance of methodological compromise that undermines reproducibility and reduces confidence in published findings [80,81].

The consequences are significant. Flawed qPCR studies routinely lead to the publication of unreliable or exaggerated fold-changes, which obscure true biological signals and waste limited resources in biomarker discovery [71,82]. In basic research flawed qPCR studies leads to associations with spurious pathways, invalid mechanistic claims, and misdirected downstream work in basic research [83]. In diagnostics, poor data compromise the interpretation of test results, delay informed public health decisions, and impede the effective management of infectious disease outbreaks [84,85].

In addition to practical consequences, these flawed practices also distort legitimate scientific debate. Contradictory findings are not inherently problematic; they often reflect productive uncertainty. But when such contradictions arise from methodological flaws rather than competing theories or experimental nuance, they eliminate the distinction between genuine scientific disagreement and artefacts of poor data. The public are rarely aware of these underlying technical flaws, but they are sensitive to inconsistency. When multiple studies first claim to identify biomarkers for the same disease, then reach different conclusions, and finally fail to result in clinical application, the lay reader sees only contradiction. If those data are used to underpin diagnostic tests, public health policies, or media claims that later collapse, trust in science is broken. The implications extend beyond technical shortcomings; repeated failures to deliver on scientific promises, especially when hyped discoveries yield no clinical or practical outcomes, reduce public confidence in the credibility of entire fields and contribute to growing scepticism toward expert knowledge [13,14]. The public may not see qPCR data, but the decisions they influence often have direct implications for public welfare. In this light, the erosion of technical standards is not merely a scientific issue but a societal one.

5. Science in the public eye: trust, dissent, and the consequences of communication

Efforts to restore public trust in science often focus on improving communication: better clarity, greater openness, more engagement. This approach relies on the assumption that the public is receptive, that misinformation is a correctable error, and that clearer messaging will bridge the gap between scientific consensus and public understanding [86]. Yet emerging evidence suggests a more difficult truth: communication fails not only when content is lacking, but when the communicators misunderstand their role, and when scientists and the public no longer share common assumptions, expectations, or sources of knowledge.

Recent studies highlight this fracture. Trust in science strongly predicts the type of information sources individuals use during crises. Those who view scientists as trustworthy are more likely to consult scientific and journalistic sources, whereas those with low trust turn instead to alternative platforms. Notably, whilst both groups seek information, what differs is the narratives they accept [87].

Similar patterns have been demonstrated between scientists who hold divergent views on the causes of vaccine hesitancy and strategies to address it [88]. While most blamed disinformation and politics, many also cited poor communication and internal disagreement. Some supported coercive measures, despite acknowledging widespread institutional mistrust. This tension between recognising fragility and asserting authority speaks to deeper confusion about how science should engage with a sceptical public.

Unsurprisingly, the tone of scientific communication influences not just perception, but policy and public response. During the COVID-19 pandemic, this dynamic was laid bare by the publication of Great Barrington Declaration (GBD), launched in 2020 by academics backed by an ideological sponsor. It called for an end to lockdowns in favour of “focused protection,” and although presented as a scientific intervention, it was also a political one, delivered with rhetorical certainty and promoted through strategic media coordination [89]. A well-publicised seroprevalence study received disproportionate publicity relative to its evidence base [90], and its lead author warned in another article of a “fiasco in the making,” long before sufficient data existed to support such a claim [91].

The issue was not disagreement per se, but the projection of certainty during a time of profound uncertainty, which personalised debate, polarised interpretation, and undermined public confidence. That said, the pandemic response was not without fault on the other side. Measures such as arbitrary distancing rules, universal masking of very young children, and shifting guidance were often poorly explained and inconsistently justified, further eroding trust. The suppression, real or perceived, of dissenting scientific voices also played a role in fuelling scepticism. At the outset of the pandemic, decisions had to be made in the near-complete absence of reliable data, which made divergent expert opinions not only inevitable but necessary. The problem was not the existence of differing views, but the way they were communicated and perceived, as two opposing and authoritative camps, sowing confusion and weakening public trust. In such contexts, it is essential that scientific disagreement be framed with humility, grounded in evolving evidence, and free from personal denigration or the implication that those with alternative views are acting in bad faith.

By contrast, figures such as Anthony Fauci and Sarah Gilbert generally demonstrated restraint and adapted their positions as more data became available. The contrast between styles of communication was striking: while some voices engaged in performative dissent, rhetorically confident and attuned to ideological narratives, others practised greater caution and intellectual humility. One approach sought headlines, the other engender and preserve trust. Both were shaped by the pressures of crisis, but their impacts on public trust diverged.

The challenges facing public science are not confined to knowledge alone, they carry ethical implications. When scientific communication becomes careless, adopts performative rhetoric, or aligns with ideology, the harm is tangible. Patients may be misled by unreliable diagnostics, populations may be underserved by skewed research agendas and animals may suffer through poorly designed experiments. These are not abstract costs, they are consequences of choices.

Credibility is a combination of trust in the veracity of a scientific discovery and the responsibility with which it is being communicated. That responsibility extends beyond what is said to how it is said. It includes anticipating how scientific messages will be interpreted, reshaped, and amplified in the public domain.

6. Scientific communication, media practices, and public confusion

There are at least four distinct requirements for public trust. These are competence, integrity, benevolence, and openness [92]. Failures in any one of these can degrade trust, but openness most directly implicates communication, and poor communication erodes confidence even in otherwise reliable work. Whilst factual accuracy is essential for credibility, it is also important to anticipate how scientific claims are communicated.

The translation of scientific findings into the public domain is mediated by a complex and often distorting chain of communication: from researcher to journal, from university press office to news outlet, and finally from headline to public consciousness. Additionally, there is bias that comes from within the scientific community itself. The so-called science lobby, which consists of senior administrators, research funders, and institutional communicators promotes science in public and political arenas with the main aim of securing control over research priorities, with maximum funding and minimum external oversight. Although these aims are often couched in public-spirited terms, they are fundamentally interest-driven. Worryingly, the increasing influence of agenda-driven public relations over discriminating science journalism compromises the media’s ability to inform the public, as many science writers rely on one-sided information rather than investigative reporting [93]. This results not just in inaccurate communications, but in tendentious half-truths that then develop lives of their own. The omnipresence of web-based information has further challenged traditional journalistic practices and blurred the boundaries between reporting and promotion [94]. Any distortions are especially damaging when the underlying science is already inconsistent, as is often the case in biomarker discovery or diagnostic assay development [95].

Whilst the media are a key intermediary in shaping how the public perceives science, their motivation may run counter to scientific caution [96]. Journalists have deadlines to meet, stay ahead of the competition and editorial priorities that favour critical, selective, and sometimes sensational storytelling [97]. The need to attract attention favours dramatic descriptions, black-and-white conclusions, and confident claims and overrides the need to abide by the conditional, cautious nature of the research. Media headlines are often based on press releases that broadcast revolutionary innovations with well-defined consequences, rather than question underlying assumptions and describe possible limitations. This failure to communicate science as a non-linear process invites public scepticism once the headlines are not confirmed by subsequent implementation of whatever was being hyped. The many reports of molecular biomarkers targeting a range of diseases that subsequently are never heard of again, typically reported as “within ten years,” illustrates this point. As such tools repeatedly fail to materialise, the public comes to view such claims not as cautious projections, but as promotional hype. Similar practises in other fields, such as routinely describing economic data as “unexpected,” reinforce the perception that expert authority is disconnected from reality. Also, most journalists are not trained scientists or statisticians and so rely on the veracity of the filtered information they receive. They may view peer review as a guarantee of truth, when in practice it is a flawed process, full of obvious shortcomings with little evidence that it works [98]. This leads to the uncritical reporting of illusory breakthroughs that will be later contradicted or have to be discarded. This feeds public disappointment and contributes to a growing suspicion that scientific claims are unreliable [99].

It is easy to blame communication breakdowns on journalists or public ignorance. But that narrative lets scientists off too lightly. A tendency to confuse complexity with depth results in scientific terminology being jargon-filled and scientific publications and presentations being generally impenetrable to the general public. Our inability to convey a convincing narrative clashes with the narrative imperatives of journalism, resulting in mutual misunderstanding [100]. We expect journalists to translate our complex technical information into everyday language, but complain that maintaining a narrative requires them to strip away the caveats and uncertainties essential to scientific understanding. Ultimately, then, the responsibility for alienating the public lies with the original communication, not the transmitter or the audience. This failure is compounded by our assumption that non-specialists cannot understand, when they often can, if we allow them the opportunity. A more self-aware and less performative scientific culture would recognise that trust is earned not only through the reliability of our findings, but through the humility and clarity with which those findings are conveyed [101–103].

An additional unexpected contributor is that mainstream media may be required to broadcast a fair balance of opinions. In science reporting, this can result in false equivalence between what is a wide consensus between experts and maverick pseudoscientific views. This was an important issue during the prolonged MMR-autism controversy in the UK, where discredited claims were repeatedly presented alongside robust immunological and epidemiological evidence. The damage endures elsewhere as vaccine scepticism has been politicised in the USA and now circulates far beyond fringe groups [104,105]. As a result, low vaccination rates have led to the return of measles, a disease once eliminated [106].

And yet, it would be naïve to assume that improved communication alone will resolve the deeper fractures now evident in the public relationship with science. First, in a democracy, there is no obligation to listen [100]. Second, on its own, accurate information does not generate trust, especially if it lacks perceived relevance or fails to reflect the audience's values and circumstances [107]. Third, in many settings, science is no longer merely misunderstood, it is no longer recognised. Significant segments of the public now operate within intellectually closed systems, where even respectful, evidence-based communication is interpreted as manipulation or threat. If communication depends on shared norms such as openness and the willingness to revise one's opinions, then these conditions no longer hold across large sections of the public sphere. Many view the world through specific ideological prisms and do not perceive scientists and their institutions as intellectually competent, morally reliable, or aligned with their specific interests. The problem therefore is no longer that of poor communication, but a separation of social, ethical, political and religious ideology.

This uneasy realisation forces scientists to confront not just how they speak, but how they are heard. Some audiences may no longer be persuadable. Others remain undecided or simply confused. For those still listening, lucidity, respect, and responsibility still matter.

7. Summary

The aim of this review was to provide an explanation for the decline of public trust in science. We suggest that this is due to the challenges that affect the reliability of research results, demonstrated using qPCR as a representative example, together with poor communication, the changing role of the media, and the compartmentalisation of society. Reliability is compromised by inconsistent adherence to detailed recommendations such as the MIQE guidelines, despite broad awareness of their existence. Results based on inappropriate scientific methodology are then disseminated by incentive structures that reward flashy novelty over unexciting incremental results and institutional agendas that favour high profile over a desire for public engagement. Once accountability is optional, this leads to a disconnect between reality and expectation and so invites the cynicism and lack of trust that is prevalent today.

Public trust in science varies widely. Political, cultural, and historical elements have influenced how science and scientific advice is viewed in different societies. Public support is highest in countries with high civic engagement and transparent governance and lowest where politicians encourage, and media amplify polarisation. Remarkably, in the USA trust in science now correlates more strongly with political identity than with scientific literacy or personal experience.

There is a replication crisis in biomedicine. The scientific community itself acknowledges concern over the reliability of research results and their interpretation. The so-called replication crisis is particularly acute in biomedicine and is due to systemic weaknesses in experimental design, analysis, and reporting. Structural incentives coupled with inconsistent implementation and mostly absent enforcement reinforce these patterns by rewarding novelty over rigour and publication volume over reproducibility.

qPCR is a clear example of methodological irregularity. qPCR is central to gene expression analysis, diagnostics, and regulatory testing, and it is not just a basic research tool but its outputs are used for clinical decision making, regulatory approvals, and public health policy. Yet its flawed practises are widespread, well-publicised yet largely ignored despite the availability of clear standards (MIQE). This illustrates how a technically mature method can produce unreliable results when non-compliance at every step of its complex workflow remains the norm. Such disregard has serious consequences as it creates a body of publications that combine misleading results with a lack of reproducibility and so steer future research in a wrong direction, confound biomarker discovery and compromise diagnostic accuracy.

Communication failures amplify methodological weaknesses and erode trust. Scientific credibility requires not only accuracy but clarity and transparency of messaging. Yet scientific announcements are passed through multiple intermediaries, each with its own incentives, hidden agendas and constraints. Simplification, distortion, and exaggeration can accumulate across this chain, especially in environments dominated by public relations and constrained journalism. Scientists may also contribute to this problem, using technical language as a marker of expertise whilst failing to appreciate the storytelling imperative that prevents misunderstanding. In an era of ideological fragmentation, even accurate information can be perceived as manipulation. Rebuilding trust will depend on prominent commitment to methodological integrity, institutional accountability, and communicative transparency. Even then, broad sectors of society will remain immersed in intellectual silos that are not penetrated by even the most respectful, evidence-based communication.

8. Conclusion

The scientific method is our most powerful mechanism for generating reliable knowledge. Yet its benefits are lessened by inadequate methodological standards, opaque internal practices, and communications that are poorly articulated, often tendentious, and generally inaccessible to the public. The credibility of scientific research rests less on formal accountability than on the integrity of its practitioners. What earns trust is the public recognition that discovery is pursued for the collective benefit of knowledge, and that scientists will report what they find, even when it disappoints, contradicts, or complicates. What we say, and how we say it, matters, even when it feels like no one is listening. Scientific authority carries a responsibility to accuracy, to humility, and above all, to humanity. Our task is not only to generate knowledge, but to ensure that the way we share it sustains the trust on which its value depends.

Funding

The preparation of this article did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] G. Gauchat, Politicization of science in the public sphere: A study of public trust in the United States, 1974 to 2010, American Sociological Rev 77 (2012) 167–187. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=f4c6a536a5762e0e7530f8fcbc5c76860c46d05d.

[2] E. Tippins, R. Ysseldyk, C. Peneycad, H. Anisman, Believing in science: linking religious beliefs and identity with vaccination intentions and trust in science during the COVID-19 pandemic, Public Underst. Sci. 32 (2023) 1003–1020, https://doi.org/10.1177/09636625231174845.

[3] V. Cologna, N.G. Mede, S. Berger, J. Besley, C. Brick, M. Joubert, E.W. Maibach, S. Mihelj, N. Oreskes, M.S. Schäfer, S. van der Linden, N.I. Abdul Aziz, S. Abdulsalam, N.A. Shamsi, B. Aczel, I. Adinugroho, E. Alabrese, A. Aldoh, M. Alfano, I.M. Ali, M. Alsobay, M. Altenmüller, R.M. Alvarez, R. Amoako, T. Amollo, P. Ansah, D. Apriliawati, F. Azevedo, A. Bajrami, R. Bardhan, K. Bati, E. Bertsou, C. Betsch, A.Y. Bhatiya, R. Bhui, O. Białobrzeska, M. Bilewicz, A. Bouguettaya, K. Breeden, A. Bret, O. Buchel, P. Cabrera-Álvarez, F. Cagnoli, A. Calero Valdez, T. Callaghan, R.K. Cases, S. Çoksan, G. Czarnek, S. De Peuter, R. Debnath, S. Delouvée, L. Di Stefano, C. Díaz-Catalán, K.C. Doell, S. Dohle, K.M. Douglas, C. Dries, D. Dubrov, M. Dzimińska, U.K.H. Ecker, C.T. Elbaek, M. Elsherif, B. Enke, T.W. Etienne, M. Facciani, A. Fage-Butler, M.Z. Faisal, X. Fan, C. Farhart, C. Feldhaus, M. Ferreira, S. Feuerriegel, H. Fischer, J. Freundt, M. Friese, S. Fuglsang, A. Gallyamova, P. Garrido-Vásquez, M.E. Garrido Vásquez, W. Gatua, O. Genschow, O. Ghasemi, T. Gkinopoulos, J.L. Gloor, E. Goddard, M. Gollwitzer, C. González-Brambila, H. Gordon, D. Grigoryev, G.M. Grimshaw, L. Guenther, H. Haarstad, D. Harari, L.N. Hawkins, P. Hensel, A.C. Hernández-Mondragón, A. Herziger, G. Huang, M. Huff, M. Hurley, N. Ibadildin, M. Ishibashi, M.T. Islam, Y. Jeddi, T. Jin, C.A. Jones, S. Jungkunz, D. Jurgiel, Z. Kabdulkair, J.-J. Kao, S. Kavassalis, J.R. Kerr, M. Kitsa, T. Klabíková Rábová, O. Klein, H. Koh, A. Koivula, L. Kojan, E. Komyaginskaya, L. König, L. Koppel, K. Koren Nobre Cavalcante, A. Kosachenko, J. Kotcher, L.S. Kranz, P. Krishnan, S. Kristiansen, A. Krouwel, T. Kuppens, E.A. Kyza, C. Lamm, A. Lantian, A. Lazić, O. Lecuona, J.-B. Légal, Z. Leviston, N. Levy, A.M. Lindkvist, G. Lits, A. Löschel, A. López Ortega, C. Lopez-Villavicencio, N.M. Lou, C.H. Lucas, K. Lunz-Trujillo, M. D. Marques, S.J. Mayer, R. McKay, H. Mercier, J. Metag, T.L. Milfont, J.M. Miller, P. Mitkidis, F. Monge-Rodríguez, M. Motta, I. Mudra, Z. Muršič, J. Namutebi, E.J. Newman, J.P. Nitschke, N.-N.V. Ntui, D. Nwogwugwu, T. Ostermann, T. Otterbring, J. Palmer-Hague, M. Pantazi, P. Pärnamets, P. Parra Saiani, M. Paruzel-Czachura, M. Parzuchowski, Y.G. Pavlov, A.R. Pearson, M.A. Penner, C.R. Pennington, K. Petkanopoulou, M.B. Petrović, J. Pfänder, D. Pisareva, A. Ploszaj, K. Poliaková, E. Pronizius, K. Pypno-Blajda, D.M.A. Quiñones, P. Räsänen, A. Rauchfleisch, F.G. Rebitschek, C. Refojo Seronero, G. Rêgo, J.P. Reynolds, J. Roche, S. Rödder, J.P. Röer, R.M. Ross, I. Ruin, O. Santos, R.R. Santos, P. Schmid, S. Schulreich, B. Scoggins, A. Sharaf, J. Sheria Nfundiko, E. Shuckburgh, J. Six, N. Solak, L. Späth, B. Spruyt, O. Standaert, S.K. Stanley, G. Storms, N. Strahm, S. Syropoulos, B. Szaszi, E. Szumowska, M. Tanaka, C. Teran-Escobar, B. Todorova, A.K. Toko, R. Tokrri, D. Toribio-Florez, M. Tsakiris, M. Tyrala, Ö.M. Uluğ, I.C. Uzoma, J. van Noord, C. Varda, S. Verheyen, I. Vilares, M. Vlasceanu, A. von Bubnoff, I. Walker, I. Warwas, M. Weber, T. Weninger, M. Westfal, F. Wintterlin, A.D. Wojcik, Z. Xia, J. Xie, E. Zegler-Poleska, A. Zenklusen, R.A. Zwaan, Trust in scientists and their role in society across 68 countries., Nat Hum Behav 9 (2025) 713–730. https://doi.org/10.1038/s41562-024-02090-5.

[4] H. Borhan, Civic education as a pathway to inclusive societies: Exploring the role of education in fostering civic and social engagement, OECD Education Working Papers (2025). https://www.oecd.org/content/dam/oecd/en/publications/reports/2025/02/civic-education-as-a-pathway-to-inclusive-societies_6d52238a/3f128be8-en.pdf (accessed May 2025).

[5] Anonymous, Chapter 3: Trust in science and health professionals, Wellcome Global Monitor 2018 (2018). https://wellcome.org/reports/wellcome-global-monitor/2018/chapter-3-trust-science-and-health-professionals (accessed May 2025).

[6] S.Y. Yip, D. Namah, R. Cook, C. Isles, It must be true I read it in the tabloids, J. R. Coll/ Phys. Edinb. 48 (2018) 251–256, https://doi.org/10.4997/JRCPE.2017.312.

[7] M. Fitzpatrick, Why can't the daily mail eat humble pie over MMR? BMJ 12 (2005) 1148. https://www.bmj.com/content/331/7525/1148.short.

[8] M. Motta, D. Stecula, Quantifying the effect of Wakefield et al. (1998) on skepticism about MMR vaccine safety in the U.S., PLoS One 16 (2021) e0256395. https://doi.org/10.1371/journal.pone.0256395.

[9] K. Gilliland, A. Kilinsky, Vaccine hesitancy: where are we now? Pediatr. Ann. 54 (2025) e154–e159, https://doi.org/10.3928/19382359-20250307-01.

[10] B. Kennedy, A. Tyson, Americans' Trust in Scientists, Positive Views of Science Continue to Decline, (2023). https://www.pewresearch.org/science/2023/11/14/americans-trust-in-scientists-positive-views-of-science-continue-to-decline/), (accessed May 2025).

[11] B. Hyland-Wood, J. Gardner, J. Leask, Toward effective government communication strategies in the era of COVID-19, Human. Soc. (2021). https://www.nature.com/articles/s41599-020-00701-w.

[12] K.P. Kepp, K. Bardosh, T. De Bie, L. Emilsson, J. Greaves, T. Lallukka, T. Muka, J. C. Rangel, N. Sandström, M.C. Schippers, J. Schmidt-Chanasit, T. Vaillancourt, Zero-covid advocacy during the COVID-19 pandemic: a case study of views on Twitter/X, Monash Bioeth. Rev. 42 (2024) 169–199, https://doi.org/10.1007/s40592-024-00205-2.

[13] B. Seyd, J.A. Hamm, W. Jennings, L. McKay, V. Valgarðsson, M. Anness, "Follow the science": popular trust in scientific experts during the coronavirus pandemic, Public Underst. Sci. 34 (2025) 2–18, https://doi.org/10.1177/09636625241253968.

[14] A. Siani, I. Green, Scientific misinformation and mistrust of COVID-19 preventive measures among the UK population: A pilot study, Vaccines (2023). https://www.mdpi.com/2076-393X/11/2/301/pdf.

[15] K. Escandón, A.L. Rasmussen, I.I. Bogoch, E.J. Murray, K. Escandón, S.V. Popescu, J. Kindrachuk, COVID-19 false dichotomies and a comprehensive review of the evidence regarding public health, COVID-19 symptomatology, SARS-CoV-2 transmission, mask wearing, and reinfection, BMC Infect Dis 21 (2021) 710, https://doi.org/10.1186/s12879-021-06357-4.

[16] M. Baker, Is there a reproducibility crisis? Nature 533 (2016) 452–454.

[17] D.B.S. Resnik, Reproducibility and research integrity, Account Res 24 (2017) 116–123.

[18] P. Rodgers, A. Collings, What have we learned? Elife 10 (2021) e75830 https://doi.org/10.7554/eLife.75830.

[19] P.G. Hensel, Reproducibility and replicability crisis: how management compares to psychology and economics–a systematic review of literature, Eur. Manage. J. 39 (2021) 577–594.

[20] J.P. Ioannidis, Why most published research findings are false., PLoS Med 2 (2005) e124. https://doi.org/10.1371/journal.pmed.0020124.

[21] J.C. Ashton, It has not been proven why or that most research findings are false, Medical Hypotheses (2018). https://www.sciencedirect.com/science/article/pii/S0306987717312331.

[22] N.A. Alwan, R.A. Burgess, S. Ashworth, R. Beale, N. Bhadelia, D. Bogaert, J. Dowd, I. Eckerle, L.R. Goldman, T. Greenhalgh, D. Gurdasani, A. Hamdy, W.P. Hanage, E.B. Hodcroft, Z. Hyde, P. Kellam, M. Kelly-Irving, F. Krammer, M. Lipsitch, A. McNally, M. McKee, A. Nouri, D. Pimenta, V. Priesemann, H. Rutter, J. Silver, D. Sridhar, C. Swanton, R.P. Walensky, G. Yamey, H. Ziauddeen, Scientific consensus on the COVID-19 pandemic: we need to act now., (2020). https://pubmed.ncbi.nlm.nih.gov/33069277.

[23] A.D. Higginson, M.R. Munafò, Current incentives for scientists lead to underpowered studies with erroneous conclusions, PLoS Biol. (2016), https://doi.org/10.1371/journal.pbio.2000995&type=printable.

[24] M.R. Munafò, B.A. Nosek, D.V.M. Bishop, K.S. Button, C.D. Chambers, N.P. du Sert, U. Simonsohn, E. Wagenmakers, J.J. Ware, J.P.A. Ioannidis, A manifesto for reproducible science, Nat. Hum. Behav. 1 (2017) 0021. https://www.nature.com/articles/s41562-016-0021.

[25] C.G. Begley, L.M. Ellis, Drug development: raise standards for preclinical cancer research, Nature 483 (2012) 531–533, https://doi.org/10.1038/483531a.

[26] F. Prinz, T. Schlange, K. Asadullah, Believe it or not: how much can we rely on published data on potential drug targets? Nat. Rev. Drug Discov. 10 (2011) 712, https://doi.org/10.1038/nrd3439-c1.

[27] C.R. Madlock-Brown, D. Eichmann, The (lack of) impact of retraction on citation networks, Sci. Eng. Ethics (2014), https://doi.org/10.1007/s11948-014-9532-1.

[28] P.E. Smaldino, R. McElreath, The natural selection of bad science., R. Soc. Open Sci., 3 (2016) 160384. https://doi.org/10.1098/rsos.160384.

[29] M.J. Bolland, A. Avenell, A. Grey, Publication integrity: what is it, why does it matter, how it is safeguarded and how could we do better? J. R. Soc. N. Z 55 (2025) 267–286, https://doi.org/10.1080/03036758.2024.2325004.

[30] R.J. Ellis, Questionable research practices, low statistical power, and other obstacles to replicability: why preclinical neuroscience research would benefit from registered reports, Eneuro 9 (2022), https://doi.org/10.1523/ENEURO.0017-22.2022. ENEURO.0017-22.2022.

[31] U. Dirnagl, G.N. Duda, D.W. Grainger, P. Reinke, R. Roubenoff, Reproducibility, relevance and reliability as barriers to efficient and credible biomedical technology translation, Adv. Drug Deliv. Rev. 182 (2022) 114118, https://doi.org/10.1016/j.addr.2022.114118.

[32] D. Fanelli, Is science really facing a reproducibility crisis, and do we need it to? Proc. Natl. Acad Sci. 115 (2018) 2628–2631, https://doi.org/10.1073/pnas.1708272114.

[33] H.D. VanGuilder, K.E. Vrana, W.M. Freeman, Twenty-five years of quantitative PCR for gene expression analysis, Biotechniques 44 (2008) 619–26. https://doi.org/000112776 [pii]10.2144/000112776.

[34] D. Dutta, S. Naiyer, S. Mansuri, N. Soni, V. Singh, K.H. Bhat, N. Singh, G. Arora, M.S. Mansuri, COVID-19 diagnosis: a comprehensive review of the RT-qPCR method for detection of SARS-CoV-2, Diagnostics (basel) 12 (2022) 1503, https://doi.org/10.3390/diagnostics12061503.

[35] H. Ma, K.N. Bell, R.N. Loker, qPCR and qRT-PCR analysis: Regulatory points to consider when conducting biodistribution and vector shedding studies, Mol. Ther. Methods Clin. Dev. 20 (2021) 152–168, https://doi.org/10.1016/j.omtm.2020.11.007.

[36] J.A. Garson, J.F. Huggett, S.A. Bustin, M.W. Pfaffl, V. Benes, J. Vandesompele, G. L. Shipley, Unreliable real-time PCR analysis of human endogenous retrovirus-W (HERV-W) RNA expression and DNA copy number in multiple sclerosis., AIDS Res Hum Retroviruses 25 (2009) 377–8; author reply 379-81. https://doi.org/10.1089/aid.2008.0270.

[37] S.A. Bustin, J. Murphy, RNA biomarkers in colorectal cancer, Methods 59 (2013) 116–125, https://doi.org/10.1016/j.ymeth.2012.10.003.

[38] A. Hays, M. Wissel, K. Colletti, R. Soon, M. Azadeh, J. Smith, R. Doddareddy, M. Chalfant, W. Adamowicz, S.S. Ramaswamy, S.L. Dholakiya, S. Guelman, B. Gullick, J. Durham, K. Rennier, P. Nagilla, A. Muruganandham, M. Diaz,

C. Tierney, K. John, J. Valentine, T. Lockman, H.-Y. Liu, B. Moritz, J. P. Ouedraogo, M.-S. Piche, M. Smet, J. Murphy, K. Koenig, A. Zybura, C. Vyhlidal, J. Mercier, N. Jani, M. Kubista, D. Birch, K. Morse, O. Johansson, Recommendations for Method Development and Validation of qPCR and dPCR Assays in support of Cell and Gene Therapy Drug Development, AAPS J 26 (2024) 24, https://doi.org/10.1208/s12248-023-00880-9.

[39] M. Wissel, M. Poirier, C. Satterwhite, J. Lin, R. Islam, J. Zimmer, A. Khadang, J. Zemo, T. Lester, M. Fjording, A. Hays, N. Hughes, F. Garofolo, R. Guilbaud, E. Groeber, H. Renfrew, K. Colletti, M. Yu, J. Lin, X. Fang, S. Shah, W. Garofolo, S. Kar, R. Hayes, J. Pirro, C. Kane, M. Luna, A. Xu, S. Cape, M. O'Dell, R. Wheller, H. Ritzen, J. Vance, E. Farley, K. Matys, E. Tabler, W. Mylott, M. Yuan, S. Karnik, T. Voelker, I. DuBey, C. Williard, J. Shi, J. Yamashita, Recommendations on qPCR/ddPCR assay validation by GCC, Bioanalysis 14 (2022) 853–863, https://doi.org/10.4155/bio-2022-0109.

[40] D. Evans, S. Cowen, M. Kammel, D.M. O'Sullivan, G. Stewart, H.P. Grunert, J. Moran-Gilad, J. Verwilt, J. In, J. Vandesompele, K. Harris, K.H. Hong, N. Storey, S. Hingley-Wilson, U. Dühring, Y.K. Bae, C.A. Foy, J. Braybrook, H. Zeichhardt, J. F. Huggett, The Dangers of Using Cq to Quantify Nucleic Acid in Biological Samples: A Lesson From COVID-19., Clin Chem 68 (2021 12 30) 153–162. https://doi.org/10.1093/clinchem/hvab219.

[41] S.C. Taylor, E.M. Mrkusich, The state of RT-quantitative PCR: firsthand observations of implementation of minimum information for the publication of quantitative real-time PCR experiments (MIQE), J Mol Microbiol Biotechnol 24 (2014) 46–52, https://doi.org/10.1159/000356189.

[42] A. Bivins, D. Kaya, K. Bibby, S.L. Simpson, S.A. Bustin, O.C. Shanks, W. Ahmed, Variability in RT-qPCR assay parameters indicates unreliable SARS-CoV-2 RNA quantification for wastewater surveillance., Water Res 203 (2021) 117516. https://doi.org/10.1016/j.watres.2021.117516.

[43] S.A. Bustin, Absolute quantification of mRNA using real-time reverse transcription polymerase chain reaction assays, J Mol Endocrinol 25 (2000) 169–193. https://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=11013345.

[44] G.S. Buzard, D. Baker, M.J. Wolcott, D.A. Norwood, L.A. Dauphin, Multi-platform comparison of ten commercial master mixes for probe-based real-time polymerase chain reaction detection of bioterrorism threat agents for surge preparedness, Forensic Sci Int 223 (2012) 292–297, https://doi.org/10.1016/j.forsciint.2012.10.003.

[45] J.M. Ruijter, C. Ramakers, W.M. Hoogaars, Y. Karlen, O. Bakker, M.J. van den Hoff, A.F. Moorman, Amplification efficiency: linking baseline and bias in the analysis of quantitative PCR data, Nucleic Acids Res 37 (2009) e45.

[46] S. Bustin, The continuing problem of poor transparency of reporting and use of inappropriate methods for RT-qPCR, Biomol Detect Quantif 12 (2017) 7–9, https://doi.org/10.1016/j.bdq.2017.05.001.

[47] S.A. Bustin, V. Benes, J.A. Garson, J. Hellemans, J. Huggett, M. Kubista, R. Mueller, T. Nolan, M.W. Pfaffl, G.L. Shipley, J. Vandesompele, C.T. Wittwer, The MIQE guidelines: minimum information for publication of quantitative real-time PCR experiments, Clin. Chem. 55 (2009) 611–22. https://doi.org/clinchem.2008.112797 [pii]10.1373/clinchem.2008.112797.

[48] S.A. Bustin, J.M. Ruijter, M.J.B. van den Hoff, M. Kubista, M.W. Pfaffl, G.L. Shipley, N. Tran, S. Rödiger, A. Untergasser, R. Mueller, T. Nolan, M. Milavec, M. J. Burns, J.F. Huggett, J. Vandesompele, C.T. Wittwer, MIQE 2.0: revision of the minimum information for publication of quantitative real-time PCR experiments guidelines., Clin. Chem. (2025) hvaf043, https://doi.org/10.1093/clinchem/hvaf043.

[49] S.C. Taylor, K. Nadeau, M. Abbasi, C. Lachance, M. Nguyen, J. Fenrich, The ultimate qPCR experiment: producing publication quality, reproducible data the first time, Trends Biotechnol. 37 (2019) 761–774, https://doi.org/10.1016/j.tibtech.2018.12.002.

[50] ISO 20395, (2019). https://www.iso.org/obp/ui#iso:std:iso:20395:ed-1:v1:en (accessed May 2025).

[51] S. Bustin, T. Nolan, Talking the talk, but not walking the walk: RT-qPCR as a paradigm for the lack of reproducibility in molecular research, Eur. J. Clin. Invest. 47 (2017) 756–774, https://doi.org/10.1111/eci.12801.

[52] S.A. Bustin, V. Benes, J. Garson, J. Hellemans, J. Huggett, M. Kubista, R. Mueller, T. Nolan, M.W. Pfaffl, G. Shipley, C.T. Wittwer, P. Schjerling, P.J. Day, M. Abreu, B. Aguado, J.F. Beaulieu, A. Beckers, S. Bogaert, J.A. Browne, F. Carrasco-Ramiro, L. Ceelen, K. Ciborowski, P. Cornillie, S. Coulon, A. Cuypers, S. De Brouwer, L. De Ceuninck, J. De Craene, H. De Naeyer, W. De Spiegelaere, K. Deckers, A. Dheedene, K. Durinck, M. Ferreira-Teixeira, A. Fieuw, J.M. Gallup, S. Gonzalo-Flores, K. Goossens, F. Heindryckx, E. Herring, H. Hoenicka, L. Icardi, R. Jaggi, F. Javad, M. Karampelias, F. Kibenge, M. Kibenge, C. Kumps, I. Lambertz, T. Lammens, A. Markey, P. Messiaen, E. Mets, S. Morais, A. Mudarra-Rubio, J. Nakiwala, H. Nelis, P.A. Olsvik, C. Perez-Novo, M. Plusquin, T. Remans, A. Rihani, P. Rodrigues-Santos, P. Rondou, R. Sanders, K. Schmidt-Bleek, K. Skovgaard, K. Smeets, L. Tabera, S. Toegel, T. Van Acker, W. Van den Broeck, J. Van der Meulen, M. Van Gele, G. Van Peer, M. Van Poucke, N. Van Roy, S. Vergult, J. Wauman, M. Tshuikina-Wiklander, E. Willems, S. Zaccara, F. Zeka, J. Vandesompele, The need for transparency and good practices in the qPCR literature, Nat. Methods 10 (2013) 1063–1067, https://doi.org/10.1038/nmeth.2697.

[53] S.A. Bustin, Improving the quality of quantitative polymerase chain reaction experiments: 15 years of MIQE, Mol. Aspects Med. 96 (2024) 101249, https://doi.org/10.1016/j.mam.2024.101249.

[54] A. Tichopad, A. Didier, M.W. Pfaffl, Inhibition of real-time RT-PCR quantification due to tissue-specific contaminants, Mol. Cell Probes 18 (2004) 45–50, https://doi.org/10.1016/j.mcp.2003.09.001.

[55] S. Fleige, M.W. Pfaffl, RNA integrity and the effect on the real-time qRT-PCR performance, Mol. Aspects Med. 27 (2006) 126–139. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=16469371.

[56] A. Tichopad, T. Bar, L. Pecen, R.R. Kitchen, M. Kubista, M.W. Pfaffl, Quality control for quantitative PCR based on amplification compatibility test, Methods 50 (2010) 308–312, https://doi.org/10.1016/j.ymeth.2010.01.028.

[57] A. Stahlberg, M. Kubista, M. Pfaffl, Comparison of reverse transcriptases in gene expression analysis, Clin. Chem. 50 (2004) 1678–1680. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=15331507.

[58] A. Stahlberg, J. Hakansson, X. Xian, H. Semb, M. Kubista, Properties of the reverse transcription reaction in mRNA quantification, Clin. Chem. 50 (2004) 509–515. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=14726469.

[59] S. Bustin, H.S. Dhillon, S. Kirvell, C. Greenwood, M. Parker, G.L. Shipley, T. Nolan, Variability of the reverse transcription step: practical implications, Clin. Chem. 61 (2015) 202–212, https://doi.org/10.1373/clinchem.2014.230615.

[60] C. Tricarico, P. Pinzani, S. Bianchi, M. Paglierani, V. Distante, M. Pazzagli, S. A. Bustin, C. Orlando, Quantitative real-time reverse transcription polymerase chain reaction: normalization to rRNA or single housekeeping genes is inappropriate for human tissue biopsies, Anal. Biochem. 309 (2002) 293–300, https://doi.org/10.1016/s0003-2697(02)00311-1.

[61] K. Dheda, J.F. Huggett, J.S. Chang, L.U. Kim, S.A. Bustin, M.A. Johnson, G. A. Rook, A. Zumla, The implications of using an inappropriate reference gene for real-time reverse transcription PCR data normalization, Anal. Biochem. 344 (2005) 141–143. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=16054107.

[62] J. Huggett, K. Dheda, S. Bustin, A. Zumla, Real-time RT-PCR normalisation; strategies and considerations, Genes Immun. 6 (2005) 279–284. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=15815687.

[63] K. Dheda, J.F. Huggett, S.A. Bustin, M.A. Johnson, G. Rook, A. Zumla, Validation of housekeeping genes for normalizing RNA expression in real-time PCR, Biotechniques 37 (2004) 112–119. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=15283208.

[64] J. Vandesompele, K. De Preter, F. Pattyn, B. Poppe, N. Van Roy, A. De Paepe, F. Speleman, Accurate normalization of real-time quantitative RT-PCR data by geometric averaging of multiple internal control genes, 0034.1-0034.11, Genome Biol. 3 (2002), http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=12184808.

[65] R.C. Edmunds, J.K. McIntyre, J.A. Luckenbach, D.H. Baldwin, J.P. Incardona, Toward enhanced MIQE compliance: reference residual normalization of qPCR gene expression data, J Biomol Tech 25 (2014) 54–60, https://doi.org/10.7171/jbt.14-2502-003.

[66] J. Hellemans, J. Vandesompele, Selection of reliable reference genes for RT-qPCR analysis, in: R. Biassoni, A. Raso (Eds.), Quantitative Real-Time PCR: Methods and Protocols, Humana Press, New York, NY, 2014, pp. 19–26, https://doi.org/10.1007/978-1-4939-0733-5_3.

[67] R.G. Rutledge, D. Stewart, Critical evaluation of methods used to determine amplification efficiency refutes the exponential character of real-time PCR, BMC Mol. Biol. 9 (2008) 96, https://doi.org/10.1186/1471-2199-9-96.

[68] J.M. Ruijter, R.J. Barnewall, I.B. Marsh, A.N. Szentirmay, J.C. Quinn, R. van Houdt, Q.D. Gunst, M.J.B. van den Hoff, Efficiency correction is required for accurate quantitative PCR analysis and reporting, Clin. Chem. 67 (2021) 829–842, https://doi.org/10.1093/clinchem/hvab052.

[69] J.M. Tuomi, F. Voorbraak, D.L. Jones, J.M. Ruijter, Bias in the Cq value observed with hydrolysis probe based quantitative PCR can be corrected with the estimated PCR efficiency value, Methods 50 (2010) 313–322, https://doi.org/10.1016/j.ymeth.2010.02.003.

[70] A. Ruiz-Villalba, J.M. Ruijter, M.J.B. van den Hoff, Use and misuse of Cq in qPCR data analysis and reporting, Life 11 (2021) 496. https://www.mdpi.com/2075-1729/11/6/496/htm.

[71] J.R. Dijkstra, L.C. van Kempen, I.D. Nagtegaal, S.A. Bustin, Critical appraisal of quantitative PCR results in colorectal cancer research: can we rely on published qPCR results? Mol. Oncol. 8 (2014) 813–818, https://doi.org/10.1016/j.molonc.2013.12.016.

[72] A.M. Abdel Nour, E. Azhar, G. Damanhouri, S.A. Bustin, Five years MIQE guidelines: the case of the Arabian countries, PLoS One 9 (2014) e88266, https://doi.org/10.1371/journal.pone.0088266.

[73] G. Johnson, A.A. Nour, T. Nolan, J. Huggett, S. Bustin, Minimum information necessary for quantitative real-time PCR experiments, Methods Mol. Biol. 1160 (2014) 5–17, https://doi.org/10.1007/978-1-4939-0733-5_2.

[74] A.M.A. Nour, G. Nemer, A. Khalil, The MIQE guidelines' tenth anniversary: the good and bad students, Gene Rep. 19 (2020) 100630. https://scholarworks.aub.edu.lb/bitstream/handle/10938/28972/2020-3224.pdf?sequence=1.

[75] N. Zanardi, M. Morini, M.A. Tangaro, F. Zambelli, M.C. Bosco, L. Varesio, A. Eva, D. Cangelosi, PIPE-T: a new Galaxy tool for the analysis of RT-qPCR expression data, Sci. Rep. 9 (2019) 17550, https://doi.org/10.1038/s41598-019-53155-9.

[76] A. Untergasser, J.M. Ruijter, V. Benes, M.J.B. van den Hoff, Web-based LinRegPCR: application for the visualization and analysis of (RT)-qPCR amplification and melting data, BMC Bioinf. 22 (2021) 398, https://doi.org/10.1186/s12859-021-04306-1.

[77] G. Maussion, R.A. Thomas, I. Demirova, G. Gu, E. Cai, C.-X.-Q. Chen, N. Abdian, T.J.P. Strauss, S. Kelaï, A. Nauleau-Javaudin, Auto-qPCR; a python-based web

app for automated and reproducible analysis of qPCR data, Sci. Rep. 11 (2021) 21293. https://www.nature.com/articles/s41598-021-99727-6.
[78] C. Rancurel, T.V. Tran, C. Elie, F. Hilliou, SATQPCR: Website for statistical analysis of real-time quantitative PCR data, Mol. Cell. Probes (2019). https://www.sciencedirect.com/science/article/am/pii/S0890850819301604.
[79] Z. Dwight, R. Palais, C.T. Wittwer, uMELT: prediction of high-resolution melting curves and dynamic melting profiles of PCR products in a rich web application, Bioinformatics 27 (2011) 1019–1020, https://doi.org/10.1093/bioinformatics/btr065.
[80] R. Sanders, S. Bustin, J. Huggett, D. Mason, Improving the standardization of mRNA measurement by RT-qPCR, Biomol. Detect. Quantif. 15 (2018) 13–17, https://doi.org/10.1016/j.bdq.2018.03.001.
[81] R. Sanders, D.J. Mason, C.A. Foy, J.F. Huggett, Considerations for accurate gene expression measurement by reverse transcription quantitative PCR when analysing clinical samples, Anal. Bioanal. Chem. 406 (2014) 6471–6483, https://doi.org/10.1007/s00216-014-7857-x.
[82] C. Grätz, M.L.U. Bui, G. Thaqi, B. Kirchner, R.P. Loewe, M.W. Pfaffl, Obtaining reliable RT-qPCR results in molecular diagnostics-MIQE goals and pitfalls for transcriptional biomarker discovery, Life (basel) 12 (2022) 386, https://doi.org/10.3390/life12030386.
[83] C. Grätz, M. Schuster, F. Brandes, A.S. Meidert, B. Kirchner, M. Reithmair, G. Schelling, M.W. Pfaffl, A pipeline for the development and analysis of extracellular vesicle-based transcriptomic biomarkers in molecular diagnostics, Mol. Aspects Med. 97 (2024) 101269, https://doi.org/10.1016/j.mam.2024.101269.
[84] M. Teymouri, S. Mollazadeh, H. Mortazavi, Z. Naderi Ghale-Noie, V. Keyvani, F. Aghababaei, M.R. Hamblin, G. Abbaszadeh-Goudarzi, H. Pourghadamyari, S.M.R. Hashemian, H. Mirzaei, Recent advances and challenges of RT-PCR tests for the diagnosis of COVID-19., Pathol Res Pract 221 (2021) 153443. https://doi.org/10.1016/j.prp.2021.153443.
[85] S.A. Bustin, RT-qPCR testing and performance metrics in the COVID-19 Era, Int. J. Mol. Sci. 25 (2024) 9326, https://doi.org/10.3390/ijms25179326.
[86] Anonymous, Public Trust in Science and Technology, Turing Commons (2022). https://alan-turing-institute.github.io/turing-commons/skills-tracks/ped/chapter5/trust/ (accessed May 2025).
[87] F. Zimmermann, C. Petersen, M. Kohring, Who, if not science, can you trust to guide you through a crisis? the relationship between public trust in science and exposure to established and alternative online sources in times of crisis, J. Sci. Commun. 23 (2024) A05. https://jcom.sissa.it/article/pubid/JCOM_2309_2024_A05/.
[88] E.W. Welch, T.P. Johnson, T. Chen, J. Ma, S. Islam, L.F. Michalegko, M. Caldarulo, A. Frandell, How scientists view vaccine hesitancy, Vaccines 11 (2023) 1208. https://www.mdpi.com/2076-393X/11/7/1208/pdf.
[89] J. Howard, We Want Them Infected: how the failed Quest for Herd Immunity led doctors to Embrace the Anti-Vaccine Movement and Blinded Americans to the Threat of COVID, Redhawk Publications, Hickory, N.C. USA, 2023.
[90] E. Bendavid, B. Mulaney, N. Sood, S. Shah, R. Bromley-Dulfano, C. Lai, Z. Weissberg, R. Saavedra-Walker, J. Tedrow, A. Bogan, T. Kupiec, D. Eichner, R. Gupta, J.P.A. Ioannidis, J. Bhattacharya, COVID-19 antibody seroprevalence in Santa Clara County, California, Int. J. Epidemiol. 50 (2021) 410–419, https://doi.org/10.1093/ije/dyab010.
[91] J.P. Ioannidis, A fiasco in the making? As the coronavirus pandemic takes hold, we are making decisions without reliable data, accessed May 2025, DSTAT (2020), https://www.statnews.com/2020/03/17/a-fiasco-in-the-making-as-the-coronavirus-pandemic-takes-hold-we-are-making-decisions-without-reliable-data/.
[92] J.C. Besley, N.M. Lee, G. Pressgrove, Reassessing the variables used to measure public perceptions of scientists, Sci. Commun. 43 (2021) 3–32. https://drive.google.com/file/d/1T9Mk3gXISql5QkFHPeYQKVTvhuhQ01tI/view.
[93] W. Göpfert, The Strength of PR and the Weakness of Science Journalism, Routledge, New York, NY, USA, 2007.
[94] B. Trench, How the Internet Changed Science Journalism, Routledge, New York, NY USA, 2007.
[95] D. de Gonzalo-Calvo, M. Marchese, J. Hellemans, F. Betsou, N.L. Skov Frisk, L. T. Dalgaard, P. Lakkisto, C. Foy, A. Scherer, M.L. Garcia Bermejo, Y. Devaux, C.o.s.t.a.c. (https://cardiorna. eu EU-CardioRNA, Consensus guidelines for the validation of qRT-PCR assays in clinical research by the CardioRNA consortium, Mol. Ther. Methods Clin. Dev. 24 (2022) 171–180, https://doi.org/10.1016/j.omtm.2021.12.007.
[96] G. Dempster, G. Sutherland, L. Keogh, Scientific research in news media: a case study of misrepresentation, sensationalism and harmful recommendations, J. Sci. (2022). https://jcom.sissa.it/article/pubid/JCOM_2101_2022_A06/download/pdf.
[97] B. Fjæstad, Why Journalists Report Science as they do, Routledge, New York, NY. USA, 2007.
[98] R. Smith, Peer review: a flawed process at the heart of science and journals, J R Soc Med 99 (2006) 178–182, https://doi.org/10.1177/014107680609900414.
[99] S.A. Bustin, The reproducibility of biomedical research: sleepers awake, Biomol. Detect. Quantif. 2 (2014) 35–42, https://doi.org/10.1016/j.bdq.2015.01.002.
[100] T. Radford, Scheherazade Telling stories, not educating people, Routledge, New York, NY USA, 2007.
[101] N. Baron, Escape from the Ivory Tower: a Guide to making your Science Matter, Island Press, 2010 https://play.google.com/store/books/details?id=bJXGoQxaijsC&source=gbs_api.
[102] C. Dean, Am I Making Myself Clear?: A Scientist's Guide to Talking to the Public, Harvard University Press, 2009 http://books.google.co.uk/books?id=qKu3AD-kPU0C&hl=&source=gbs_api.
[103] S.M. Illingworth, H.A. Roop, Developing key skills as a science communicator: Case studies of two scientist-led outreach programmes, Geosciences 5 (2015) 2–14. https://www.mdpi.com/2076-3263/5/1/2.
[104] T. Bolsen, R. Palm, Politicization and COVID-19 vaccine resistance in the U.S., Prog Mol Biol Transl Sci 188 (2022) 81–100. https://doi.org/10.1016/bs.pmbts.2021.10.002.
[105] C.T. Robertson, K. Bentele, B. Meyerson, A.S.A. Wood, J. Salwa, Effects of political versus expert messaging on vaccination intentions of Trump voters, PLoS One 16 (2021) e0257988, https://doi.org/10.1371/journal.pone.0257988.
[106] D.M. Higgins, S.T. O'Leary, A world without measles and rubella: addressing the challenge of vaccine hesitancy, Vaccines (basel) 12 (2024) 694, https://doi.org/10.3390/vaccines12060694.
[107] K. Intemann, Science communication and public trust in science, Interdiscip. Sci. Rev. (2023) 350–365, https://doi.org/10.1080/03080188.2022.2152244.