Addressing antibody validation failures: a multi-stakeholder Delphi consensus study on actionable solutions

Short title: Delphi consensus on antibody validation reform

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Abstract

The experimental use of antibodies that have not been validated for context-specific use frequently misdirects biomedical research. Experimental results that derive from the use of inadequately validated antibodies are estimated to waste over $1 billion annually in the United States alone and to consume millions of animal and human biological samples in experiments whose conclusions may be unreliable. Community validation frameworks, reporting standards, and independent characterisation initiatives have made important progress, and multi-stakeholder coordination efforts are emerging. However, the research community lacks a formally developed, consensus-based action plan that specifies what each stakeholder group should do, by when, and with what priority. We conducted a modified Delphi study with international experts representing academic researchers, scientific publishers, research funders, antibody manufacturers, and institutional research leaders to develop actionable recommendations for improving antibody validation,

selection, and reporting practices. Thirty-two participants rated 33 proposed actions on effectiveness and feasibility using 9-point scales, with consensus assessed using the RAND/UCLA Appropriateness Method. Over two rounds, the panel achieved consensus on 15 items as both effective and feasible for implementation by 2030. These spanned institutional actions (training in antibody validation, integration into research integrity frameworks, support for local expertise networks), funder actions (dedicated validation budgets, grant application requirements, endorsement of community reporting standards), publisher actions (complete antibody reporting packages, clear validation standards), manufacturer actions (assignment of unique identifiers at source), and cross-stakeholder coordination (a shared roadmap for improvement). An additional 15 items were rated as effective but with uncertain feasibility, reflecting a consistent pattern in which the panel agreed on the value of proposed interventions but expressed reservations about realistic implementation timelines. One item was rejected by the panel with concerns around effectiveness and feasibility. Participants described four interconnected barriers to progress: diffuse ownership of the problem across stakeholders; market dynamics that inadequately reward antibody quality; difficulty justifying investment when returns are distributed across the research system; and coordination challenges among actors with different incentive structures. These barriers are addressable through coordinated action, and the findings complement existing technical and data-sharing initiatives by providing the structured, stakeholder-endorsed policy framework needed to translate awareness of the problem into concrete practice and policy changes.

Abbreviations

COM-B, Capabilities + Opportunities + Motivation Behaviour model; IPR, inter-percentile range; IPRAS, inter-percentile range adjusted for symmetry; IWGAV, International Working Group on Antibody Validation; MDAR, Materials Design Analysis Reporting; MRC, Medical Research Council; NC3Rs, National Centre for the Replacement, Refinement and Reduction of Animals in Research; OGA, Only Good Antibodies; RRID, Research Resource Identifier; YCharOS, Antibody Characterisation by Open Science.

Introduction

Antibodies are among the most widely used tools in biomedical research, enabling researchers to detect, quantify, and isolate specific proteins within complex biological samples. However, research antibodies do not always bind exclusively to their intended targets. Poor antibody specificity has repeatedly misdirected biomedical research across diverse fields, leading to incorrect conclusions about protein function, unreliable biomarker discovery, and misidentification of drug targets [1-10]. These failures represent not isolated occurrences but a persistent and systemic issue affecting the reliability of the published literature.

The scale of this problem is substantial. An estimated $28.2 billion per year is spent in the United States on preclinical research that is not reproducible, with issues relating to biological reagents likely being the biggest contributor [11]. Antibody-related failures alone account for an estimated $1 billion annually in the US in direct economic waste [12, 13], a figure that excludes the substantial opportunity cost of misdirected research effort. Beyond the economic dimension, there is a large and largely unquantified ethical cost: the waste of animals both in antibody production and in research studies that employ unsuitable antibodies, and the waste of donated human biological materials in experiments whose conclusions may be unreliable [14]. Recent estimates suggest that at least 4 million animal samples and 6 million human tissue samples have been consumed globally in

experiments using antibodies that failed independent testing, without context-specific validation since December, 2000 [14].

How well an antibody performs in binding to its target varies between applications, protocols, and the cell or tissue types used for each experiment. Consequently, it is important that performance is assessed for each context of use, a process referred to as validation, and it is the responsibility of the researcher to carry out these studies for their specific protocol [15]. The complexity and scale of antibody use have contributed to a marketplace containing a high proportion of poorly performing antibodies [1]. Recent independent benchmarking by the YCharOS (Antibody Characterisation by Open Science) consortium quantified the likely scale of the problem: greater than 50% of 614 commercial antibodies against 65 neuroscience-related proteins failed characterisation experiments in three commonly used applications, and 88.4% of papers using poorly performing antibodies in immunofluorescence presented no relevant validation data [1]. Moreover, each protein target was linked to an average of approximately 12 published papers that presented data using poorly performing antibodies, perpetuating the use of these reagents and the associated issues of reproducibility.

Efforts to address this problem have operated on multiple fronts. Technical advances include the IWGAV five-pillar validation framework, which outlines complementary strategies (genetic, orthogonal, independent antibody, tagged protein, and immunocapture mass spectrometry), for establishing antibody selectivity [15], and the large-scale independent characterisation work of the YCharOS consortium, which has provided open, head-to-head comparisons of commercial antibodies using knockout cell lines as isogenic controls [1]. Reporting standards such as the Materials Design Analysis Reporting (MDAR) framework have sought to improve transparency at the point of publication [16], and tools including the Research Resource Identifier (RRID) initiative have enabled more precise tracking of antibody use across the literature [17]. Individual

manufacturers have also invested in more rigorous characterisation, in some cases removing or relabelling products found to perform poorly [1, 14].

In parallel, multi-stakeholder coordination has begun to emerge. Kahn et al. [12] assembled a history of efforts to address the antibody characterisation crisis and proposed sector-specific actions for researchers, universities, journals, vendors, scientific societies, disease foundations, and funding agencies. The Only Good Antibodies (OGA) community, , of which members of the present study team are founding contributors [18], has brought together stakeholders across the research ecosystem to work toward making best practice in antibody use more feasible, easy, and rewarding, drawing on the Centre for Open Science's framework for culture change in research. These initiatives represent important progress. However, the field still lacks a formally developed, consensus-based action plan in which proposed interventions have been systematically rated for both effectiveness and feasibility by a diverse expert panel. Without such structured prioritisation, it is difficult for stakeholders to know which actions to implement first, where the strongest agreement exists, and where feasibility barriers require targeted attention.

The underlying reasons for the persistence of this problem are complex and multifaceted, encompassing the inherent challenges of producing and characterising high-quality antibodies, but also researcher awareness, education, and incentive structures [14]. Researchers identify time, cost, and lack of supervisor support as primary barriers to better validation practices, while strongly supporting structural solutions including open data sharing, dedicated validation funding, and publisher requirements [14]. Behavioural analysis drawing on the COM-B (Capabilities + Opportunities + Motivation Behaviour) model suggests that individual capability and motivation interact with the opportunity provided by the research environment, such that improvements to practice require changes not only in individual behaviour but in the systems and structures that shape it [14, 18]. This suggests that the problem requires coordinated action across the research ecosystem.

Having established the scale and drivers of the problem [14], and situated it within the broader landscape of ongoing technical and community efforts [1, 12, 18], this study sought to move from identifying what needs to change, to building structured agreement on how to change it. We convened a multi-stakeholder Delphi consensus process to systematically develop and prioritise recommendations for improving antibody validation, selection, and reporting practices. Drawing on structured assessment by 32 international experts representing researchers, publishers, funders, manufacturers, and institutional leaders, this study presents a consensus process for each expert stakeholder group alongside an analysis of implementation barriers and opportunities for coordinated action.

Methods

Study Design and Ethical Approval

We conducted a modified Delphi study to develop stakeholder-informed recommendations for improving antibody validation, selection, and reporting practices in biomedical research. The Delphi method is a structured consensus-building approach that systematically collects and synthesises expert opinion through iterative questionnaires with controlled feedback [19]. This study was approved by the University of Leicester College of Life Sciences Research Ethics Committee (reference number [2025-1122-5743]) and conducted in accordance with the General Data Protection Regulation (GDPR, 2018). All participants provided informed consent before participation. The study protocol anticipated up to four rounds of consultation between August 2025 and February 2026, with each round allowing 2-3 weeks for completion. Data collection and management were conducted using the Clinvivo platform (https://www.clinvivo.com; Clinvivo Ltd, London, UK), a secure GDPR-compliant system designed specifically for Delphi studies.

Participant Recruitment

We identified expert stakeholders from five key sectors involved in antibody use and research governance: academic biomedical research, scientific publishing, research funding, antibody

manufacturing, and institutional research leadership. Experts were defined as individuals who are representative of their profession, have the power to implement findings, or who would not be challenged as experts in their field [21]. Thirty-eight experts were identified through networks based on their expertise in antibody validation, editorial roles at major biomedical journals, leadership positions at research funding organisations, executive roles in commercial antibody production, or responsibility for research integrity policies at academic institutions. Tailored recruitment emails were sent to each stakeholder group. Participants were informed that the study aimed to develop a consensus-based action plan to improve antibody validation and reporting across the research ecosystem, and that their anonymised responses would be aggregated to inform policy recommendations for journals, funders, institutions, and manufacturers.

The Delphi Process

The Delphi process consisted of iterative rounds of anonymous questionnaire completion with structured feedback. Initial draft statements for Round 1 were developed from two sources: recommendations emerging from a stakeholder meeting convened by the National Centre for the Replacement, Refinement and Reduction of Animals in Research (NC3Rs) in February 2024 [20], and themes identified through focus group discussions (and validated with a survey) with antibody-using researchers conducted in the summer of 2023 [14]. These sources yielded 23 proposed actions spanning four domains: journal and publisher policies (n=9 items covering reporting requirements, validation transparency, and editorial capacity building), research funder actions (n=9 items covering grant requirements, validation funding, and manufacturer engagement), institutional and educational interventions (n= 3 items covering training, ethics frameworks, and local champions), and cross-stakeholder coordination mechanisms (n= 2 items covering roadmaps, shared infrastructure, and benchmarking initiatives). Each item described a specific action that one or more stakeholder groups could adopt to improve antibody practices (S6 Text).

Round 1 was conducted from August 12 to September 12, 2025, with two deadline extensions to maximise response rates. Participants received weekly email reminders from Clinvivo, and the research team sent a final reminder on the originally scheduled closing date. Round 2 was conducted from November 6 to November 23, 2025, following the same reminder protocol. The decision to proceed to additional rounds was based on pre-specified criteria: lack of consensus, persistence of significant disagreement requiring resolution, or evidence that additional rounds would meaningfully shift ratings (e.g., based on qualitative feedback).

Rating System and Assessment of Consensus

Participants rated each proposed action on two 9-point rating scales. The effectiveness scale permitted panellists to rate how meaningfully they thought the item would improve the selection, validation, or reporting of antibodies in research (1=extremely ineffective, 9=extremely effective). The feasibility scale permitted panellists to rate how realistically they thought items could be adopted across relevant settings by 2030 (1=extremely infeasible, 9=extremely feasible). Participants could select "don't know" if an item fell outside their area of expertise. For each item, participants could provide free-text comments to share their rationale, identify potential risks or unintended consequences, or suggest alternative wordings.

To assess disagreement, we employed the RAND/UCLA Appropriateness Method [19]. For each item, we calculated the median rating, the inter-percentile range (IPR; difference between the 30th and 70th percentiles), and the inter-percentile range adjusted for symmetry (IPRAS). The IPRAS accounts for asymmetric rating distributions using the equation: IPRAS = IPRr + (AI × CFA), where IPRr is the inter-percentile range required for disagreement when perfect symmetry exists (2.35), AI is the asymmetry index (calculated as the distance between the central point of the IPR and the scale midpoint of 5), and CFA is the correction factor for asymmetry (1.5). These values of 2.35 and 1.5 were empirically derived by Fitch et al. [19] to best reproduce classic RAND definitions of disagreement for 9-point scales. Percentiles were calculated using Stata version 18

(StataCorp LLC, College Station, TX; RRID:SCR_012763) with the R-2 formula (Stata's default method).

An item was classified as having disagreement when IPR > IPRAS for that item. Items were classified according to median ratings: effective/feasible (median 7-9), ineffective/infeasible (median 1-3), or uncertain (median 4-6). For medians falling on category boundaries (3.5 or 6.5) due to even participant numbers, we applied a "round down" rule, classifying 3.5 as ineffective/infeasible and 6.5 as uncertain. This meant a conservative approach was taken to describing ratings as effective or feasible. Qualitative free-text comments were reviewed by the research team to inform item refinement, identify new proposed actions, and develop narrative summaries for feedback to participants in subsequent rounds.

Progression Decisions Between Rounds

Items were progressed, removed, or modified between rounds based on their ratings, the presence or absence of disagreement, or qualitative feedback. Items rated as both effective (median ≥7) and feasible (median ≥7) without disagreement were accepted as recommendations and did not require re-rating in subsequent rounds unless there were suggestions for rewording in the qualitative comments. Items rated as both ineffective (median ≤3) and infeasible (median ≤3) without disagreement were rejected and removed from further consideration. Items classified as uncertain on either dimension, or those with disagreement, were considered for re-rating in the next round, particularly if qualitative comments suggested that rewording, clarification, or presentation of divergent perspectives might shift opinions.

Between Round 1 and Round 2, panel members' free-text comments were reviewed to identify: (1) suggestions for new action items to add to the consensus process, (2) proposed modifications to existing item wording, and (3) substantive concerns or alternative perspectives that should be shared with the panel. Items were reworded when comments indicated ambiguity or suggested semantically meaningful improvements. New items suggested by multiple participants or

representing distinct actionable proposals were added to Round 2. For items with disagreement or uncertainty, we prepared feedback summaries that synthesised the range of panel perspectives to support informed re-rating. Items with substantive wording changes based on panel feedback were re-rated regardless of initial ratings, to ensure consensus reflected the revised formulation.

Results

Participant Characteristics and Response Rates

Thirty-eight individuals were invited to participate in Round 1. Thirty-two completed the round (response rate: 84.2%). All Round 1 participants were invited to Round 2, and 30 completed this round (response rate: 93.8%; overall retention: 78.9% of original invitees).

The 32 Round 1 participants included 13 females (40.6%), 17 males (53.1%), and 2 who preferred not to disclose sex (6.3%). Among the 30 participants who reported their age, the mean was 51.5 years (SD=11.3). Participants were primarily based in the United Kingdom (n=16, 50.0%) and United States (n=13, 40.6%), with additional representation from Canada (n=2, 6.3%) and Germany (n=1, 3.1%). The panel was highly educated, with 27 participants (84.4%) holding PhD-level qualifications, 2 (6.3%) holding master's degrees, and 3 (9.4%) holding bachelor's degrees. Participants represented diverse fields within the biomedical research ecosystem: academic biomedical research (n=7, 21.9%), scientific publishing (n=6, 18.8%), antibody manufacturing (n=6, 18.8%), research funding (n=4, 12.5%), industrial biomedical research (n=2, 6.3%), and other fields (n=7, 21.9%) including antibody informatics, infrastructure provision, and the charity sector. Within these sectors, participants held senior decision-making roles: 37.5% (n=12) reported full autonomy to make decisions on behalf of their organisations, 34.4% (n=11) made decisions with input from senior leaders, and 28.1% (n=9) made recommendations with final decisions made by senior leaders. Detailed breakdowns of career stages within each employment sector are provided in S1 Table.

Overview of Items and Consensus Development

A total of 33 proposed action items were rated across two rounds (Figure 1). Round 1 presented 23 items spanning four domains: journal and publisher policies (9 items, R1–R9), research funder actions (9 items, R10–R18), institutional and educational interventions (3 items, R19–R21), and cross-stakeholder coordination (2 items, R22–R23), see S6 Text for full item wording. All 32 participants rated effectiveness and feasibility for each of the 23 proposed actions. Panel ratings demonstrated strong consensus on most items, with disagreement identified on only 2 of 46 ratings (effectiveness and feasibility combined).

Following Round 1 analysis, 11 items (R1, R2, R10–R15, R19, R20, R22) achieved consensus as both effective (median ≥7) and feasible (median ≥7) without disagreement and were immediately accepted as recommendations without requiring re-rating. The remaining 12 items from Round 1 were re-presented in Round 2, including six with revised wording based on panel comments (R3, R8, R9, R17, R18, R21). Based on participant free-text suggestions, 10 additional action items (A1–A10) were added to Round 2. Round 2 thus presented 22 items for rating: 12 re-rated items from Round 1 and 10 newly proposed items.

In Round 2 disagreement only occurred on 1 of 44 ratings. Among the 22 items presented in Round 2, four achieved agreement as both effective and feasible (R3, R21, A1, A7), joining the 11 items accepted in Round 1 for a total of 15 consensus recommendations at the close of Round 2. One item (R5) shifted from uncertain in Round 1 to consensually infeasible in Round 2 (median feasibility declined from 4.0 to 3.0) and was the only item to be rated either infeasible or ineffective. Two items (A4, A5) were rated as uncertain on both effectiveness and feasibility.

Final Consensus Outcomes

Across the two rounds, the panel evaluated 33 proposed actions, achieving consensus on 15 items as both effective (median ≥7) and feasible (median ≥7), without disagreement (Table 1). These 15 recommendations span all four stakeholder domains and represent actions that expert panellists

agreed would meaningfully improve antibody practices and could realistically be implemented by 2030.

The panel rated 17 items as uncertain on at least one dimension (Table 2). In 15 of these 17 cases, items were rated as effective (median ≥7) but with uncertain feasibility (median 4–6), indicating that while panellists believed these actions would improve antibody practices, they had reservations about realistic implementation by 2030. This pattern, high confidence in effectiveness, uncertainty about feasibility, was the dominant finding for items not achieving consensus, and is a recurring theme in the stakeholder-specific recommendations presented below. One item was rejected by the panel, with concerns around both effectiveness and feasibility (Table 3). A summary of the ratings across all items is presented in Figure 2.

Following analysis of Round 2 results, the research team decided not to proceed to a third round. This decision was based on three convergent factors. First, a high proportion of items (15 of 33, 45.5%) had achieved clear consensus as both effective and feasible across the two rounds. Second, disagreement remained minimal, with disagreement being present on only one item in Round 2. Third, rating stability between rounds was high: among the 12 items re-rated in Round 2, median effectiveness ratings remained identical for 9 items (75.0%) and median feasibility ratings remained identical for 10 items (83.3%), with no item shifting by more than 1 point on either scale. The minimal rating changes between rounds indicated that further iteration would be unlikely to resolve the persistent pattern of items rated as effective but with uncertain feasibility. Full quantitative results for all items across both rounds are presented in S2 and S3 Tables, with complete qualitative commentary provided in S7 and S8 Texts.

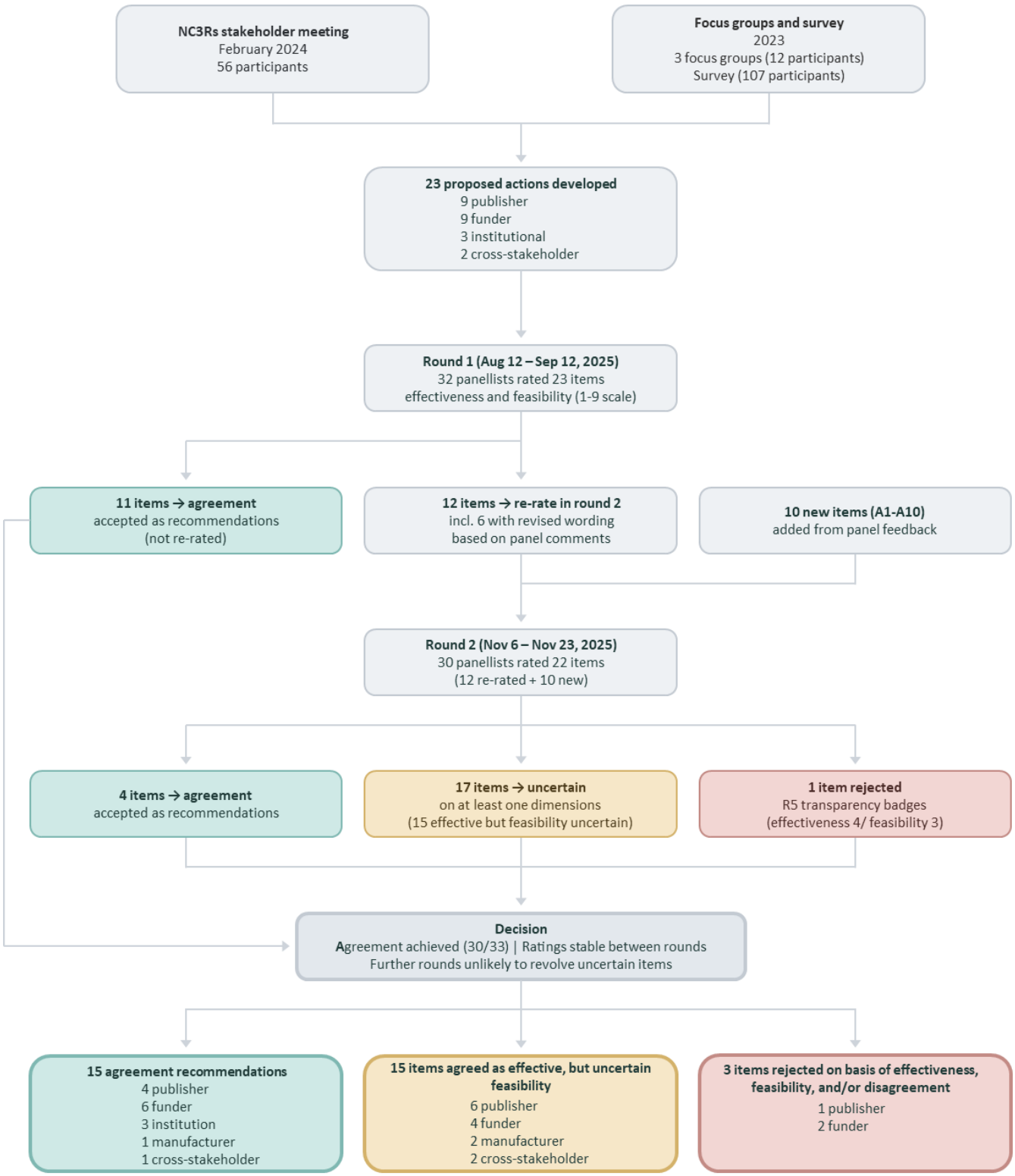

Figure 1. Overview of the Delphi process including formulation of recommendations and their assessment across rounds.

290 **TABLE 1: Consensus Recommendations - Items Rated Both Effective and Feasible with agreement**

Item	Full Recommendation	Median Effectiveness	Median Feasibility	Stakeholder Group targeted by recommendation
Journal and Publisher Policies				
R1	Authors should include the Research Resource Identifier (RRID) for each antibody used, where available.	7.0	8.0	Journals, Authors
R2	Authors should provide sufficient metadata to allow unambiguous identification of each antibody. This includes: Clone ID (for monoclonal antibodies), Catalogue number and lot number (for polyclonal antibodies), Vendor or source.	8.0	8.0	Journals, Authors
R3	Authors should report the dilution ratio at which each antibody is used. In addition, authors should state the antibody protein concentration where possible. Examples include dilution ratios such as 1:1000 or 1:500, or concentrations expressed in µg/mL.	8.0	8.0	Journals, Authors

A1	Journals should have a clearly stated standard for antibody validation and reporting.	7.5	7.0	Journals
Research Funder Actions				
R10	Funders should include a section in the application form where applicants must detail the steps they will take to validate the antibodies used.	7.5	8.0	Funders
R11	Applicants to biomedical funding schemes should include a specific line item within their budget for resources to conduct robust antibody validation (if relevant to their proposal).	8.0	7.0	Funders
R12	Funders should create or expand targeted schemes to support the development and validation of critical antibody-based research tools. These could include, for example: Characterisation of under-studied antibodies, Generation of KO/KD cell lines, Cross-platform benchmarking of antibody performance, Replacement of animal-derived antibodies.	8.0	7.0	Funders

R13	Funders should share information within the applicant guidance that antibody performance is an important limitation in many experimental methods. Applicants should be encouraged to address this in methodological or reproducibility sections, as this will be part of how these sections are evaluated by reviewers and panels.	7.0	7.0	Funders
R14	Funders should encourage grantees to deposit antibody validation data in open-access repositories, ideally linked to RRIDs or registry entries. This expectation could be embedded in end-of-grant reporting or incentivised through visibility or reproducibility initiatives.	7.0	7.0	Funders
R15	Funders should formally endorse community-developed reporting standards that promote antibody transparency and validation (e.g., IWGAV, MDAR). Such endorsements can help reinforce aligned expectations across funders and journals.	7.0	7.0	Funders
Institutional and Educational Actions				
R19	Training in antibody validation should be offered in relevant bioscience courses and programmes. This could include: Undergraduate education (e.g., in	8.0	7.0	Institutions, Learned Societies

	immunology, neuroscience, or molecular biology programmes), Postgraduate or doctoral training (e.g., through doctoral training centres), Postdoctoral or continuing professional development. Training should be field-appropriate, not universally required across all domains.			
R20	Universities and research institutions should incorporate antibody validation expectations into research integrity and ethics review frameworks. This may include: Asking researchers to consider antibody validation as part of research ethics approval processes, Providing guidance or templates for documenting validation plans.	7.0	7.0	Institutions
R21	Universities, research institutions and learned societies should recognise and support the Antibody Champions Scheme. This UK-based initiative, co-funded by the Medical Research Council (MRC) and the National Centre for the replacement, refinement and reduction of animals in research (NC3Rs), will be launched in 2026. It will be a voluntary scheme of local champions or experts in antibody validation. These individuals will serve as: Points of contact for advice on antibody selection, validation design, and data interpretation; Trainers or facilitators in	7.0	7.0	Institutions, Learned Societies

	antibody validation best practice workshops or research methods courses; Advocates for antibody good practice within departments or core facilities. Support could include protected time, acknowledgement in performance reviews, or funding for training and outreach.			
Cross-Stakeholder Coordination				
R22	Stakeholders should work together to develop a shared roadmap for improving antibody validation practices by 2030. This would outline: Stakeholder-specific actions and responsibilities, Target timelines and milestones, Mechanisms for accountability and feedback.	7.0	7.0	All Stakeholders
Manufacturer Actions				
A7	Antibody manufacturers should be encouraged to assign RRIDs to their products at source.	8.0	7.0	Manufacturers

293 **TABLE 2: Items with Agreed Uncertain Effectiveness and/or Feasibility**

Item	Full Recommendation	Median Eff	Median Feas	Pattern
Effective but Feasibility Uncertain				
R4	Journals should require authors to deposit antibody validation data in an open-access repository, linked to a persistent identifier (e.g., RRID, DOI). Repositories might include: Zenodo, institutional repositories, manufacturer portals, or The Antibody Registry (linked to Biomed Resource Watch).	8.0	5.0	Effective, Uncertain Feasibility
R6	Publishers should provide training resources for reviewers and editors to help them evaluate antibody validation information in submitted manuscripts.	7.0	5.0	Effective, Uncertain Feasibility
R7	Publishers and other stakeholders should support the development and use of automated tools to flag potential antibody validation issues in submitted manuscripts – e.g., for antibodies that have already been withdrawn from the market because of performance issues.	8.0	5.0	Effective, Uncertain Feasibility

R8	As part of the submission process, authors should describe how antibody specificity was assessed, making reference to the International Working Group on Antibody Validation (IWGAV) framework. A brief paragraph, checklist, or table should indicate which of the IWGAV pillars were used, if any (e.g., genetic, orthogonal, independent antibody, tagged protein, IP-MS).	7.0	6.0	Effective, Uncertain Feasibility
R9	Where antibodies are critical to key experimental conclusions, where technically feasible, authors should either: present validation data based on a genetic strategy (e.g., knockout or knockdown), or cite previously published genetic validation data.	8.0	5.0	Effective, Uncertain Feasibility
R16	Funders should directly engage with manufacturers to encourage them to: Publish antibody validation datasets, Adopt consistent metadata standards (e.g., RRID, clone ID, lot number).	7.0	5.0	Effective, Uncertain Feasibility
R17	Funders should collaborate with independent benchmarking initiatives such as YCharOS or equivalent open-science consortia. They should directly co-fund the validation of antibodies against key targets to create suites of validated tools that can be used by researchers to improve data quality and thereby increase return on investment for the funder.	8.0	6.0	Effective, Uncertain Feasibility

R18	Funders should promote industry participation in independent benchmarking initiatives by asking applicants to consider working with initiatives such as YCharOS or equivalent open-science consortia as part of their work. This could be achieved either by including the recommendation in the guidance notes or flagging to applicants at the panel review stage.	7.0	6.0	Effective, Uncertain Feasibility
R23	A coordinated, shared infrastructure should be developed (or expanded) to: Aggregate antibody validation data, Provide standardised formats and tools for sharing, Enable journals, funders, and institutions to access validation status or red flags. This may involve expanding existing platforms such as YCharOS, or building interoperability across initiatives like RRID, Benchsci, CiteAb, and Antibody Registry.	8.0	6.0	Effective, Uncertain Feasibility
A2	Detailed Protocols and Validation data should be included in the manuscript or supplemental data.	8.0	6.0	Effective, Uncertain Feasibility
A3	Journals should appoint a specialist editor that focuses on reproducibility.	7.0	5.5	Effective, Uncertain Feasibility

A6	Funders should mandate that if funds are used to develop an antibody as part of a research project, the reagent must be a recombinant antibody and must be made available to the wider community.	7.0	6.0	Effective, Uncertain Feasibility
A8	Manufacturers should perform a standard set of validation experiments on their reagent antibodies and make the data available.	8.0	6.5	Effective, Uncertain Feasibility
A9	Manufacturers should shift production to all recombinant antibodies.	7.0	5.0	Effective, Uncertain Feasibility
A10	A learned society for antibody validation should be established.	7.0	5.0	Effective, Uncertain Feasibility
Uncertain on Both Dimensions				
A4	Funders should maintain and provide researchers with a list of manufacturers who validate their antibodies.	6.0	5.0	Uncertain Both

A5	Funders should mandate the use of recombinant antibodies (or at least monoclonals) when available. Justification should be required if a polyclonal is used.	6.0	5.0*	Uncertain Both

294 *Panel disagreement on feasibility (IPR=4 > IPRAS=2.35)

295

296 **TABLE 3: Rejected Recommendation - Item Rated Uncertain effectiveness, and Infeasible, with agreement**

Item	Full Recommendation	Median Effectiveness	Median Feasibility
R5	Journals should introduce a tiered scoring system or transparency badge to recognise papers that meet higher standards of antibody reporting and validation.	4.0	3.0

297

Stakeholder Group
Institutions
Funders
Manufacturers
Publishers / Journals
Cross-stakeholder
Panel disagreement
Effective & Feasible
(Agreement)
Effective but
Feasibility Uncertain
R1
R10
R2
R3
R13
R14
R15
A1
R11
R12
R20
R21
R22
R19
A7
A8
R8
R18
R17
R23
A6
A2
A3
A4
A5
R6
R16
R4
R7
A9
A10
R9
R5
Median Feasibility Rating
Median Effectiveness Rating
3
4
5
6
7
8
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300 **Figure 2. Effectiveness and feasibility ratings for all 33 proposed actions.** Each point
301 represents one proposed action, plotted by median effectiveness (x-axis) and median feasibility
302 (y-axis) ratings on 9-point scales. Points are colour-coded by stakeholder group. Dashed lines
303 indicate the boundary between ratings classified as effective/feasible (median ≥7) and uncertain
304 (median 4–6), following our RAND/UCLA round-down rule for boundary medians of 6.5. The
305 upper-right quadrant contains items rated as both effective and feasible with agreement (15
306 items). The lower-right quadrant contains items rated as effective but with uncertain feasibility
307 (15 items). Item with panel disagreement (A5, IPR > IPRAS) is shown as open circle with dashed
308 borders; all other items achieved agreement. One item (R5) was rejected by the panel (uncertain
309 effectiveness, infeasible). Points at identical coordinates have been slightly offset for readability.

310

311 **Stakeholder-Specific Recommendations**

312 The following sections present the consensus recommendations, predicted to be both effective and
313 feasible, and items predicted to be effective but with uncertain feasibility for implementation by 2030,
314 organised by stakeholder group. For each recommendation, we provide the panel's quantitative
315 assessment alongside key themes from the qualitative feedback that contextualise the ratings and
316 inform implementation considerations. Full qualitative analysis for the 15 consensus recommendations,
317 is presented in S1 Text, and detailed stakeholder consultation drafts including implementation options
318 are provided in S2–5 Texts.

319 **Key Recommendations for Institutions**

Box 1. Summary of Institutional Recommendations

Consensus recommendations (effective and feasible by 2030):

- R19: Training in antibody validation in relevant bioscience courses and programmes (Eff 8.0 / Feas 7.0)
- R20: Incorporate antibody validation into research integrity and ethics review frameworks (Eff 7.0 / Feas 7.0)
- R21: Recognise and support local champions or experts in antibody validation (Eff 7.0 / Feas 7.0)

All three institutional items achieved full consensus (ie rated effective and feasible without disagreement). No items with uncertain feasibility. This is unique among stakeholder groups.

Median ratings: Eff = Effectiveness; Feas = Feasibility; rated on 9-point scales.

320 The panel viewed institutional actions as foundational to the broader reform effort, with one panellist
321 noting that "without laying such a groundwork of training and advocacy, antibody validation will never
322 become the norm."

Training in antibody validation received strong endorsement (median effectiveness 8.0, feasibility 7.0; R19). The panel recommended that training should be offered in relevant bioscience courses and programmes, including undergraduate education in fields such as immunology, neuroscience, and molecular biology, postgraduate and doctoral training, and continuing professional development. Importantly, the panel emphasised that training should be field-appropriate rather than universally mandated across all domains. Panel members highlighted the need to address laboratory culture alongside formal training, noting that "*in many cases the emphasis on validation and proper controls comes down to lab culture. If a student is trained to validate antibodies but the PI/senior lab members do not agree this is a priority, it will not be done*." The need to train established researchers as well as trainees was a recurring theme: "*Need to train the senior staff as well!"*

The panel endorsed incorporating antibody validation expectations into institutional research integrity and ethics review frameworks (median effectiveness 7.0, feasibility 7.0; R20). This could include asking researchers to consider antibody validation as part of research ethics approval processes and providing guidance or templates for documenting validation plans. However, panel members debated the appropriate framing, with some questioning whether antibody validation constitutes an ethical issue in the traditional sense: "*I don't really see this as an ethical issue. Lumping it into ethics with big issues like image manipulation, data fabrication, animal use, etc doesn't seem appropriate*." Others noted that the waste of animal and human samples resulting from poor antibody validation carries clear ethical implications. Panel members also noted that "*a lot of research does not go through ethics committees,*" emphasising the importance of complementary mechanisms beyond ethics review alone.

The third institutional recommendation called for universities, research institutions, and learned societies to recognise and support local champions or experts in antibody validation (median effectiveness 7.0, feasibility 7.0; R21). These individuals could serve as points of contact for advice on antibody selection and validation design, trainers or facilitators in reproducibility workshops, advocates

347 for good practice within departments or core facilities, and contributors to cross-institutional
348 reproducibility networks. Support could include protected time, acknowledgement in performance
349 reviews, or funding for training and outreach. The panel viewed this as foundational, for example
350 noting that "*all of the questions in this section are not going to make antibody research more*
351 *reproducible per se but will lay the foundation for increased awareness and adoption of best practice*."
352 However, concerns about institutional buy-in and sustainability were raised, with panellists questioning
353 how to maintain expertise networks given high turnover of research staff and limited institutional
354 awareness of the problem.

355 **Key Recommendations for Funders**

Box 2. Summary of Funder Recommendations

Consensus recommendations (effective and feasible by 2030):

- R10: Require antibody validation plans in grant applications (Eff 7.5 / Feas 8.0)
- R11: Dedicated budget line for antibody validation in funded projects (Eff 8.0 / Feas 7.0)
- R12: Create or expand targeted tool development and validation schemes (Eff 8.0 / Feas 7.0)
- R13: Signal importance of antibody validation in applicant guidance (Eff 7.0 / Feas 7.0)
- R14: Encourage deposition of validation data in open-access repositories (Eff 7.0 / Feas 7.0)
- R15: Formally endorse community-developed reporting standards (e.g., IWGAV, MDAR) (Eff 7.0 / Feas 7.0)

Effective but feasibility uncertain (4 items):

- R17: Co-fund independent benchmarking initiatives (Eff 8.0 / Feas 6.0)
- R18: Promote researcher participation in benchmarking (Eff 7.0 / Feas 6.0)

- R16: Directly engage manufacturers on transparency (Eff 7.0 / Feas 5.0)
- A6: Mandate funded antibodies be recombinant and publicly available (Eff 7.0 / Feas 6.0)

Median ratings: Eff = Effectiveness; Feas = Feasibility; rated on 9-point scales.

356

357 The panel viewed funders as occupying a critical position in the research lifecycle: before experiments
358 are conducted, when validation planning and budgeting can be embedded from the outset (full
359 qualitative comments in S7 and S8 Texts).

360 The panel reached consensus that funders should provide dedicated financial support for antibody
361 validation. This encompasses two complementary actions: applicants to biomedical funding schemes
362 should include a specific budget line item for resources to conduct robust antibody validation where
363 relevant to their proposal (median effectiveness 8.0, feasibility 7.0; R11), and funders should create or
364 expand targeted schemes to support the development and validation of critical antibody-based research
365 tools (median effectiveness 8.0, feasibility 7.0; R12). Both items received the highest effectiveness
366 ratings among funder recommendations. Panel members noted, however, that budget constraints could
367 pose challenges, with one participant observing that *"research proposals typically employ multiple*
368 *antibodies (5–10+). Would the applicant be required to validate all antibodies prior to use? This*
369 *would result in a pretty significant budget increase."*

370 The panel also endorsed embedding antibody validation expectations into grant application processes
371 through escalating approaches. At a minimum, funders should include information in applicant
372 guidance that antibody performance is an important limitation in many experimental methods and
373 encourage applicants to address this in methodological sections (median effectiveness 7.0, feasibility
374 7.0; R13). More substantively, funders should include a section in application forms where applicants

375 must detail the steps they will take to validate the antibodies used (median effectiveness 7.5, feasibility
376 8.0; R10). Panel members nevertheless cautioned against box-ticking: *"Another box ticking exercise for*
377 *the applicant, which is filled with little care and using generic text each time."* Panel members
378 cautioned that effectiveness would depend on whether validation plans are genuinely evaluated during
379 review.

380 Two further consensus recommendations addressed community standards and data sharing. Funders
381 should formally endorse community-developed reporting standards that promote antibody transparency
382 and validation, such as those from the IWGAV and MDAR frameworks (median effectiveness 7.0,
383 feasibility 7.0; R15). Funders should also encourage grantees to deposit antibody validation data in
384 open-access repositories, ideally linked to RRIDs or antibody registry entries (median effectiveness
385 7.0, feasibility 7.0; R14). Panel members noted that endorsement alone, while a *"feasible and low lift"*
386 action, may be insufficient without accompanying enforcement mechanisms, and expressed concern
387 about the quality of deposited data without robust review processes.

388 Beyond the consensus recommendations, co-funding of independent benchmarking initiatives such as
389 YCharOS were deemed effective (median effectiveness 8.0), but feasibility remained uncertain
390 (median 6.0; R17). Panel members agreed that creating suites of validated tools through independent
391 benchmarking would substantially improve data quality and increase return on investment, but
392 expressed concern about alignment with funder mandates and funding mechanism constraints. Several
393 additional funder recommendations were rated as effective but with feasibility concerns, including
394 promoting researcher participation in benchmarking (median effectiveness 7.0, feasibility 6.0; R18),
395 mandating that funded antibodies be recombinant and publicly available (median effectiveness 7.0,
396 feasibility 6.0; A6), and engaging manufacturers directly on transparency (median effectiveness 7.0,
397 feasibility 5.0; R16).

398

399 **Key Recommendations for Manufacturers**

Box 3. Summary of Manufacturer Recommendations

Consensus recommendation (effective and feasible by 2030):

- A7: Assign RRIDs to products at source (Eff 8.0 / Feas 7.0)

Effective but feasibility uncertain (2 items):

- A8: Perform standard validation experiments and make data available (Eff 8.0 / Feas 6.5)
- A9: Shift production toward recombinant antibodies (Eff 7.0 / Feas 5.0)

One consensus item; feasibility barriers for remaining items reflect commercial viability and market dynamics. S5 Text for consultation draft.

Median ratings: Eff = Effectiveness; Feas = Feasibility; rated on 9-point scales.

400 The manufacturer landscape presented a distinctive pattern: one recommendation achieved full
401 consensus, while the remaining items were rated as effective but with significant feasibility barriers
402 reflecting the commercial context in which manufacturers operate. Panel members, including
403 manufacturer representatives, repeatedly acknowledged that leading manufacturers already exemplify
404 good practice, while others lag behind.

405 The panel reached consensus that antibody manufacturers should assign Research Resource Identifiers
406 (RRIDs) to their products at source (median effectiveness 8.0, feasibility 7.0; A7). This was the only
407 manufacturer recommendation to achieve full consensus, and the response was notably enthusiastic,
408 with some panellists describing it as *"really, an easy one"* and noting it *"would be fantastic."* RRIDs
409 assigned at source would enable researchers to uniquely identify and cite specific antibodies,
410 facilitating systematic tracking of antibody performance across the literature and supporting automated
411 screening of submissions by journals. Panel members acknowledged, however, that some suppliers

may not cooperate: *"There are some suppliers that will ignore this, in the same way they have ignored the calls to improve validation."*

Manufacturers performing a standard set of validation experiments and making the data available was rated as effective (median effectiveness 8.0) but with uncertain feasibility (median 6.5; A8). The tension between rigorous context-specific validation and commercial viability was central to panel deliberations. Some panellists were emphatic that this was unrealistic, e.g. with one noting "*Not going to happen. Too expensive*", while others noted that "*reputable manufacturers are already doing this*" and that "*validation is a continual/on-going process for every antibody*." A shift toward recombinant antibody production was similarly rated as effective (median 7.0) but with uncertain feasibility (median 5.0; A9), with the panel noting that manufacturer production decisions are ultimately driven by customer demand.

424 **Key Recommendations for Publishers and Journals**

Box 4. Summary of Publisher and Journal Recommendations

Consensus recommendations (effective and feasible by 2030):

- R1: Authors include RRIDs for each antibody used (Eff 7.0 / Feas 8.0)
- R2: Authors provide complete antibody metadata for unambiguous identification (Eff 8.0 / Feas 8.0)
- R3: Authors report dilution ratio and protein concentration (Eff 8.0 / Feas 8.0)
- A1: Journals establish clear antibody validation and reporting standards (Eff 7.5 / Feas 7.0)

Effective but feasibility uncertain (4 items, all Eff ≥7.0):

- R4: Require validation data in open-access repositories (Eff 8.0 / Feas 5.0)
- A2: Include validation protocols in manuscripts or supplements (Eff 8.0 / Feas 6.0)
- R7: Automated tools to flag antibody validation issues (Eff 8.0 / Feas 5.0)
- R9: Genetic validation for critical antibodies (Eff 8.0 / Feas 5.0)
- R6: Train reviewers and editors on validation assessment (Eff 7.0 / Feas 5.0)
- A3: Appoint specialist reproducibility editors (Eff 7.0 / Feas 5.5)

Four consensus items centred on reporting requirements. Other effective items face barriers around editorial resources, cost, and infrastructure. See S1 Text for full analysis of consensus items; S2 Text for consultation draft.

Median ratings: Eff = Effectiveness; Feas = Feasibility; rated on 9-point scales.

425

426 Publisher recommendations reflected a common pattern: the panel agreed that several interventions
427 would substantially improve research quality but identified practical barriers around editorial resources,

428 cost, and infrastructure. Four items achieved full consensus, while four additional items deemed
429 effective had uncertain feasibility.

430 The panel reached consensus on a package of reporting requirements that together enable unambiguous
431 antibody identification and experimental replication. Authors should include Research Resource
432 Identifiers for each antibody used where available (median effectiveness 7.0, feasibility 8.0; R1),
433 provide sufficient metadata to allow unambiguous identification of each antibody including clone ID,
434 catalogue number, lot number, and vendor (median effectiveness 8.0, feasibility 8.0; R2), and report the
435 dilution ratio and protein concentration where possible for each antibody used (median effectiveness
436 8.0, feasibility 8.0; R3). These three items work synergistically: complete metadata enables antibody
437 identification, while RRIDs provide persistent identifiers that link to characterisation databases and the
438 broader literature. The panel also reached consensus that journals should establish clear standards for
439 antibody validation and reporting that authors must meet (median effectiveness 7.5, feasibility 7.0; A1),
440 noting that this would only be maximally effective *"if there were community standards already in*
441 *place or consensus across most journals."*

442 The panel rated both the deposition of validation data in open-access repositories (median effectiveness
443 8.0, feasibility 5.0; R4) and the inclusion of detailed validation protocols in manuscripts or
444 supplementary data (median effectiveness 8.0, feasibility 6.0; A2) as effective, but with uncertain
445 feasibility. Similarly, the development and use of automated tools to flag potential antibody validation
446 issues in submitted manuscripts were predicted to be effective, but again uncertain feasibility (median
447 effectiveness 8.0, feasibility 5.0; R7). Panel members viewed automated tools as potentially
448 transformative but questioned who would fund their development and maintenance, and noted that *"not*
449 *all publishers/journals have the financial means"* to implement them. The requirement that authors
450 present genetic validation data for critical antibodies (median effectiveness 8.0, feasibility 5.0; R9) was
451 rated as effective but faced feasibility barriers around technical limitations (essential genes cannot be

knocked out), cost, and the difficulty of defining which antibodies are "critical" to a study's conclusions.

Building editorial capacity for validation assessment was rated as effective but with feasibility concerns. Both training reviewers and editors to evaluate antibody validation information (median effectiveness 7.0, feasibility 5.0; R6) and appointing specialist reproducibility editors (median effectiveness 7.0, feasibility 5.5; A3) faced scepticism about reviewer engagement and publisher resources. Panellists doubted that reviewers would invest time in additional training given already onerous review obligations, and many journals were seen as lacking resources for specialist editor positions.

Cross-Stakeholder Consensus Items

Box 5. Summary of Cross-Stakeholder Items

Consensus recommendation:

- R22: Develop a shared roadmap for improving antibody validation practices by 2030 (Eff 7.0 / Feas 7.0)

Effective but feasibility uncertain:

- R23: Coordinated shared infrastructure for aggregating antibody validation data (Eff 8.0 / Feas 6.0)
- A10: Establish a learned society for antibody validation (Eff 7.0 / Feas 5.0)

Rejected:

- R5: Tiered scoring system or transparency badge (Eff 4.0 / Feas 3.0) — the only item rejected by the panel (uncertain effectiveness, infeasible)

Median ratings: Eff = Effectiveness; Feas = Feasibility; rated on 9-point scales.

Two cross-stakeholder items merit specific attention. The panel reached consensus that stakeholders should work together to develop a shared roadmap for improving antibody validation practices by 2030

464 (median effectiveness 7.0, feasibility 7.0; R22). This roadmap would outline stakeholder-specific
465 actions and responsibilities, target timelines and milestones, and mechanisms for accountability and
466 feedback.

467 The development of coordinated, shared infrastructure for aggregating antibody validation data was
468 deemed potentially effective (median effectiveness 8.0) but uncertain feasibility (median 6.0; R23).
469 This infrastructure would aggregate validation data, provide standardised formats and tools for sharing,
470 and enable journals, funders, and institutions to access validation status or identify known problem
471 antibodies. Panel members viewed this as potentially transformative, supporting several other
472 recommendations, from automated manuscript screening to informed grant review, but recognised the
473 substantial coordination and resource challenges involved. Several recommendations across
474 stakeholder groups would benefit significantly from such shared infrastructure, suggesting that its
475 development could unlock a cascade of downstream improvements.

476 The establishment of a learned society for antibody validation was rated as effective (median 7.0) but
477 with uncertain feasibility (median 5.0; A10). While the panel recognised the potential value of a
478 professional body to coordinate standards, training, and advocacy, concerns were raised about
479 sustainability and the risk of duplicating existing networks. Conversely, the only item rejected by the
480 panel across both rounds was the introduction of a tiered scoring system or transparency badge for
481 antibody reporting (R5), which declined from uncertain to infeasible between rounds, reflecting
482 scepticism about badge-based incentive schemes in this context.

483

Discussion

This Delphi study engaged 32 international experts from across the research ecosystem to develop a formally prioritised, consensus-based set of recommendations for addressing antibody validation failures in biomedical research. The panel achieved consensus on 15 items as both effective and feasible for implementation by 2030, spanning institutional, funder, manufacturer, and publisher actions as well as cross-stakeholder coordination. An additional 15 items were rated as effective but with uncertain feasibility, reflecting a consistent pattern in which experts were confident that proposed interventions would improve antibody practices but less certain about realistic implementation within the target timeframe. Together with existing technical solutions [1], data-sharing initiatives [17, 21], and emerging stakeholder coordination efforts [12, 18], these findings provide a structured framework for multi-stakeholder action.

Barriers to Implementation

Four interconnected barriers emerge from the panel's assessment that help explain both the persistence of the antibody validation problem and the challenges of implementing solutions.

First, diffuse ownership enables collective inaction. Antibody validation failures impose costs across the research system — wasted funding, unreliable literature, consumed biological materials — but no single stakeholder bears the full cost or has authority to mandate change unilaterally. Researchers lack incentives to validate when publication and funding systems do not reward the practice; publishers hesitate to impose requirements that could divert submissions to less demanding competitors; funders may view validation as outside their mandate; and manufacturers competing on price and catalogue breadth face limited incentives to invest in validation when researchers continue to purchase on the basis of previous use and supplier reputation [14]. Panel members described a pattern of mutual deflection, with responsibility for validation perceived as belonging to other stakeholder groups rather than one's own (S7 Text, R22). Several characterised the broader landscape as too fragmented for

508 meaningful alignment to feel achievable. However, the panel's endorsement of a shared roadmap (R22)
509 and the interdependencies across recommendations point toward a countervailing dynamic: participants
510 noted that journal requirements would create *de facto* mandates for manufacturers, that researcher
511 demand would shift manufacturer behaviour, and that funder investment in infrastructure would enable
512 practices that other stakeholders could then require.

513 Second, market dynamics create structural tensions. The research antibody market operates
514 predominantly under a Research Use Only model that prioritises catalogue breadth and low unit cost
515 over rigorous validation. Manufacturer representatives acknowledged significant economic barriers to
516 comprehensive validation, describing the costs as prohibitive and warning that extensive validation
517 programmes would reduce revenue without a corresponding market incentive (S7 Text, A8). At the
518 same time, one manufacturer described their company's ongoing commitment to validation, illustrating
519 that the barrier is structural rather than universal. Yet the apparent low cost of inadequately validated
520 antibodies is illusory when downstream costs are considered: failed experiments, repeated purchasing,
521 wasted samples, and unreliable findings impose far greater costs on the research system than better
522 validation would. Creating market conditions in which quality is rewarded — through purchasing
523 decisions informed by independent characterisation data, journal requirements that make validation
524 data visible, and funder signals that prioritise quality — is necessary to shift the equilibrium.

525 Third, resource justification challenges persist despite clear return on investment. Participants noted
526 competing demands on limited resources, with some questioning whether funders would prioritise
527 antibody validation given the breadth of competing demands on their budgets, even while
528 acknowledging the value of the proposed actions (S8 Text, A10). The economic case is compelling at a
529 system level — the estimated $1 billion annually in direct waste in the US alone [12, 13], plus far
530 greater opportunity costs — but the return is diffuse and difficult for individual stakeholders to capture.
531 A funder investing in validation infrastructure benefits the entire community, not just its own grantees;

532 an institution investing in training produces graduates who carry improved practices elsewhere. The
533 benefits are real but distributed across time and across the ecosystem, and compounded by the
534 difficulty of demonstrating negative outcomes that were prevented.

535 Fourth, coordination challenges reflect the scale of the problem. With more than 22,000 human protein
536 targets, millions of antibody products, and a global research community, the coordination challenge is
537 immense. No single authority can mandate standards, and voluntary adoption requires alignment across
538 actors with different incentives, timescales, and resources. The panel's findings suggest, however, that
539 complete alignment is not a prerequisite for progress. The 15 consensus recommendations represent
540 actions individual stakeholders can implement without waiting for others, and participants emphasised
541 sequencing over simultaneity: several argued that funders must first act as enablers — establishing
542 resources, infrastructure, and training — before mandates can be effective (S8 Text, A5), while others
543 suggested that even imperfect initial standards would allow journals to demonstrate a credible
544 commitment to improving antibody reporting practices (S8 Text, A1).

545 These barriers are consistent with recent multi-stakeholder commentaries. Kahn et al. [12] noted that
546 the origins of the antibody crisis are 'many and varied' and that 'it is unrealistic to expect a complete
547 solution in the near future', while emphasising that significant progress is achievable through concerted
548 action. In earlier work by members of this study team [18], we argued that behavioural and cultural
549 change could be supported by engaging stakeholders at every level using established frameworks for
550 research culture change. The Delphi findings complement these analyses by providing quantitative
551 evidence of where expert agreement is strongest and where feasibility barriers remain.

552 **Next Steps and Implementation**

553 The findings lend themselves to a programme of targeted stakeholder consultation. To support this, we
554 have prepared separate documents for each stakeholder group — publishers, funders, institutions, and

manufacturers — presenting consensus recommendations alongside implementation options derived from the panel's qualitative feedback (S2–5 Texts). These present options rather than prescriptions, recognising that the optimal approach will vary across organisations, countries, and contexts. Items rated as effective with uncertain feasibility are not dismissed but treated as implementation challenges to be addressed through consultation. Interdependencies across stakeholder groups are made explicit throughout, supporting coordinated rather than siloed implementation.

Several elements of the recommended infrastructure already exist. The NC3Rs Antibody Champions programme provides a model for the local champions recommendation (R21) and delivers masterclasses for doctoral training aligned with R19. The OGA Academy offers structured online training [18], the OGA Antibody Database provides searchable characterisation data, and YCharOS continues to expand its open characterisation pipeline [1]. The eLife stakeholder roadmap [12] proposed actions that align closely with many consensus items, and the RRID initiative [17] provides identification infrastructure on which several publisher-focused recommendations depend. These resources demonstrate that the recommendations can be implemented by building on proven approaches. Notably, several recommendations are interdependent: shared infrastructure for aggregating validation data (R23) would support automated manuscript screening (R7), informed grant review (R10), and evidence-based purchasing decisions, suggesting that investment in infrastructure could unlock a cascade of downstream improvements across stakeholder groups.

Limitations

Several limitations should be considered. Participants were identified through existing professional networks, and the panel may therefore share perspectives that do not fully represent the diversity of views across the global research community. The panel was weighted toward the United Kingdom and United States, and the biomedical research ecosystem in other countries may face different challenges. Some sectors (particularly research funders, n=4) had few representatives, meaning feasibility

assessments for funder-directed recommendations may not capture the full diversity of perspectives. The high retention rate (93.8%) and low disagreement suggest a relatively cohesive panel, which may underestimate the range of views from a broader consultation.

The Delphi method captures expert opinion at a specific point in time and does not constitute empirical evidence of effectiveness. The consensus recommendations represent the panel's assessment of what is likely to be effective and feasible, but actual effectiveness will depend on implementation context. The panel reached consensus after two rounds, which limited iterative refinement where uncertainty persisted. However, rating stability between rounds suggests that additional rounds would have been unlikely to shift results substantially. The qualitative data were synthesised narratively rather than through formal thematic analysis, consistent with RAND/UCLA practice where free-text comments inform item interpretation rather than serving as independent qualitative data. Full qualitative commentary is provided in S7 and S8 Texts.

Conclusions

The rating of 'effective but uncertain feasibility' that characterises many of the proposed actions should not be interpreted as reason for inaction. It reflects an honest assessment that the pace and sequencing of change matter as much as the direction. The 15 consensus recommendations provide an evidence-based starting point for immediate action; the remaining items rated as effective represent a second wave whose feasibility is likely to increase as early implementation builds infrastructure, shifts incentives, and establishes new norms. This staged approach — enablement to expectation to mandate — was consistently endorsed by the panel and is reflected in the consultation documents (S2–5 Texts). Together with existing technical and community initiatives, these findings provide a structured basis for coordinated multi-stakeholder action to address a persistent and costly source of unreliability in biomedical research.

Supporting Information

S1 Table. Detailed participant characteristics by employment sector.

S2 Table. Full quantitative results for Round 1 (n=32 participants, 23 items), including median effectiveness and feasibility ratings, inter-percentile range (IPR), IPR adjusted for symmetry (IPRAS), consensus classification, and disagreement assessment.

S3 Table. Full quantitative results for Round 2 (n=30 participants, 22 items: 12 re-rated from Round 1, 10 new), including median effectiveness and feasibility ratings, IPR, IPRAS, consensus classification, and disagreement assessment.

S1 Text. Full item-by-item qualitative analysis with detailed recommendations and implementation considerations for consensus items.

S2 Text. Publisher and journal consultation draft.

S3 Text. Research funder consultation draft.

S4 Text. Institutional and educational body consultation draft.

S5 Text. Antibody manufacturer consultation draft.

S6 Text. Full item sets for Round 1 and Round 2.

S7 Text. Round 1 qualitative feedback (participant comments).

S8 Text. Round 2 qualitative feedback (participant comments).

Data Availability

All data underlying the findings reported in this study are available within the article and its Supporting Information files. Full quantitative results including median ratings, inter-percentile ranges, and consensus classifications for all items across both Delphi rounds are provided in S2 and S3 Tables. Complete qualitative feedback from participants is provided in S7 and S8 Texts.

624 Individual-level raw ratings are not provided to protect participant anonymity, consistent with
625 the ethical approval for this study.

626 Competing Interests

627 HV and MB have received funding for a research studentship from Abcam Ltd, and contributions in
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664

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