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Contamination control in micro- and nanoplastics research: a diagnostic framework for reproducible analysis

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Micro- and nanoplastics (MNPs) not only contaminate natural environments but also the analytical workflows used to study them. At nanoplastic-relevant size scales, background contamination from airborne particles, consumables, reagents, and laboratory infrastructure increasingly compromises data interpretation, reproducibility, and cross-study comparability. Although contamination-aware practices are widely acknowledged, they remain inconsistently implemented and variably reported across the literature. Here, we introduce the Contamination Control Scorecard (CCS), a structured, risk-weighted diagnostic (non-prescriptive) framework that organises major contamination pathways alongside reporting transparency in MNP research workflows. By systematically mapping laboratory practices across key procedural domains and separating process control from disclosure practices, the CCS supports contamination-aware interpretation of analytical results and highlights recurring sources of uncertainty. This perspective positions the CCS as an evolving tool to promote transparent reporting, methodological reflection, and reproducible micro- and nanoscale environmental analysis, with broader relevance to trace-level measurements.

Environmental significance

At very small particle sizes, procedural contamination can equal or obscure true environmental signals, posing a fundamental challenge for micro- and nanoplastics analysis. Because reliable detection underpins assessments of environmental exposure, ecological risk, and potential human health impacts, contamination-driven uncertainty undermines data interpretation and comparability across studies. This perspective introduces a diagnostic framework that systematically identifies contamination pathways and reporting gaps across micro- and nanoplastics research workflows. By explicitly separating procedural contamination control from reporting transparency, the framework supports contamination-aware interpretation of analytical results and advances more reproducible, comparable, and policy-relevant environmental analysis.

Contamination as a limiting factor in micro- and nanoplastics analysis

In recent years, micro- and nanoplastic (MNP) pollution has become a global environmental concern, with studies reporting their presence in oceans, soils, the atmosphere, food, drinking water, and even human blood, brain, and placental tissue.[1–11] As public awareness grows and more concrete data is needed for policymaking on exposure and risks, researchers are developing increasingly sensitive analytical methods to detect and characterize MNPs across various matrices.[12]

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Alongside these analytical advances, there is a critical challenge, which is the widespread contamination risk of analytical workflows themselves.[13–16] At the micro- and especially nanoplastic scale, laboratory-derived particles can equal or exceed true sample signals. Major contamination pathways in MNP research workflows include (see Fig. 1): (1) airborne particles and fibers released from polyester lab coats, fleece clothing, or ventilation systems settling into open samples.[17–23] (2) Consumables and labware, *i.e.*, uncalcined glassware, plastic tubes, gloves, pipette tips, and petri dishes, can contain particles released through abrasion, heat, or from air deposition.[16,24–28] (3) Reagents and solvents can contain particles on the order of 10^4 to 10^5 per liter due to processing steps and packaging.[15,16,29–31] (4) Equipment such as microscopes with plastic instrument components, coatings, and filtration membranes may leach contaminants, producing false positives.[32,33]

Taken together, these contamination risks contribute cumulatively across multiple stages of the analytical

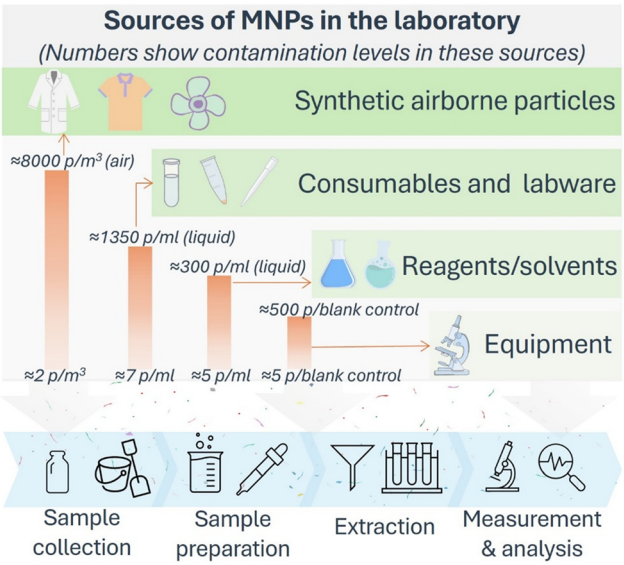

Fig. 1 Major sources of MNPs contamination in laboratory environments. Numbers represent reported concentrations of MNPs measured in air, reagents, plastic consumables, and blank controls (ref. 15, 16, 22, 23, 31 and 33). No quantitative data were found in the literature isolating the contribution of individual equipment (*e.g.*, microscope, oven); therefore, values from the literature are aggregated in blank controls. Bottom: minimum, top: maximum. Workflow steps where contamination can be introduced are shown at the bottom. Illustration created by the authors.

workflow, such that even when individual risks appear minor, their combined effect can dominate final MNP analysis. Beyond increasing background noise, contamination can alter apparent particle size distributions, morphologies, and polymer types, biasing source attribution and exposure assessments. Ultimately, inflated exposure estimates or misidentified particles can distort risk assessments, regulatory thresholds, and mitigation strategies.[34–36] At the nanoscale, where particle signals approach analytical detection limits, even low-level contamination may be indistinguishable from true particles, thereby amplifying these effects.

Gaps in existing QA/QC frameworks for operational contamination control

Analytical fields facing trace-level contamination, such as forensic science, trace metal analysis, and PFAS monitoring, have developed validated quality assurance/quality control (QA/QC) protocols, contamination-controlled infrastructure, and certified materials.[37–40] In contrast, contamination control in MNP research remains inconsistently implemented and unevenly reported. Recent studies indicate that approximately 20% of MNP studies do not report blank controls at all, and among those that do, only a small fraction provide particle-size-resolved blank data.[14] Moreover, certified contamination-free consumables, reagents, and solvents are largely unavailable for MNP analysis, leaving laboratories to rely on *ad hoc* mitigation strategies.

Existing QA/QC guidelines and quality assessment frameworks, such as those proposed by Koelmans *et al.*, have substantially improved transparency and evaluation of overall study reliability in microplastics research.[13,33,41,42] However, these frameworks do not operationalize or diagnose contamination control across the analytical workflow. Contamination pathways are not treated as diagnostic components, and procedural rigor is not separated from reporting transparency in a way that enables systematic comparison or identification of contamination risk sources. As a result, studies employing fundamentally different contamination-control strategies may receive similar overall quality scores, while laboratories lack practical tools to diagnose where contamination is most likely to arise within their workflows.

To ensure analytical credibility and policy relevance, contamination control must be treated as a central methodological dimension of MNP analysis. Although practices such as ensuring clean working environments,[17,43,44] monitoring these working environments,[45,46] reducing plastic use and exposure throughout the complete workflow,[17,47] including plastic contamination-screened reagents,[33] and comprehensive blank reporting[42] are widely recommended, but their implementation remains fragmented without a coherent framework to structure and interpret them.

To address this fragmentation in how contamination control is implemented and reported across MNP analytical workflows, we introduce the Contamination Control Scorecard (CCS) as a semi-quantitative diagnostic framework that organizes contamination pathways alongside reporting transparency in MNP research. Unlike existing QA/QC scoring approaches that primarily assess overall study reliability, the CCS explicitly maps plastic contamination pathways across analytical workflows and separates procedural control from reporting transparency. Drawing on contamination-aware QA/QC approaches established in analytical fields facing trace-level contamination, the CCS provides a practical basis for harmonizing workflows, improving interlaboratory comparability, and strengthening the interpretability and policy relevance of MNP data.[37–40]

The MNP-contamination control scorecard (MNP-CCS): concept, structure, and illustrative application

The first version of the MNP-CCS (MNP-CCS1.0) includes five process categories: laboratory environment, consumables and equipment, reagents and solvents, blank controls, and personnel and practices, and a transparency and reporting category (Table S1). Each indicator within these categories is scored on a 0–2 scale (0 = absent or not reported, 1 = partial implementation, and 2 = complete implementation). Indicators are weighted by risk level (high = 3, medium = 2, low = 1). These risk weights were assigned to reflect the relative likelihood that different contamination pathways would dominate background signals. Weighting decisions

were informed by reported orders of magnitude of contamination from major sources (*e.g.*, laboratory air, reagents, and consumables) and practical experience from trace-level analytical workflows, as well as the extent to which a pathway can systematically affect multiple stages of the analytical process.[13,14,16,31,33] These weights are intended as transparent, literature-informed starting assumptions and are designed to remain adaptable as the framework evolves. Fig. 2 provides a conceptual overview of the CCS structure and major contamination pathways, while Table S1 details the full set of contamination indicators and scoring criteria.

The framework distinguishes between two complementary components: the Process Control Score (PCS), which reflects the rigor of contamination management across analytical workflows, and the Transparency Score (TS), which captures the completeness of reporting of contamination-control practices and results. PCS is calculated as the mean weighted score across the five process categories, while TS is derived from the normalized weighted score of the transparency and reporting indicators, ensuring that incomplete disclosure proportionally limits the final CCS value. The CCS integrates PCS and TS into a single index scaled from 1 to 100, providing a balanced and interpretable measure of internal rigor and external visibility relevant to analytical credibility, reproducibility, and policy interpretation; details of the full scoring scheme, normalization approach, and calculation formula (Eqn S1) are provided in the SI.

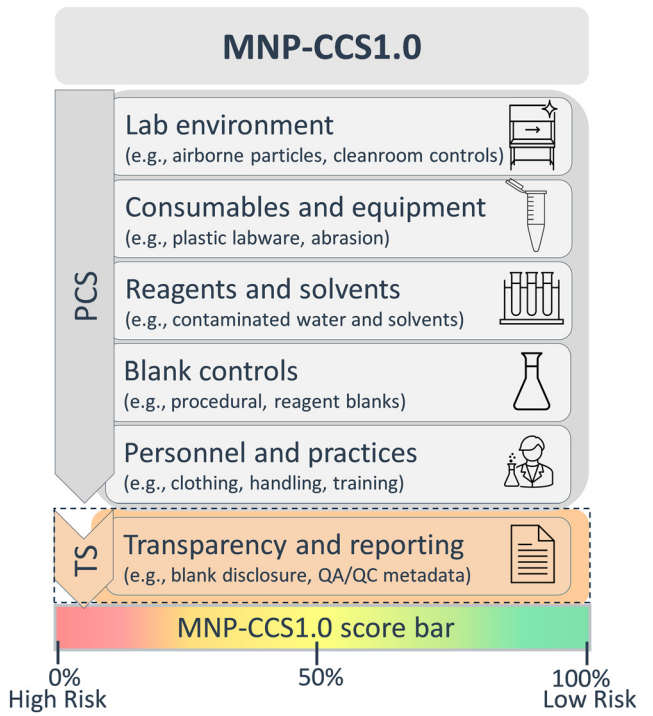

Fig. 2 Conceptual structure of the CCS. The CCS comprises five PCS categories representing dominant contamination pathways across analytical workflows and a TS reflecting reporting completeness. Example high-risk pathways are shown for illustration. Detailed indicators, weights, and scoring criteria are provided in Table S1.

To illustrate the practical application of the CCS, we apply the framework to a small set of published MNP studies on water samples (Tables S2–S7). These examples are intentionally limited in scope and are used solely to demonstrate how contamination-control measures and reporting practices are captured within the CCS framework; this exercise is not intended as a meta-analysis, nor to evaluate, rank, or synthesize findings across studies. The illustrative application demonstrates that similar overall CCS values can arise from different combinations of laboratory practices, including consumable selection, procedural blanks, environmental controls, and reporting transparency, and that strengths in one component of the analytical workflow do not necessarily compensate for weaknesses elsewhere. By resolving category-level profiles, the CCS enables diagnostic identification of recurring vulnerability points, such as environmental monitoring, reagent screening, and consistency in blank handling, and supports structured reflection on contamination risks and opportunities for incremental improvement. In this context, higher CCS values reflect greater procedural rigor and reporting completeness, whereas lower values indicate increased interpretive uncertainty and the need for greater caution, rather than serving as indicators of contamination-free analysis or data invalidity. Although background contamination can influence microplastic measurements across all size ranges, the CCS is broadly applicable and becomes particularly valuable for very small MNPs, where particle sizes approach analytical detection limits and contaminant-derived signals may be difficult to distinguish from true particle signals; rather than resolving this ambiguity, the CCS structures where it is most likely to affect interpretation and makes the associated uncertainty explicit.

While the illustrative case studies presented here focus on water samples, the CCS framework is designed to apply to more complex sample matrices. Core contamination pathways, such as laboratory air, consumables, reagents, blanks, and personnel practices, remain relevant, but their relative importance may shift with the matrix and analytical workflow. For example, in sediment or biological tissue analyses, contamination risks associated with digestion reagents, filtration steps, and prolonged sample handling may dominate over airborne contributions, warranting increased weighting of these indicators. Accordingly, the CCS accommodates matrix- and technique-specific adjustment of indicator emphasis within a consistent diagnostic structure that assesses contamination pathways and workflow controls rather than technique-specific signal generation, while avoiding a uniform weighting scheme across all applications.

Limitations, evolution, and opportunities for adoption

The CCS is not intended to suggest that contamination-free MNP analysis is achievable; background particles are ubiquitous, even in highly controlled laboratories.

Accordingly, the CCS does not aim to eliminate contamination, but to make contamination risks visible and interpretable across analytical workflows. One limitation concerns the weighting of individual indicators. Although weights are informed by reported contamination levels and established analytical practice, some subjectivity is unavoidable, and priorities may reasonably vary with sample matrix, particle size range, or analytical technique. The CCS weights should therefore be viewed as transparent and adaptable starting points rather than fixed values. Additional constraints arise from current methodological limits, particularly for nanoplastics, where contamination from reagents, filters, and instrument components becomes increasingly difficult to distinguish from true signals. While the CCS can indicate where such risks are likely to dominate analytical outcomes, it cannot overcome fundamental detection limits or substitute for method validation.

More broadly, the CCS is diagnostic rather than prescriptive, separating procedural rigor from reporting transparency to identify where contamination control is strong, incomplete, or poorly documented, and not to define minimum standards, accreditation criteria, or publication thresholds. The CCS values instead provide contextual information to support contamination-aware interpretation and comparison across studies. Consistent with diagnostic approaches commonly adopted in trace-level analytical fields, the CCS is intended to evolve through community use rather than to function as a fixed standard. Concrete mechanisms for this evolution include open access to the CCS template, versioned public releases hosted on Zenodo, and application in interlaboratory and comparative studies. Community feedback and suggestions are supported *via* a linked public GitHub repository, while feedback arising from reuse, adaptation, and citation across published work can inform iterative refinement of indicators, weights, and scoring logic.

From a practical perspective, the CCS can be readily adopted within existing analytical workflows, for example, as a structured supplementary reporting element that enables transparent documentation of contamination-control measures alongside analytical results. At the laboratory and interlaboratory levels, the CCS can support method development, training, self-auditing, and the interpretation of variability across datasets, particularly when discrepancies arise despite nominally similar analytical methods. Looking forward, broader application of the CCS across published studies could enable synthesis efforts that identify recurring bottlenecks, inform evidence-based refinements of QA/QC guidance, and support integration into digital submission tools or standardized reporting templates. Ultimately, embedding contamination-aware diagnostics into routine reporting represents a realistic step toward more robust, comparable, and policy-relevant data in MNP and across environmental research more broadly.

Author contributions

I. A. conceived and developed the study, designed the methodology, and wrote the original draft of the manuscript. M. B. J. R. provided critical feedback and contributed to manuscript review and editing. All authors approved the final version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The CCS scoring template, including an implementation with automated calculations, is openly available *via* Zenodo (https://doi.org/10.5281/zenodo.18032993), which also includes README documentation. A public GitHub repository (https://github.com/aslamimran/Contamination-Control-Scorecard) is linked for optional community feedback and suggestions.

Supplementary information (SI): includes the full CCS scoring framework (Table S1), detailed scoring criteria and weighting scheme, normalization formula (eqn S1), and illustrative case study applications (Tables S2–S7). See DOI: https://doi.org/10.1039/d5en01205h.

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