

# Critical Provenance Deficits in Pvc Nanoplastics Research: Implications for Environmental Fate and Plant Uptake Studies

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**Abstract** Poly(vinyl chloride) (PVC) nanoplastics (< 1,000 nm) are widely used in exposure and fate studies, yet the original sourcing and pre-treatment of starting materials, which govern additive profiles, particle properties, and leachates are inconsistently reported. Our primary objective was to evaluate how PVC-nanoplastics studies report feed-stock provenance and the implications for reproducibility and environmental relevance. We conducted a systematized narrative review (PubMed, database inception to 20 July 2025) of primary studies that purchased or produced PVC particles with at least one dimension < 1000 nm and used them in exposure, characterization, fate, or calibration experiments. Data extraction captured six provenance descriptors (supplier, catalogue/lot, molecular-weight/inherent-viscosity, additive profile, cleaning/aging, pre-processing), synthesis routes, morphology, and a six-item characterization completeness score. Thirty-four studies met the inclusion criteria. Across these studies, starting materials comprised virgin scientific-grade resin (41.2%), commercially purchased PVC nanoparticles (20.6%), post-consumer waste (14.7%), virgin commercial powder (11.8%), and external reference materials (11.8%). Only 1 of 34 studies (2.9%) reported a catalogue number, while 13 of 34 (38.2%) described any additive information. The median characterization score was 2 of 6 (range 0–5). Nanoprecipitation and top-down milling were the most common synthesis methods, but reporting of yields and leachate controls was inconsistent. Provenance reporting for PVC nanoplastics is frequently incomplete, particularly for catalogue/lot numbers and additive profiles that critically influence solubility, morphology, surface chemistry, and leachate composition. We propose a PVC-specific reporting extension emphasizing supplier/batch identifiers, additive quantification, weathering/cleaning verification, and leachate controls to enable reproducible, decision-useful research.

**Keywords:** Polyvinyl Chloride, Nanoplastics, Provenance Reporting, Additive Profiles, Particle Characterization, Environmental Fate, Reproducibility, Reporting Standards, Methodology

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## 1. Introduction

Global polymer production surpassed 400 million metric tons in 2022 and continues to rise at a pace that outstrips growth in formal recycling and recovery [1]. The mismatch between production and end-of-life management ensures a sustained and expanding flux of secondary micro-and nanoplastics generated through mechanical abrasion, thermal cycling, and photochemical weathering of larger items. Nanoplastics (<1000 nm) occupy a critical but under-resolved portion of this spectrum: their high surface-area-to-volume ratios and colloidal stability increase environmental residence times and mobility across compartments, while their small size allows interactions with biological barriers that are not accessible to larger particles [2]. Taken together, these

features justify treating the nano-fraction as a distinct exposure class whose occurrence, behavior, and consequences remain insufficiently captured by current monitoring programs and policy instruments [3].

### 1.1. Why the Nano-fraction Matters

At the nanoscale, particle properties change in ways that cannot be predicted simply by scaling down from microplastic studies. Features such as particle curvature, structural defects, and altered surface chemistry make nanoplastics more reactive at interfaces [4]. As a result, their sorption and desorption of chemicals can differ, and biomolecules readily form a corona around particle surfaces, which influences how they behave in complex environments. Inside organisms, nanoplastics are small enough to enter cells through processes like endocytosis and may move across tissues, rather than being limited to

bulk ingestion. These differences affect where nanoplastics distribute in the body, which tissues they reach, and the types of cellular responses they trigger. For these reasons, risk frameworks should treat nanoplastics as a distinct class of particles rather than assuming they behave the same as larger microplastics [3].

## 1.2. Detection and Monitoring Limits

Despite growing interest, environmental surveillance of plastics rarely involves particles under 100 nm<sup>3</sup>. Practical limitations arise from low refractive-index contrast for common polymers, limited mass sensitivity at small particle sizes, and matrix interference in natural waters, soils, and biological extracts. Research-grade approaches, such as asymmetric-flow field-flow fractionation (AF4) with multi-detector setups, transmission electron microscopy, and single-particle ICP-MS/tracer-friendly mass spectrometry, have advanced characterization of the nano-fraction but remain technically demanding, comparatively expensive, and only partially standardized for environmental applications [4,5,6]. Direct field evidence of nanoplastics is beginning to emerge using novel sample preparation and imaging strategies, yet occurrence datasets remain sparse relative to microplastics [7]. As a result, size distributions and chemical states for nanoplastics are still under-documented at regulatory monitoring scales [3].

## 1.3. Why Focus on PVC?

Within the broad family of commercial polymers, poly (vinyl chloride) (PVC) warrants specific attention on three fronts. First, PVC constitutes a major share of installed polymer stock across infrastructure and consumer products, piping, profiles, flooring, wire and cable insulation, packaging, and selected medical devices, such that even low per-item fragmentation rates translate into substantial environmental inputs over time [8,9]. Second, the chlorine-rich PVC backbone undergoes dehydrochlorination when subjected to heat, UV radiation, or catalytic impurities, generating HCl and conjugated polyenes that accelerate photo-oxidation, increase surface polarity, and alter interactions with co-contaminants and biota [10]. Third, PVC formulations, especially flexible grades used in flooring and cables, are additive-rich: plasticizers and stabilizers are physically blended rather than covalently bound and can migrate under ordinary use, with aging further enhancing release [11]. Recent experimental work shows long-term phthalate release from PVC microplastics and photoaging-enhanced leaching and transformation products, linking aging chemistry directly to leachate profiles [12]. The conjunction of high production volume, chlorine-driven degradation chemistry, and substantial additive loads elevates the plausibility of both particle-mediated and leachate-mediated hazards and motivates a dedicated assessment of how PVC nanoplastic test materials are generated and reported.

Several studies have demonstrated measurable plasticizer release from PVC micro- and nanoplastics into seawater and freshwater matrices over experimental timescales [12,13,14]. The magnitude of release is

influenced by additive molecular weight, polymer morphology, surface area, and environmental conditions such as temperature and salinity [13]. Importantly, laboratory synthesis choices directly influence plasticizer retention. Pre-extraction by Soxhlet or pressurized-liquid extraction, antisolvent precipitation with dialysis, or prolonged washing steps are likely to produce particles with reduced plasticizer burdens relative to the source material [15,16,17]. In the absence of quantitative additive analysis, these differences remain unreported yet have substantial implications for hazard interpretation.

## 1.4. Environmental and Biological Fate of PVC Nanoplastics

Secondary generation of PVC nanoplastics is driven by progressive embrittlement and surface cracking of larger objects under realistic use and weathering conditions [10,11,15]. Aging water and wastewater pipes provide a persistent source where hydraulic pressure, temperature fluctuations, and disinfectants contribute to mechanical fatigue and chemical alteration. Indoors, vinyl flooring and related materials shed wear particles and additive-rich dust, contributing to settled particulate loads [11]. In the e-waste stream, polymeric cable insulation is subjected to dismantling, shredding, and, where controls are lacking, open burning, all of which promote particle generation and additive volatilization [8]. Laboratory weathering protocols often isolate UV, thermal, or mechanical stressors for experimental tractability; field contexts typically combine these drivers, accelerating dehydrochlorination, oxidation, and size reduction in ways that are challenging to replicate in simplified test systems [15].

## 1.5. Biological effects: Oxidative Stress, Inflammation, and Endocrine-related Endpoints

Exposure to nano- and small microplastics is associated with oxidative stress (ROS formation, lipid peroxidation), inflammatory signaling (cytokine induction, immune modulation, tissue-level histopathology), and endocrine-related outcomes (hormone perturbation, reproductive effects, developmental alterations) [18,19,20]. Much of the mechanistic evidence derives from polystyrene and PVC nanoplastics models: experimental studies demonstrate genotoxicity and cytotoxicity in human lung cells, [21] disruption of intestinal epithelial integrity in advanced in vitro triple culture systems [20], and cytokine release by human monocytes and dendritic cells [22]. Additional evidence from aquatic and invertebrate models shows size-dependent toxicity and altered cellular function [23,24]. Multiple syntheses report endocrine-disrupting outcomes across vertebrate models at experimental concentrations, while invertebrate studies document immune shifts after repeated nanoplastic exposure. Where PVC-specific studies exist, they converge on similar endpoints and highlight the potential contribution of additive leachates unique to PVC formulations [11,12]. The relative scarcity of PVC-focused datasets underscores the need for test materials that more faithfully represent environmentally aged PVC and for systematic reporting

that allows results to be compared across laboratories and model systems.

### 1.6. Laboratory Synthesis and the Provenance Problem

Experimental studies commonly prepare PVC nanoplastic test particles by solvent displacement (nanoprecipitation), cryomilling of bulk material, or laser-based fragmentation [25,26,27,28,29]. While these routes offer practical control over nominal size ranges and experimental throughput, they seldom reproduce key attributes of field-aged particles, including oxidation state, additive depletion or redistribution, and irregular, fracture-dominated morphology [15]. Reproducibility and interpretability are further constrained by incomplete reporting of feed-stock provenance. Essential descriptors, supplier and catalogue/lot number, molecular weight or inherent viscosity, additive profile, any pre-cleaning or selective extraction steps, and details of artificial aging, are frequently absent or only partially described. A structured quality appraisal of microplastic effect studies highlighted pervasive reporting shortfalls that hinder reproducibility and meta-analysis [30]. Because these attributes govern polymer solubility, nanoprecipitation behavior, milling brittleness, yield, surface chemistry, colloidal stability, and the composition of leachates, under-reporting obscures mechanistic links between starting materials, particle properties, and biological outcomes. Transparent provenance and thorough characterization are therefore prerequisites for credible hazard assessment and for data synthesis across studies [15,30].

## 2. Aim and Scope of This Review

This review systematically evaluates how PVC-nanoplastics studies document feed-stock provenance and pre-treatment and examines the consequences of those practices for experimental comparability. Specifically, (i) we quantify reporting across six core descriptors: Plastic typing, supplier, catalogue/lot, additive profile, cleaning/aging procedure, and any pre-processing; (ii) map trends in synthesis routes, model systems, and characterization techniques; and (iii) assess whether authors explicitly link feed-stock choice to particle properties and experimental outcomes. By including exposure, calibration, and characterization studies, we aim to capture the full methodological landscape and to identify practical pathways toward more reproducible, environmentally relevant, and decision-useful PVC nanoplastics research.

## 3. Materials and Methods

### 3.1. Protocol Registration and Reporting Framework

The review protocol was developed a priori and prospectively registered on the Open Science Framework (<https://doi.org/10.17605/OSF.IO/CQYXT>.) We followed the PRISMA 2020 statement for systematic reviews and meta-analyses and mapped all items to the PRISMA

checklist during drafting of the manuscript.

### 3.2. Review Design and Objective

This study is a systematized narrative review that catalogues and critically appraises how primary research articles describe the provenance and pre-treatment of starting poly(vinyl chloride) (PVC) used to generate nanoplastics (<1  $\mu\text{m}$ ), regardless of the downstream synthesis route or experimental purpose. Articles were considered a “PVC-nanoplastics study” if they (i) purchased or produced PVC particles with at least one dimension < 1  $\mu\text{m}$  and (ii) reported any experimental exposure, characterization, fate, or calibration work involving those particles.

A single-database strategy was used because PubMed/MEDLINE provides the most comprehensive indexing of nanoplastics studies in life-science, toxicology, and environmental health disciplines, ensuring consistency in study design and terminology. PubMed’s controlled vocabulary (MeSH) for polymers and nanoparticle exposure also enables reproducible search retrieval and minimizes redundancy relative to multidisciplinary databases, making it particularly suitable for assessing reporting practices rather than broad bibliometric trends.

**Table 1. Eligibility**

Domain	Inclusion criteria	Exclusion criteria
Publication type	Peer-reviewed primary research (in vitro, in vivo, mesocosm, field or modelling studies with empirical nanoplastics generation)	Reviews, commentaries, conference abstracts, duplicated datasets
Polymer focus	Studies using or reporting PVC nanoplastics, or mixed-polymer studies that present PVC-specific results	Microplastics > 1 $\mu\text{m}$ without a nanoplastics fraction; non-PVC polymers
Language & date	Full-text English articles, database inception - 20 July 2025	Articles lacking an English full text or reliable translation
Reporting detail	Methods section or supplementary files report $\geq 2$ of 6 feed-stock descriptors (supplier, catalogue/lot, molecular-weight data, additive profile, ageing/cleaning procedure, pre-processing)	Unobtainable full text or supplementary material
Scale and Focus	Investigations in which particle dimension < 1 $\mu\text{m}$ and the research objective centers on exposure, characterization, fate, or calibration of PVC-NPs in biological, environmental, or technological contexts	Theoretical modelling with no empirical PVC-NPs; studies where PVC-NPs are not linked to experimental outcomes or used to create membranes/ other polymers

### 3.3. Information Sources

A single-database search in PubMed/MEDLINE from 1 Jan 2015 to 20 July 2025 was conducted. No other databases, registries, or grey literature sources were searched. The final PubMed search was completed on 20 July 2025. Complete search results are available in Table S3.

### 3.4. Search Strategy

Databases: PubMed Complete search results (coverage

= 1 Jan 2015 to search date). Final search date- July 20<sup>th</sup>, 2025.

Core search string (PubMed, Title/Abstract unless MeSH-tagged):

("Polyvinyl Chloride"[MeSH] OR PVC [tiab] OR "poly(vinyl chloride)" [tiab]) AND (nanoplastics\* [tiab] OR nanoparticle\* [tiab])

No synthesis keywords are included so we capture every route (nanoprecipitation, mechanical fragmentation, laser ablation, etc.). Complete search results can be found in Supplementary Table S2

### 3.5. Selection Process and Synthesis

Two stages were applied: (1) title/abstract screening; (2) full-text review against pre-specified eligibility criteria. Because only PubMed was searched, no de-duplication across databases was required. Selection decisions were mapped based on exclusion criteria which are available in Supplementary Table S1, and exclusion process is shown in Figure 1 PRISMA diagram. [31]

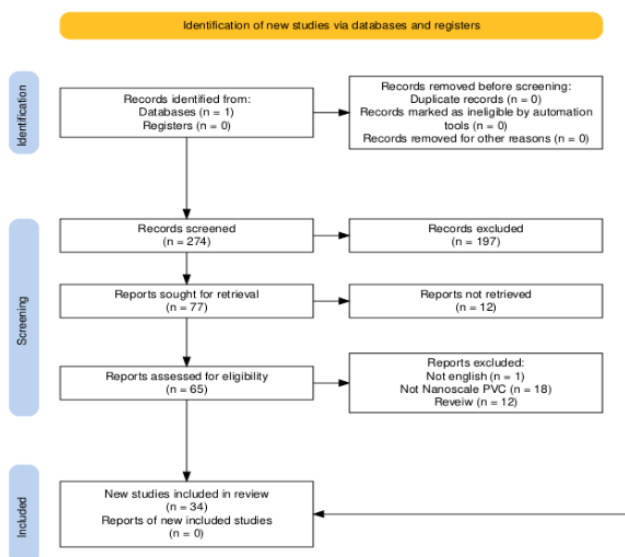


Figure 1. Prisma Diagram

A systematized narrative review focused on materials provenance and reporting practices was performed. We did not conduct quantitative meta-analysis. Data were charted into predefined fields, and synthesized results narratively with structured tables and simple frequency plots. A fit-for-purpose reporting checklist was created to summarize coverage of key descriptors; no aggregate risk-of-bias grading or certainty (GRADE) assessment was performed

Data was extracted using a piloted form capturing feedstock provenance descriptors, synthesis routes, and characterization.

## 4. Results

### 4.1. Study Selection

Thirty-four primary studies met the inclusion criteria for PVC nanoplastics and were charted for provenance

and reporting practices (full eligibility framework and information sources are detailed in Methods).

### 4.2. Study Characteristics

Across the 34 studies, the most common feedstock was virgin, scientific-grade PVC resin (14/34; 41.2%), followed by commercially purchased “PVC nanoparticles” (7/34; 20.6%), post-consumer waste (5/34; 14.7%), virgin commercial PVC powder (4/34; 11.8%), and external lab-produced reference materials (4/34; 11.8%). Representative rows are shown in Table 2 (e.g., virgin scientific-grade resin; commercial NPs; post-consumer waste; external reference materials).

Supplier types clustered into analytical reagent vendors (12/34; 35.3%) and industrial/bulk polymer suppliers (11/34; 32.4%), with smaller contributions from consortium/reference providers (4/34; 11.8%) and specialty nanoparticle vendors (2/34; 5.9%). The rest of the papers leave this unreported. Selected examples are highlighted in Table 2.

### 4.3. Provenance and Materials Reporting

Exact catalogue/lot numbers were almost nonexistent: 1/34 studies (2.9%) reported a catalogue number (Merdy et al., “Nanoplastic Production Procedure”), while 33/34 did not.

Reporting of pre-treatment/weathering steps was rare (3/34; 8.8%), appearing in studies using either virgin resin or post-consumer sources. Additive/plasticizer/filler information was reported in 13/34 studies and absent in the remainder. Yield reporting (mass recovery or particle yield) applied to 30 studies (N/A in 4 where “commercial NPs” were used solely as received); among applicable studies, 3/30 (10.0%) reported yield.

### 4.4. Particle Morphology and Characterization

Particles were described as spherical in 20/34 studies (58.8%), irregular in 10/34 (29.4%), and not reported in 4/34 (11.8%). Examples of each category appear in Table 2.

Using a predefined six-item list, we created a characterization completeness score. (+1 for each group included in study.)

1. Fourier Transform Infrared Spectroscopy,
2. Raman Spectroscopy,
3. Transmission Electron Microscopy/Scanning Electron Microscopy,
4. Dynamic Light Scattering/ Nanoparticle Tracking Analysis,
5. Zeta Potential
6. X-ray Photoelectron Spectroscopy/Time-of-Flight Secondary Ion Mass Spectrometry/Point of Zero Charge

Selected studies scored a median of 2.0/6 (IQR 2.0; range 0–5). Several exemplars reached 5/6 (e.g. Mahadevan & Valiyaveetil; Masseroni et al.), [21,24] but multiple papers scored 0/6 (e.g., Bucher et al.; Nijenhuis et al.; Zingaro et al.) [32,33,34]. Of the 34 studies

reviewed, 29 (85.3%) failed to report  $\geq$  half of the six provenance descriptors.

#### 4.5. Method Lines

Across 34 method lines, nanoprecipitation accounted for 11 entries (33%), top-down milling for 10 (30%), and

commercial ‘as-received’ particles for 8 (24%); two lines reported only post-processing steps and two were other/NA. Common modifiers included SDS stabilization, size- selection (sieving /ultracentrifugation /filtration), and occasional functionalization (iodination, Au-doping, dye).

**Table 2. Characteristics of Selected Studies**

Citation	PVC provenance type	Supplier type	Character-ization scale	Morphology	Catalogue # reported	Weathering steps	Yield Reported	Plasticizer/filler reported
(Annenkov et al.) [35]	Virgin commercial PVC powder	Industrial polymer manufacturer /bulk supplier	1	Spherical	FALSE	FALSE	FALSE	TRUE
(Boughbina-Portolés et al.) [36]	Post-consumer waste	NR	4	Spherical	FALSE	FALSE	FALSE	FALSE
(Bucher et al.) [32]	Virgin resin – scientific grade	Analytical reagent supplier	0	NR	FALSE	FALSE	TRUE	TRUE
(Cassano et al.) [26]	Virgin resin – scientific grade	Analytical reagent supplier	2	Spherical	FALSE	FALSE	FALSE	FALSE
(Das et al.) [37]	Virgin resin – scientific grade	Analytical reagent supplier	5	Irregular	FALSE	TRUE	TRUE	FALSE
(Falsini et al.) [38]	Post-consumer waste	NR	2	Irregular	FALSE	TRUE	FALSE	TRUE
(Gosselink et al.) [23]	External lab-produced NPs	Reference/consortium provider	3	Irregular	FALSE	FALSE	FALSE	FALSE
(Gosselink et al.) [39]	External lab-produced NPs	Reference/consortium provider	3	Irregular	FALSE	FALSE	FALSE	TRUE
(Ji et al.) [40]	Virgin resin – scientific grade	Analytical reagent supplier	4	Irregular	FALSE	FALSE	N/A	TRUE
(Li et al.) [41]	Commercial PVC NPs	Industrial polymer manufacturer /bulk supplier	4	NR	FALSE	FALSE	N/A	TRUE
(Mahadevan and Valiyaveetil) [21]	Virgin resin – scientific grade	Analytical reagent supplier	5	Spherical	FALSE	FALSE	FALSE	TRUE
(Mahadevan and Valiyaveetil) [42]	Virgin resin – scientific grade	Analytical reagent supplier	3	Spherical	FALSE	FALSE	FALSE	FALSE
(Masseroni et al.) [43]	External lab-produced NPs	Reference/consortium provider	5	Spherical	FALSE	FALSE	N/A	TRUE
(Masseroni et al.) [24]	External lab-produced NPs	Reference/consortium provider	5	Spherical	FALSE	FALSE	FALSE	TRUE
(Meng et al.) [44]	Virgin commercial PVC powder	Specialty nanoparticle vendor	4	Spherical	FALSE	FALSE	FALSE	TRUE
(Merdy et al.) [45]	Virgin resin – scientific grade	NR	3	Spherical	FALSE	FALSE	FALSE	FALSE
(Merdy et al.) [25]	Virgin resin – scientific grade	Analytical reagent supplier	2	Spherical	TRUE	FALSE	TRUE	FALSE
(Monikh et al.) [46]	Virgin resin – scientific grade	Analytical reagent supplier	2	Spherical	FALSE	FALSE	FALSE	FALSE
(Monikh et al.) [28]	Virgin resin – scientific grade	Specialty nanoparticle vendor	2	Spherical	FALSE	FALSE	FALSE	FALSE
(Munir et al.) [47]	Virgin resin – scientific grade	Analytical reagent supplier	2	Spherical	FALSE	FALSE	FALSE	FALSE
(Ni et al.) [48]	Commercial PVC NPs	Industrial manufacturer /bulk supplier	3	Spherical	FALSE	FALSE	N/A	TRUE
(Nijenhuis et al.) [33]	Virgin resin – scientific grade	Analytical reagent supplier	0	Irregular	FALSE	FALSE	FALSE	FALSE
(Rauert et al.) [49]	Virgin commercial PVC powder	NR	0	Irregular	FALSE	FALSE	FALSE	FALSE
(Ren et al.) [50]	Post-consumer waste	Industrial polymer manufacturer /bulk supplier	2	Spherical	FALSE	TRUE	FALSE	FALSE
(Soliman et al.) [51]	Commercial PVC NPs	Industrial polymer manufacturer /bulk supplier	2	Spherical	FALSE	FALSE	FALSE	FALSE
(Stine et al.) [29]	Post-consumer waste	other	1	Irregular	FALSE	FALSE	FALSE	FALSE
(Weber et al.)	Virgin commercial PVC	Industrial polymer	2	Irregular	FALSE	FALSE	FALSE	FALSE

Citation	PVC provenance type	Supplier type	Characterization scale	Morphology	Catalogue # reported	Weathering steps	Yield Reported	Plasticizer/filler reported
al.) [22]	powder	manufacturer /bulk supplier						
(Xu et al.) <sup>27</sup>	Virgin resin – scientific grade	Analytical reagent supplier	1	NR	FALSE	FALSE	FALSE	FALSE
(Yu et al.) [52]	Commercial PVC NPs	Industrial polymer manufacturer /bulk supplier	1	Spherical	FALSE	FALSE	FALSE	FALSE
(Zheng et al.) [55]	Commercial PVC NPs	Industrial polymer manufacturer /bulk supplier	2	Spherical	FALSE	FALSE	FALSE	TRUE
(Zhu et al.) [56]	Commercial PVC NPs	Industrial polymer manufacturer /bulk supplier	3	Spherical	FALSE	FALSE	FALSE	FALSE
(Zingaro et al.) [34]	Virgin resin – scientific grade	Analytical reagent supplier	0	NR	FALSE	FALSE	FALSE	FALSE

\*Characterization completeness score (0–6): +1 each for FTIR, Raman, TEM/SEM, DLS/NTA,  $\zeta$ -potential, XPS/ToF-SIMS/pHpzc NR= Not Reported N/A= Not Applicable

## 5. Discussion

### 5.1. The Critical Role of Additives in PVC Nanoplastic Research

Poly(vinyl chloride) (PVC) differs fundamentally from many other commodity polymers used in nanoplastic studies, such as polyethylene (PE), polypropylene (PP), and polystyrene (PS), in that it is almost never encountered in a pure, additive-free form. Commercial PVC formulations incorporate substantial proportions of plasticizers, stabilizers, fillers, and pigments essential to achieving the desired mechanical, thermal, and optical properties. Flexible PVC grades frequently contain high loadings of plasticizers, often phthalate esters such as di(2-ethylhexyl) phthalate (DEHP) or high-molecular-weight alternatives (e.g., DiNP, DiDP, DINCH), at concentrations that may exceed 30–40% by mass. Rigid grades typically incorporate mineral fillers (e.g., calcium carbonate) and pigments (e.g., titanium dioxide), while all grades require heat stabilizers due to the inherent thermal instability of the PVC backbone. Stabilizers may include organotin compounds, Ca/Zn systems, or, in legacy materials, lead or cadmium-based salts. These additives are generally not covalently bound to the polymer matrix and are therefore susceptible to migration, leaching, volatilization, or transformation under environmental and experimental conditions.

This chemical complexity imparts a series of unique considerations for nanoplastic studies. Additives influence not only the environmental behavior of PVC particles, through alterations in density, surface chemistry, hydrophobicity, and brittleness, but also their toxicological profile via additive-derived leachates. Moreover, common laboratory synthesis routes, particularly nanoprecipitation and mechanical milling, differentially alter additive content. As a result, experimental outcomes in PVC nanoplastic studies cannot be interpreted solely on the basis of particle size, shape, and polymer identity; they must also be contextualized by additive profile.

### 5.2. Route-dependent Modification of Additive Profiles

Nanoprecipitation protocols dissolve the bulk polymer,

often co-extracting plasticizers, and other additives into the solvent phase, followed by precipitation in an antisolvent. Depending on solvent selection, pre-extraction treatments, and post-processing steps such as dialysis or centrifugation, the resulting particles may be substantially depleted of low-molecular-weight additives compared to the parent material. This depletion can alter surface charge, hydrophobicity, and mechanical integrity, with downstream effects on colloidal stability and interaction with test organisms.

By contrast, top-down mechanical milling, particularly cryogenic milling or grinding, tends to preserve the additive composition of the parent article, including fillers and pigments. However, mechanical stress can induce chain scission, surface oxidation, and increased surface area, all of which can accelerate additive release during exposure.

### 5.3. Plasticizers: Mobility and Toxicological Significance

Plasticizers, especially ortho-phthalates, are among the most consequential additives in PVC. They readily migrate from the polymer matrix into contacting media, and their leaching has been documented extensively from PVC medical devices and consumer products. For nanoplastic research, the mobility of plasticizers creates a persistent risk of confounding: observed biological effects may reflect additive exposure rather than, or in addition to, particle-mediated mechanisms.

### 5.4. Heat Stabilizers: Persistence and Leachability

PVC's susceptibility to dehydrochlorination during processing and use necessitates the inclusion of heat stabilizers. Organotin compounds remain in use in rigid PVC products such as pressure pipes; Ca/Zn stabilizer systems have largely replaced cadmium salts; and legacy materials may still contain lead-based stabilizers. Several stabilizer types possess intrinsic toxicity; organotins for example, are known endocrine disruptors in aquatic species. Stabilizers may leach as intact complexes or as degradation products under experimental conditions. In the context of nanoplastic studies, this means that particle dispersions derived from rigid PVC sources may introduce metals or organometallic species into exposure media,

potentially confounding particle-specific effects. Analytical verification of stabilizer content in both particles and leachates is therefore essential.

### 5.5. Fillers and Pigments: Mechanical and Analytical Implications

Mineral fillers such as calcium carbonate modify fracture mechanics and influence particle morphology during milling, typically promoting angular fragmentation. Fillers also affect particle density, with implications for separation, sedimentation, and bioavailability in aquatic systems. Pigments such as titanium dioxide impart additional analytical complexity by contributing strong scattering and characteristic IR/Raman signals that can overlap with PVC's spectral features. For studies employing vibrational spectroscopy for polymer identification, accounting for these signals is critical to avoid misclassification or overestimation of PVC purity.

### 5.6. Weathering chemistry and Leachate Formation

PVC degradation under environmental stressors is chemically distinct from that of polyolefins and styrenics. Thermal and photolytic processes initiate dehydrochlorination, forming conjugated polyenes and releasing hydrogen chloride gas. These emissions can acidify exposure media, alter ionic strength, and act as stressors. Aging and cleaning steps, whether deliberate (e.g., UV-thermal cycles) or incidental to synthesis, could modify particle surfaces and leachate chemistry. Experimental designs should incorporate filtered-leachate controls and targeted analyses of inorganic and organic acids to distinguish between particle-mediated and leachate-mediated effects.

### 5.7. Integrating Additive Context into Interpretation

The present review identified three predominant material sources in the literature: nano-precipitated particles, mechanically milled particles, and commercially obtained nanoparticles. When interpreted through the lens of additive chemistry, these categories exhibit distinct expected profiles: nano-precipitated particles are depleted in mobile additives; milled particles retain the additive composition of the source article; and commercial nanoparticles remain of unknown formulation without supplier and batch disclosure. Recognizing these differences is critical to understanding variability in reported bioeffects and to ensuring that comparisons across studies are valid.

### 5.8. Implications of Catalogue Number

Failure to supply the exact product catalogue number for a Sigma-Aldrich PVC powder makes it impossible for readers to know which resin grade was used. Sigma sells several "plain" PVC powders that look identical in a lab notebook but differ by an order of magnitude in molecular weight ( $M_w \approx 40 \text{ k}$  to  $230 \text{ k Da}$ ), inherent viscosity, and

residual stabilizer package. Those attributes govern how readily the polymer dissolves (or fails to dissolve) in a relevant solvent, the chain entanglement that drives nanoprecipitation, and the brittleness that controls particle-size reduction during cryo-milling. Two studies that both list "PVC powder purchased from Sigma" can therefore yield nanoplastics with diameters that differ by hundreds of nanometers, surface chemistries that diverge in chlorine-to-oxygen ratio, or additive leachates that swing from undetectable to toxicologically relevant, all before any downstream ageing or toxicology assay is performed.

Omitting the catalogue number also blocks access to the batch-specific Certificate of Analysis and Certificate of Composition that Millipore-Sigma provides. Those documents list heavy-metal stabilizers, trace phthalates, K-value and, for Selectophore grades. Without them, reviewers cannot judge whether a reported "additive-free" exposure was truly additive-free or whether the apparent biological effect might instead be driven by residual barium, organic tin, or plasticizer. In short, the product number is the only simple handle that connects a Methods section to the hidden material properties that determine solubility kinetics, nanoparticle yield, colloidal stability, and toxicological outcome; leaving it out undermines both reproducibility and the mechanistic claims a study can credibly make. Of course, all these challenges can be rectified by rigorous testing of the experimental material, but these are prohibitively expensive and complex. Recommendations for PVC-specific reporting

To address the reproducibility and relevance gaps identified, we recommend a PVC-specific extension to existing microplastic reporting frameworks:

1. Provenance and identification – Supplier and catalog/lot number; resin grade
2. Additive quantification – Plasticizer identity and mass fraction; stabilizer type and concentration; filler/pigment identity and loading.
3. Weathering and cleaning – Detailed conditions for any pre-treatments; verification of chemical changes (FTIR, XPS, ion chromatography).
4. Synthesis route – Solvent systems, concentrations, process parameters, yields, and recovery efficiency.
5. Exposure verification – Measured particle concentration (mass and number),  $\zeta$ -potential in exposure medium, additive concentrations in the medium over time.
6. Leachate controls – Filtered leachate and additive-spiked controls to decouple particle and chemical effects.
7. Data transparency – Deposition of raw spectra, micrographs, and code to enable independent verification.

### 5.9. Future Directions

Priority research needs include inter-laboratory comparisons using reference PVC materials that differ systematically in additive package or weathering history, as well as coordinated efforts to co-report particle and leachate effects using orthogonal analytical techniques. Only through such integrative approaches can PVC

nanoplastic hazard data be rendered both reproducible and environmentally relevant.

### 5.10. Broader Implications for Regulatory Monitoring and Cross-Polymer Comparability

The underreporting of PVC feedstock provenance has consequences that extend beyond this polymer system. Incomplete documentation of supplier origin, additive formulation, and pre-processing obscures inter-laboratory comparability and undermines the development of standardized toxicity thresholds across polymer classes. Transparent provenance reporting would enable alignment with emerging quality-assurance frameworks that emphasize traceable material characterization, such as the OECD Working Party on Manufactured Nanomaterials (WPMN) Test Guidelines for plastic waste assessment. By establishing consistent descriptors across PVC, PE, PP, PS, and other commonly studied nanoplastics, researchers can generate datasets that are not only reproducible but also interoperable within regulatory risk-assessment models. Ultimately, improving cross-polymer comparability strengthens the interpretability of nanoplastics research for environmental monitoring and policy formulation.

## 6. Conclusions

This review highlights pervasive gaps in provenance reporting within PVC nanoplastics research and underscores their implications for reproducibility, comparability, and environmental interpretation. Despite increasing experimental sophistication, only a small fraction of studies report essential descriptors such as supplier, catalogue number, additive profile, or pre-treatment method, leaving the majority of published data partially unverifiable. Because these parameters directly influence surface chemistry, solubility, and leachate composition, their omission weakens mechanistic inferences and complicates cross-study synthesis. The proposed PVC-specific reporting checklist offers a practical framework for improving transparency and aligning with emerging quality assurance initiatives in micro- and nanoplastics research. Adoption of standardized provenance reporting will not only strengthen data integrity but also support the integration of PVC nanoplastic evidence into regulatory risk assessment and environmental monitoring frameworks such as those developed by OECD and NIST.

## 7. Limitations of the Review Methods

This review focused on studies indexed in PubMed, which means that some relevant records from other databases may not have been captured. Screening and data extraction were performed by a single reviewer following predefined criteria. While this streamlined approach ensures consistency, future reviews could expand coverage to further strengthen reproducibility.

## 8. Declarations

### 8.1. Availability of Data and Materials

Supplementary Tables used for calculation can be found in the OSF files or requested from the corresponding author.

Open Science Framework (<https://doi.org/10.17605/OSF.IO/CQYXT>.)

### 8.2. Competing Interests

The authors declare that they have no competing interests.

### 8.3. Funding

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### 8.4. Authors' Contributions

**Jared D. Mimbs:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Visualization.

**Greg Hunlen:** Validation, Writing – Review

**Bipul K. Biswas:** Conceptualization, Supervision, Project administration, Writing – review & editing, Funding acquisition.

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