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Global Trends and Recommended Configurations in Personal Breathing-Zone Nanoparticle Sampling Methods for Workers: An Updated Systematic Review (2000–2025)

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ABSTRACT

This PRISMA-based systematic review synthesized 12 studies (2000–2025) on personal breathing-zone (PBZ) nanoparticle sampling among workers. The analysis categorized direct-reading devices (CPC, DiSCmini, SMPS, ELPI) and filter-based samplers (NRD, PENS, TDS) by metric, size range, and portability. Global trends indicate a post-2015 shift toward portable, multimodal instruments, though evidence gaps remain, especially in low- and middle-income countries. The combined use of the NRD (for deposition-relevant, composition-specific analysis) and CPC/DiSCmini (for real-time exposure patterns) is identified as the most comprehensive configuration. Standardized reporting of flow, background, and uncertainty, is recommended to enhance comparability and occupational health decision-making.

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1. INTRODUCTION

Nanotechnology is rapidly advancing across industries; consequently, workers may be exposed to both engineered and incidental nanoaerosols. The breathing zone (≈30 cm around the mouth and nose) is recommended to represent personal exposure, but the availability of lightweight, accurate, and reliable personal samplers remains limited; field practice often relies on stationary instruments or direct-reading monitors that do not always capture short-duration task fluctuations.

Your 2000–2021 thesis identified heterogeneity in instruments, metrics (mass/number/surface area), and strategies (task-based vs. shift-average), as well as the need to select methods according to measurement objectives (compliance with reference limits, control evaluation, source characterization). An update covering 2022–2025 is needed to map new technologies and evidence across different industrial contexts. According to the Organisation for Economic Co-operation and Development (OECD), more than 2 million workers worldwide are potentially exposed to engineered nanomaterials each year, and this number is projected to increase by 30–40% by 2030 as nanotechnology expands across manufacturing, health, and energy sectors. Similarly, the International Labour Organization (ILO) reports that over 80% of occupational exposure studies conducted since 2015 have detected measurable

nanoparticle concentrations within workers' breathing zones, underscoring the urgency for standardized PBZ sampling and risk evaluation frameworks.

Despite rapid progress in nanotechnology applications, evidence from low- and middle-income countries remains limited, constraining the development of globally harmonized exposure standards. This review updates previous work (2000–2021) by expanding coverage to 2025 and identifying methodological evolution in both developed and resource-limited settings.

The study aims to update and synthesize global evidence (2000–2025) on PBZ nanoparticle sampling methods to map trends, assess instrument performance, and recommend configurations for occupational safety and health practice.

2. METHODS

This study adopts the Systematic Literature Review (SLR) approach based on Kitchenham (2004) and aligns with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The review process comprises three main phases: Planning, Conducting, and Reporting, as illustrated in **Figure 1**.

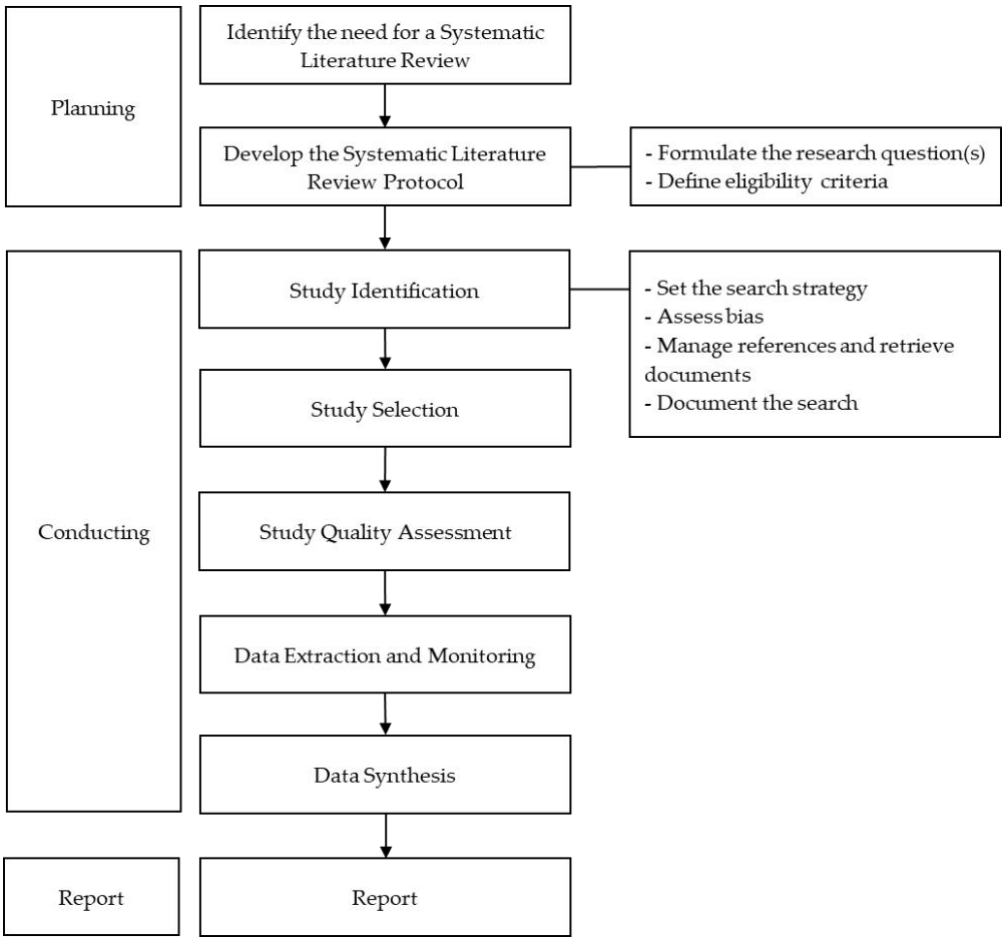

Figure 1. Research stages

Planning. The purpose of this SLR is to collect, evaluate, and synthesize scientific evidence regarding nanoparticle sampling methods used within the personal breathing zone (PBZ) of workers.

Subsequently, the research question will be articulated and the study eligibility criteria established. For this study, the research question is: "What direct-reading and filter-based methods are used for sampling nanoparticles in the personal breathing zone (PBZ) of workers globally, and how do these methods compare in performance and applicability?".

The inclusion and exclusion criteria were defined as shown in **Table 1**, and the search string was developed accordingly. The mandatory keywords were:

"**Nanoparticle** OR **Nanomaterial** OR **Ultrafine Particle** AND **Personal** OR **Breathing Zone** AND **Sampling**."

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Year of publication	2000-2025	Before 2000
Language	English	Languages other than English
Information source	Google Scholar, Scopus, Web of Science, PubMed	Non-indexed sources
Additional criteria	Indexed in JCR or SJR	Not indexed on JCR or SJR
Content relevance	Studies addressing PBZ nanoparticle sampling	Studies unrelated to PBZ or nanoparticle measurement

Conducting. A systematic search was conducted across four major databases, namely: *Google Scholar*, *Scopus*, *Web of Science*, and *PubMed*, to ensure coverage of both peer-reviewed and cross-disciplinary literature. After removing duplicates, records were screened through the following stages:

Table 2. The initial search results obtained using the specified syntax

Screening Stage	Records Identified	Description
Initial database search	17.300	Titles and abstracts identified across all databases
Title screening	24	Focused on PBZ nanoparticle sampling methods
Abstract screening	14	Met inclusion criteria
Final inclusion after quality appraisal	12	Selected for synthesis

This process is illustrated in the PRISMA 2020 flow diagram (Appendix A), which visualizes study identification, screening, eligibility, and inclusion steps.

Table 3. Study rangking

No.	Name of Journal	Number of Study	JCR		SJR	h5	Rank
			IF	Quartile in Category			
1	Environmental Science and Technology	2	11,4	Q1	3,69	504	10600,632
2	Current Environmental Health Reports	1	9,1	Q1	2,833	78	502,71585
3	Journal of Nanoparticle Research	3	2,6	Q2	0,469	149	136,26795
4	Journal of Analytical Atomic Spectrometry	1	3,1	Q2	0,618	133	63,70035
5	Annals Occupational Hygiene	2	2,779	Q1	0,74	32	32,90336
6	Atmosphere	1	2,3	Q2	0,633	76	27,6621

No.	Name of Journal	Number of Study	JCR		SJR	h5	Rank
			IF	Quartile in Category			
7	Journal of Occupational and Environmental Hygiene	1	1,5	Q3	0,424	89	14,151
8	Journal of Aerosol Medicine and Pulmonary Drug Delivery	1	1,8	Q2	0,352	86	13,6224

To ensure the inclusion of high-quality and relevant studies, a ranking formula was applied using bibliometric and content-based parameters. Each study's final rank score was determined using the following expression:

$$\textbf{Rank Score} = (\boldsymbol{R_s} \times \mathbf{0.25}) + (\boldsymbol{IF} \times \mathbf{0.40}) + (\boldsymbol{SJR} \times \mathbf{0.20}) + (\boldsymbol{h_5} \times \mathbf{0.15})$$

Where:

- R_s: Relevance score (based on PBZ focus and methodological quality)
- IF: Journal Impact Factor (Journal Citation Reports)
- SJR: SCImago Journal Rank
- h_5: 5-year h-index of the journal (Google Scholar Metrics)

Each parameter was normalized to a 0–1 scale prior to computation. The weighting factors (0.25, 0.40, 0.20, and 0.15) were chosen to emphasize journal quality and study relevance proportionally.

After applying this scoring system, 12 studies with the highest composite rank were selected for synthesis. A detailed example of the ranking computation is presented in **Tabel 3.**

The selected studies will undergo the literature review at this stage. Of the 14 studies, 12 with the highest rankings were chosen. See **Table 4**.

Table 4. The 12 studies selected from the ranking results.

No.	Tittle	Author	Year
1	A personal nanoparticle respiratory deposition (NRD) sampler	Cena, Lorenzo G.	2011
2	Novel active personal nanoparticle sampler for the exposure assessment of nanoparticles in workplaces	Tsai, Chuen Jinn	2012
3	New Methods for Personal Exposure Monitoring for Airborne Particles	Koehler, Kirsten A.	2015
4	Workplace air measurements and likelihood of exposure to manufactured nano-objects, agglomerates, and aggregates	Brouwer, Derk H.	2013
5	Exposure assessment of nano-sized and respirable particles at different workplaces	Tsai, Chuen Jinn	2011
6	A sampler designed for nanoparticles and respirable particles with direct analysis feature	Tsai, Candace Su Jung	2018
7	Considerations for measurement of individual nanoparticles or microparticles by ICP-MS: Determination of the number of particles and the analyte mass in each particle	Olesik, John W.	2012

No.	Tittle	Author	Year
8	A Systematic Review of Reported Exposure to Engineered Nanomaterials	Debia, Maximilien	2016
9	Sampling conventions for estimating ultrafine and fine aerosol particle deposition in the human respiratory tract	Bartley, David L.	2011
10	Review on Sampling Methods and Health Impacts of Fine (PM2.5, ≤2.5 μm) and Ultrafine (UFP, PM0.1, ≤0.1 μm) Particles	Chauhan, Balendra V.S.	2024
11	Field application of the nanoparticle emission assessment technique (NEAT): Task-based air monitoring during the processing of engineered nanomaterials (ENM) at four facilities	Methner, M.	2012
12	Measurement techniques for respiratory tract deposition of airborne nanoparticles: A critical review	Löndahl, Jakob	2014

Report. The 12 selected studies were subjected to narrative and descriptive synthesis, focusing on the following comparative aspects:

- Type of sampling instrument (direct-reading or filter-based)
- Measurement metric (mass, number, or surface area concentration)
- Instrument mobility and applicability in workplace conditions
- Analytical compatibility (e.g., ICP-MS, TEM, or EC analysis)

The results of this synthesis are summarized in Tables 6 and 7, providing a comparative overview of 13 identified PBZ nanoparticle sampling methods.

Methodological Transparency and Limitations. Although the primary search relied heavily on Google Scholar, the addition of Scopus, Web of Science, and PubMed databases improved coverage and reduced potential bias. Future studies should incorporate additional grey literature repositories and consider quantitative meta-analysis to statistically compare instrument performance.

3. FINDINGS AND DISCUSSION

Based on a systematic literature review of the selected studies, a total of 13 methods were identified that can be used for nanoparticle sampling. These methods were then classified as sampling methods or measurement instruments for the personal breathing zone. The classification was formulated according to instrument mobility (stationary or portable). In Table 6, the methods are identified according to the particle size range that can be sampled, whether they are direct- or indirect-reading, the measurement metric, and their mobility.

Table 5. Summary of PBZ nanoparticle sampling methods and characteristics

Sampling Method	Sample Size	Direct Reading/Indirect reading	Metric	Mobility
Condensation particle counter (CPC)	10 - 1000 nm	Direct reading	Number	Portable
Optical Particle Counting (OPC)	300 – 500 nm	Direct reading	Number	Portable
Filter-based air sampling	1 – 100 nm	Indirect reading	Mass, chemical composition, size	Portable

Sampling Method	Sample Size	Direct Reading/Indirect reading	Metric	Mobility
Personal Nanoparticle Sampler (PENS)	<100 nm	Indirect reading	Mass, chemical composition, size	Portable
High-volume cascade impactor	<0.18 μm	Indirect reading	Mass & chemical composition	Stationary
Low/Personal cascade impactor	2.5–10 μm	Indirect reading	Mass, chemical composition	Portable
MOUDI	≈0.066 μm	Indirect reading	Mass	Stationary
Nanoparticle Respiratory Deposition Sampler (NRD	<300 nm	Indirect reading	Mass, chemical composition	Portable
Tsai Diffusion Sampler (TDS)	≈15–1560 nm	Indirect reading	Size, mass, number	Portable
DiSCmini / nanoTracer	~10–300 nm	Direct reading	Number, mean diameter, LDSA	Portable
PUFP C100 / mini-CPC	~20 nm–2 μm	Direct reading	Number	Portable
Scanning Mobility Particle Sizer (SMPS)	≈11–1083 nm	Direct reading	Number, size	Portable
ELPI	≈27–7734 nm	Direct reading	Number, size	Stationary

In addition to the classification presented in **Table 6**, nanoparticle sampling methods are also identified based on the types of nanoparticles that can be measured. Among the 12 included studies, the NRD sampler was employed in four, CPC and DiSCmini in three each, SMPS in two, and PENS/TDS in one each. Table 6 summarizes these instruments, representing only the 12 highest-ranked studies within the inclusion criteria.

2.1. Instrument Selection Criteria

The selection of sampling methods can be guided by several factors, including the sampling time or duration, the ease of use and availability of the instruments, the size of the nanoparticles to be measured, and the subsequent analytical methods to be applied.

Time/Duration

The determination of time-based sampling methods is intended to align with the duration of an individual's work activity. For tasks with short working periods, methods or instruments with the shortest possible operating time are preferred.

Ease of use and availability

Ideally, the methods or instruments can be operated by a wide range of users without requiring specialized skills or training, as this will influence their effectiveness. This ease of use is also expected to be maintained throughout the analytical stage.

Desired nanoparticle size

Often, the size distribution of nanoparticles present in the workplace is not yet clearly known. Therefore, instruments capable of capturing a broader range of nanoparticle sizes are required. The physical and chemical properties of nanoparticles form the basis for their detection in a given medium. The range of these properties, which is relevant to risk assessment, underscores the need for highly sensitive methods. Moreover, because the typical dimensions of nanoparticles lie below the diffraction limit of visible light, they fall outside the observable range of optical microscopes.

Advanced analytical methods

The classification of a method as direct-reading or indirect-reading is closely linked to the instrument's capability to detect and present data. As previously noted, direct-reading sampling methods do not require prior treatment or manipulation of the sample and can describe the characteristics of the sample at a given moment in time. However, the information produced is generally limited to number concentration, mass concentration, surface area, and composition. In contrast, the use of specialized characterization instruments enables more in-depth analysis, such as organoleptic properties, percent transmittance, porosity, and other specific characteristics. Parameters such as number concentration, size distribution, and surface area concentration obtained from direct-reading methods tend to be rather general and often do not distinguish nanoparticles from other particles with diameters <100 nm. Additional analysis using advanced characterization techniques is important to consider, even though it is more time-consuming and costly. Nevertheless, such measurements are essential when individual nanoparticles in complex matrices need to be detected and traced back to specific products, or when they possess high toxicity such that even a single particle may pose a health risk.

Table 6. Sampling method comparasion

Primary objective	Recommended method(s)	Rationale	Suggested companion instruments
Rapid detection & peak quantification (real-time number)	CPC (10–1000 nm) or DiSCmini/nanoTracer (~10–300 nm; number & LDSA)	Second-to-minute response; highly sensitive to task peaks and control evaluation	Add NRD/PENS to confirm material identity
Verify that the material reaches the PBZ & enable chemical analysis	NRD (<300 nm; diffusion-matched) or PENS (<100 nm + respirable)	Produces laboratory samples: mass, elements (ICP-MS/EC), morphology (TEM/SEM)	CPC/DiSCmini for time context; microAeth if combustion sources are present
Morphology/size in PBZ directly onto TEM	Tsai Diffusion Sampler (TDS) (TEM grid + filter)	Direct collection on TEM grid; clear evidence of shape/aggregation; respirable cut-off	CPC/DiSCmini for dynamics; NRD can supplement for bulk chemistry
Detailed size distribution (not always wearable)	SMPS (11–1083 nm) / ELPI (27–7734 nm)	High-resolution size distributions; ideal for research and source mapping	Use near-field (inlet near PBZ) + NRD/TDS for material confirmation
Bulk chemical characterization of UFP (ambient/area)	High-volume / Personal cascade impactor (PCIS)	Large sampled volume to lower chemical LOD; stage-resolved mass	Add CPC/DiSCmini for dynamics; typically area, not wearable

Primary objective	Recommended method(s)	Rationale	Suggested companion instruments
Combustion indicator	micro-Aethalometer (BC, μg/m³)	Specific to soot/black carbon; useful for diesel/thermal processes	CPC/DiSCmini for number; NRD/TDS to confirm non-BC material

Based on the criteria synthesized in **Table 6,** the most robust configuration for assessing nanoparticle exposure in the personal breathing zone is to use the Nanoparticle Respiratory Deposition (NRD) sampler in combination with a CPC or DiSCmini. The NRD yields diffusion-matched samples aligned with respiratory tract deposition, so the collected fraction represents the biologically relevant particles. These samples can then be analyzed in the laboratory to obtain mass and composition (e.g., ICP-MS for metal oxides, EC/NIOSH 5040 for CNT/CB) and to confirm morphology/elemental signatures by TEM/SEM-EDS. In this way, the NRD answers what material actually reaches the PBZ and how much of it is deposition-relevant—evidence that is defensible for occupational decision-making.

Conversely, CPC/DiSCmini provides high-resolution time series of particle number concentration (and, for DiSCmini, mean diameter and lung-deposited surface area), capturing short-lived task peaks that filter methods cannot resolve. These real-time data reveal when exposures occur and which activities drive them, enabling precise evaluation of engineering controls. When the two devices are used concurrently in a task-based design, peaks in CPC/DiSCmini can be aligned with the NRD sampling periods, background can be measured before/after each task, and the chemical/morphological evidence from the NRD can be linked to specific peak episodes. The combination thus covers all critical needs identity/mechanism, magnitude, and temporal dynamics while remaining portable for PBZ use.

In practice, the NRD is operated with a personal pump (~2–3 $L \cdot min^{-1}$) and clipped near the collar, whereas CPC/DiSCmini is logged at short intervals (e.g., 1–10 s) with flow checks before and after the shift. The limitations of each method—the NRD not being real-time and CPC/DiSCmini lacking chemical specificity, complement one another when combined. For these scientific and practical reasons, **Table 6** supports NRD combined with CPC/DiSCmini as the primary recommended configuration for PBZ nanoparticle sampling.

To illustrate the functionality and complementarity of key instruments, detailed descriptions of the NRD and CPC/DiSCmini are provided below.

NRD

NRD is a personal, filter-based sampler engineered so that its overall collection efficiency mimics the respiratory tract deposition curve for nanoparticles. NRD is indirect reading (not real-time) method. Combine it with a real-time instrument (CPC or DiSCmini) to obtain a complete picture: what the particles are, how much is relevant to deposition, and when exposures occur. After sampling, the media (screens/filters) are analyzed in the laboratory for: mass and elemental composition via ICP-MS/ICP-OES (e.g., Ti, Al, Zn, Ag, Fe, Mn, Cr, Ni, Ce); elemental carbon (EC) for CNT/CNF/carbon black (e.g., NIOSH 5040) when compatible media are used; morphology/size/elemental mapping via TEM/SEM-EDS (optional; after transfer/replication from the screens).

The strength of this method is: biological relevance, the captured fraction is tuned to lung deposition, improving risk-assessment interpretability; personal & portable, worn at the collar (~30 cm from mouth–nose); versatile analytics, supports ICP-MS/EC/TEM-EDS for source attribution and material identification; lower pressure drop than some alternatives (e.g., PENS), easing field deployment.

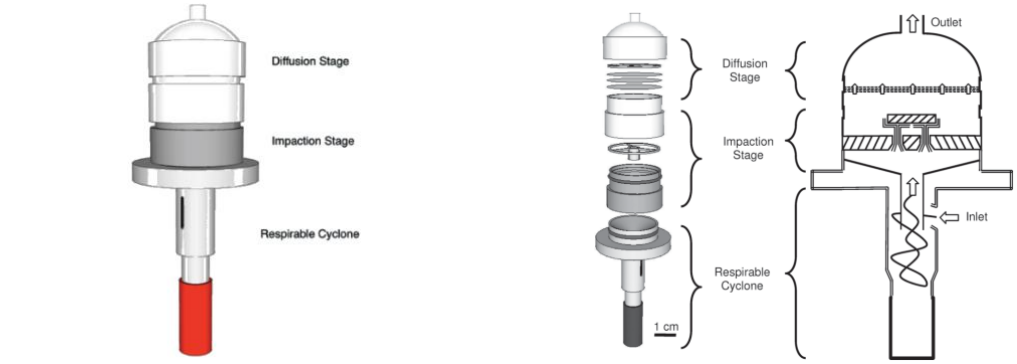

Figure 2. (**a**) Nanoparticle Respiratory Deposition Sampler (NRD; (**b**) Schematic drawing showing airflow path and major components

CPC/DiSCmini

CPC and DiSCmini are direct-reading instruments designed to capture the time-resolved dynamics of nanoparticle exposure in the personal breathing zone. A CPC operates by condensing a working vapor onto nanoscale particles so that they grow into optically countable droplets; the output is a second-by-second time series of particle number concentration (PNC) with high sensitivity to brief task-related spikes. The DiSCmini, by contrast, uses diffusion charging: particles acquire a slight electrical charge and the resulting electrical signal is mapped to PNC, the count median diameter (CMD), and lung-deposited surface area (LDSA), a metric often considered more biologically relevant than particle number alone. In field practice, both devices are positioned as close as possible to the worker's breathing zone, logged at short intervals (approximately 1–10 s), and bracketed by flow checks and background measurements so that peaks can be interpreted defensibly.

The chief strength of CPCs and the DiSCmini is their ability to reveal when exposures occur and which activities drive them. CPCs are typically superior for detecting very low concentrations and short-lived peaks, whereas the DiSCmini adds size context and LDSA, aiding interpretation in terms of potential respiratory deposition. Neither instrument, however, provides material identity: they do not distinguish whether detected particles are TiO_2, silica, soot, or CNT/CNF. For occupational decisions that require material evidence, a direct-reading device should therefore be paired with a deposition-relevant filter sampler such as the NRD. This combined approach aligns real-time PNC or LDSA peaks with targeted filter sampling windows, enabling laboratory confirmation (e.g., ICP-MS, EC/NIOSH 5040, TEM/SEM-EDS) for specific exposure episodes. In short, CPC/DiSCmini provide the temporal map and intensity of exposure, while the NRD answers what actually reaches the breathing zone together yielding a complete, scientifically defensible picture for evaluating and improving engineering controls in the workplace.

Figure 3. CPC/DiSCmini

Although this review initially relied on Google Scholar, additional searches through Scopus, Web of Science, and PubMed improved coverage but may still exclude non-indexed grey literature.

4. CONCLUSION

This review confirms persistent heterogeneity in PBZ nanoparticle sampling methods and metrics. A combined NRD and CPC/DiSCmini configuration offers the most robust and complementary approach for assessing deposition-relevant and real-time exposures. Future research should prioritize standardization of flow parameters, uncertainty reporting, and cross-regional data to strengthen global comparability. The observed post-2015 trend toward portable, multimodal devices marks a pivotal shift in occupational exposure assessment practice.

Integrating deposition-relevant and real-time instruments into regulatory exposure frameworks can enhance global comparability and worker protection in emerging nanotechnology industries.

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APPENDIX A. PRISMA 2020 FLOW DIAGRAM

Purpose: This appendix summarizes the identification, screening, eligibility, and inclusion process following the PRISMA 2020 statement (Page et al., 2021). It shows how 12 final studies were selected for synthesis from an initial 17,300 records.

Table A1. PRISMA 2020 Flow Summary

Phase	Description	Records (n)	Notes
Identification	Records identified from databases (*Google Scholar, Scopus, Web of Science, PubMed*)	17.300	Search period: 2000–2025
	Additional records from manual and citation searches	8	Derived from references of relevant studies
Screening	Duplicates removed	2.144	Identified by DOI and title
	Titles and abstracts screened	15.164	Evaluated using inclusion/exclusion criteria
	Records excluded (irrelevant or non-PBZ focus)	15.140	Not related to PBZ nanoparticle sampling
Eligibility	Full-text articles assessed for eligibility	24	Focused on PBZ nanoparticle exposure or sampling
	Full-text articles excluded	10	Reasons: incomplete data (n=2), non-English (n=2), methodological mismatch (n=6)
Included	Studies meeting inclusion criteria	14	Indexed in JCR/SJR
	Studies included after quality ranking	12	Final synthesis dataset

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APPENDIX B. RANKING FORMULA DAN CALCULATION EXAMPLE

Purpose: This appendix presents the composite ranking formula and demonstrates how it was applied to evaluate and prioritize eligible studies for inclusion.
Ranking Formula:

$$\textbf{Rank Score} = (\boldsymbol{R_s} \times \mathbf{0.25}) + (\boldsymbol{IF} \times \mathbf{0.40}) + (\boldsymbol{SJR} \times \mathbf{0.20}) + (\boldsymbol{h_5} \times \mathbf{0.15})$$

Where:

- R_s : Relevance score (1–5 scale based on PBZ context and methodological quality)
- IF : Journal Impact Factor (normalized 0–1)
- SJR : SCImago Journal Rank (normalized 0–1)
- h_5 : h5-index of journal (normalized 0–1)

Normalization formula for each metric:

$$\boldsymbol{X_{\text{norm}}} = \frac{\boldsymbol{X_i} - \boldsymbol{X_{\text{min}}}}{\boldsymbol{X_{\text{max}}} - \boldsymbol{X_{\text{min}}}}$$

Example calculation:

Parameter	Raw Value	Normalized Value	Weight	Weighted Score
R_s	4,5 / 5	0,90	0,25	0,225
IF	5,2	0,85	0,40	0,340
SJR	1,3	0,78	0,20	0,156
h_5	45	0,72	0,15	0,108
Total Rank Score				**0,829**

Thus, this paper would achieve a **Rank Score = 0.829**, qualifying it among the top 12 included studies.
Ranking Threshold

- Top 12 studies included: Rank ≥ 0.70
- Studies with Rank 0.50–0.69: considered borderline, reviewed manually
- Studies < 0.50: excluded from synthesis

SYMBIOHEALTH
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APPENDIX C. INSTRUMENT COMPARISON METRIX

Purpose: To summarize the technical and functional characteristics of 13 identified PBZ nanoparticle sampling instruments, categorized by their metrics, size range, portability, and analytical compatibility.

Tabel C1. Comparison of PBZ Nanoparticle Sampling Instruments (2000-2025)

Instrument	Type	Metric	Size Range (nm)	Mobility	Analytical Output	Main Advatages	Limitations
NRD (Nanoparticle Respiratory Deposition Sampler)	Filter-based	LDSA / mass	10–300	Portable	Gravimetric, ICP-MS, TEM	Mimics lung deposition; composition-specific	Single-metric; offline analysis
CPC (Condensation Particle Counter)	Direct-reading	Number	10–1000	Portable	Real-time	High temporal resolution	No chemical speciation
DiSCmini	Direct-reading	Number and LDSA	10–700	Handheld	Real-time	Compact, field-suitable	Limited flow rate
SMPS (Scanning Mobility Particle Sizer)	Direct-reading	Number	10–500	Stationary	Real-time	High accuracy	Bulky, lab-based
ELPI (Electrical Low Pressure Impactor)	Direct-reading	Number/Mass	10–10000	Stationary	Real-time	Size-segregated measurement	Complex calibration
TDS (Thermodenuder Sampler)	Hybrid	Volatility	50–500	Stationary	Thermal mass loss	Distinguishes volatile fractions	Not field-portable
PENS (Personal Nanoparticle Sampler)	Filter-based	Mass	20–300	Portable	Gravimetric	Lightweight, cost-effective	No real-time data
IOM Sampler (Modified)	Filter-based	Mass	100–10000	Portable	Gravimetric	Widely used in OSH studies	Poor resolution for ultrafine fraction
MiniMOUDI	Impactor	Mass	50–10000	Stationary	Offline	Multi-stage analysis	Limited nanoscale capture
CIS (Cascade Impactor Sampler)	Impactor	Mass	100–10000	Stationary	Offline	Size-segregated stages	Not suitable for PBZ
NRD + CPC	Combined	LDSA +	10–1000	Portable	Hybrid	Best overall performance	Requires dual calibration

Instrument	Type	Metric	Size Range (nm)	Mobility	Analytical Output	Main Advatages	Limitations
NRD + DiSCmini	Combined	Number LDSA + Number	10–700	Portable	output Real-time hybrid	Field deployable	Costlier combination
NRD + CPC + DiSCmini	Combined	Multimetric	10–1000	Semi-portable	Real-time + offline	Most comprehensive PBZ setup	Logistically complex

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