Supplementary Information (SI) for Environmental Science: Nano.

Nanowaste Management in Laboratory Practice: Supplementary Information

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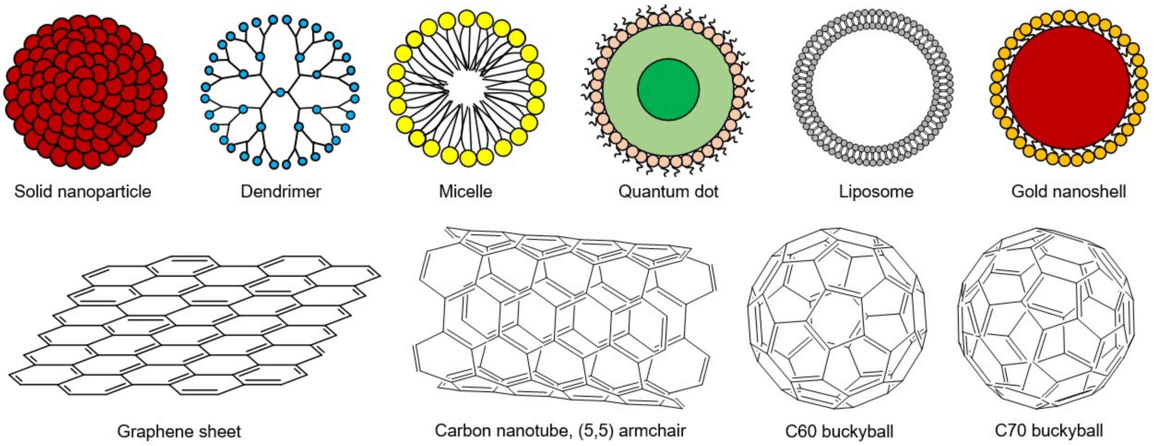
Content:

Supplementary Fig. S1; Supplementary Tab. S1; Supplementary Tab. S2; Case Studies 1-4; Sections *Definitions and Characterization methods, In-house treatment and recycling to prevent upstream nanowaste*; *Specific rules for flammable nanowaste*; *Details on labeling nanowaste* and *on the permeability of protective gloves*.

Supplementary Figure S1



Supplementary Figure S 1: Common types of nanomaterials that require special waste management. Adapted from Stuttgen and co-workers 2019[16].

Supplementary Table S1

Supplementary Table S 1: Rapid nanowaste hazards and risks determination. Figure adapted from Stuttgen *et al.* 2019[16] and Zalk *et al* 2011[45].

Nanowaste Type	Hazards	Risk
Dry powder	Fire, explosion, catalytic reactions, inhalation, skin contact, and ingestion	High
Aerosol	Inhalation, skin contact, and ingestion	High
Liquid suspensions / dispersions / emulsions / slurries	Spill and reactivity, skin contact, and ingestion	Medium
Embedded in a solid matrix	Abrasion, machining, polishing, etc. leading to inhalation, skin contact, and ingestion	Low

Supplementary Table S2

Supplementary Table S 2 In-house treatment options for nanowaste types typically encountered in research laboratories, aimed at removing their nano-specific properties. For details of the treatments, refer to the Supplementary Information section 'In-house treatment and recycling to prevent upstream nanowaste' and previous work[46-52]. The effectiveness of each treatment must be validated to confirm removal of nano-specific properties. Note that for several nanomaterials, treatment options have not yet been established; these are indicated in the table.

			In-house treatment of waste feasible / recommendable		
Nanowaste	**Treatment**	**Waste resulting after treatment**	**Small scale**	**Large scale**	**End product**
Mixtures of (unknown) nanomaterials	Currently none known. Treatment conditions to be determined experimentally	As long as no treatment known: dispose of as nanowaste. If validated treatment available: very hazardous chemical waste	No	No	Until more sustainable treatment found: nanowaste
Stabilized, capped, or otherwise functionalized nanomaterials with hazardous elements	Currently none known. Treatment conditions to be determined experimentally	As long as no treatment known: dispose of as nanowaste. If validated treatment available: very hazardous chemical waste, or chemical waste	No	No	
Al_2O_3 and clays	Currently none known, highly inert material. Treatment conditions to be determined	As long as no treatment known: dispose of as nanowaste. If validated treatment available: chemical waste	No	No	
TiO_2	29.5% HNO_3, 7.3% HF, 5.5% H_2O_2, and 5.5% HCl + H_3BO_3	Very hazardous aqueous chemical waste (HF)	No	No	
	950 °C + O_2	Nontoxic sintered TiO_2 in glass matrix	No	No	
Stabilized, capped, or otherwise functionalized nanomaterials without hazardous elements	Currently none known. Treatment conditions to be determined experimentally, likely acid treatment will work	As long as no treatment known: dispose of as nanowaste. If validated treatment available: chemical waste	No	Yes	Acidic chemical waste
CeO_2	HNO_3 + H_2O_2, optional NaOH neutralization	Aqueous chemical waste	No	Yes	
ZnO	HCl + HNO_3, optional NaOH neutralization	Aqueous chemical waste	No	Yes	
Fe + Fe oxides	HCl + HNO_3, optional NaOH neutralization	Aqueous chemical waste	No	Yes	
Cu + Cu oxides	HCl + HNO_3	Aqueous chemical waste	No	Yes	
Ag	HNO_3 or *aqua regia,* optional NaOH neutralization	Aqueous chemical waste	No	No	
	Recycling: collect separately, hierarchical mesoporous calcite	Recycled nanoparticles	Yes	Yes	
Au	*Aqua regia,* optional NaOH neutralization	Aqueous chemical waste	No	No	
	Recycling: collect separately, NaCl, then HCl +	Recycled metal salt	Yes	Yes	
SiO_2	KOH, optional HCl neutralization	Aqueous chemical waste / household waste	No	Yes	Basic chemical waste
Carbonaceous nanomaterials including buckyballs, soot, graphite/graphene, MWCNTs, SWCNTs	>800 °C + O_2	CO_2, NO_x	No	No	CO_2
Cellulose, carbon nanodots	Double-bag	Household waste to be burned at >800 °C	No	No	
	Compost (cellulase in fungi and microbes)	Soil	Yes	Yes	

Definitions of terms

- **Uncapped nanomaterials: Bare particles without deliberate stabilizing agents. They are often more prone to aggregation, dissolution, or transformation.**
- **Capped nanomaterials: Particles coated with small molecules, ligands, or surfactants to stabilize suspensions (e.g., citrate-capped Au nanoparticles).**
- **Functionalized nanomaterials: Nanoparticles with covalently or strongly bound chemical groups to impart new surface properties (e.g., carboxylated CNTs, amine-functionalized silica).**
- **Stabilized nanomaterials: Suspensions where stability is maintained by electrostatic or steric repulsion, achieved via capping agents, polymers, or ionic strength control.**

Characterization methods

There is a wide variety of analytical methods to assess surface modification and stability of nanomaterials, and the interested reader is referred to the extensive body of published literature. Briefly, commonly applied methods include:

- **Microscopy methods:** Transmission electron microscopy (TEM), scanning electron microscopy (SEM), and atomic force microscopy (AFM) provide visualization of nanomaterial morphology, shell thickness, and, in some cases, aggregation state.
- **Spectroscopy methods:** Fourier transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), and nuclear magnetic resonance spectroscopy (NMR) allow identification of surface functional groups, chemical composition, and chemical states of surface-associated species.
- **Scattering and sizing methods:** Dynamic light scattering (DLS) and nanoparticle tracking analysis (NTA) are commonly used to probe hydrodynamic size, size distribution, aggregation state, and colloidal stability.
- **Electrokinetic methods:** Zeta potential measurements provide information on surface charge and are widely used as an indirect indicator of surface modification and colloidal stability.
- **Optical methods:** UV–Vis spectroscopy can be used to monitor aggregation, surface functionalization, or ligand exchange processes, particularly for plasmonic or strongly absorbing nanomaterials.
- **Chemical and thermal methods:** Thermogravimetric analysis (TGA), elemental analysis, or inductively coupled plasma–based techniques (e.g., ICP-OES/MS) enable quantification of surface coatings, grafting density, or compositional changes.

For practical laboratory applications, a combination of complementary methods is typically required to obtain a reliable and comprehensive assessment of nanomaterial surface modification and stability.

What is nanowaste?

There are currently no fully agreed-on international definitions for nanomaterials, which poses legal and practical challenges that have been reviewed in detail by Miernicki and co-workers[53]. As a consequence, no harmonized definition exists for nanowaste either[13]. Nevertheless, a general consensus holds that waste containing nanomaterials (hereafter termed nanowaste) includes manufacturing residues from nanomaterial production, end-of-life nano-enabled products, and waste unintentionally contaminated with nanomaterials[15]. Arbitrary size cut-offs in the definitions of nanomaterials can exclude hazardous nanowaste from proper disposal. For example, according to European regulations,[16,54] a nanomaterial is defined as a "natural, incidental or manufactured material containing particles […] where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1–100 nm." This definition covers typical nanomaterials such as fullerenes, graphene flakes, and single-walled carbon nanotubes with one or more external dimensions below 1 nm (**Supplementary Figure S1**), but excludes other hazardous particles such as inhalable quartz dust between 300 nm and 4 µm in diameter that can trigger silicosis[55], or other respirable fibers[30]. To address this limitation, more inclusive definitions have been proposed[30] and are already in use. For example, the Swiss Federal Office of Public Health and the Federal Office for the Environment also include particles up to 500 nm in diameter and certain respirable fibers up to 10 µm in diameter[16]. For sufficient protection against occupational exposure when managing nanowaste, we recommend using this broader, more inclusive definition of nanomaterials, because size-related physicochemical phenomena linked to toxicological effects are also possible above the threshold of 100 nm[43,56].

In-house treatment and recycling to prevent upstream nanowaste

Intact nanomaterials that cannot be degraded or otherwise treated to lose their nano-specific properties should be disposed of as regular, preferably aqueous, nanowaste, as discussed in the main text. In other cases, based on the principle of source separation and because external treatment of nanowaste is both energy-intensive and costly, facilities that produce nanomaterials should consider reducing the amount of nanowaste by applying in-house treatments[37]. In practice, this means treating nanowaste at the point of origin so that it loses its nano-specific properties, for example, by dissolution in acid or by high-temperature sintering[37]. A more recent development is the possibility to recover and recycle nanomaterials from nanowaste[47,49]. In principle, degradable nanomaterials can be treated in-house by physical, biological, or chemical methods (**Supplementary Table S2**). In practice, however, many available treatments are too laborious for small laboratory volumes, or they require specialized furnaces or highly hazardous reagents, making them impractical. **Supplementary Table S2** therefore provides, in addition to degradation methods, an assessment of the feasibility of in-house treatment for both small and large quantities of nanomaterials. Once degradation is confirmed and the nanoscale properties have been lost, the resulting materials are equivalent to regular chemical waste, whether liquid or solid. Examples of feasible in-house treatments include the dissolution of nanoscale metallic iron, iron oxides, zinc oxide, copper (oxide), and silver nanomaterials in acids. Silica nanoparticles hydrolyze in the presence of strong bases such as potassium hydroxide[52] and, more slowly, even in water[57]. Depending on concentrations and the economic value of the materials, recycling may also be considered for precious nanomaterials such as gold[47,49]. For instance, metallic gold can be dissolved using hydrochloric acid and hydrogen peroxide (or nitric acid), recovering gold cations for reuse. Ten liters of gold nanowaste at a concentration of 200 mg L^{-1} contain approximately 2 g of gold, currently worth about 214 USD (August 2025). However, chemical degradation methods also have significant drawbacks, including the use of highly hazardous reactants (e.g., hydrofluoric acid to dissolve titanium dioxide) and the generation of corrosive secondary wastes, which then require their own costly disposal. In such cases, it is preferable to work with a specialized waste treatment company. Another factor is the cost of human labor, which, depending on the country, can make small-scale in-house treatment uneconomical. The recommendations for or against in-house treatment given in **Supplementary Table S2** take these considerations into account. When handling dilute aqueous suspensions, emulsions, or colloidal dispersions, it is advisable to first precipitate and concentrate the nanoparticles to make the volumes manageable. For brevity, the following text refers to all these as “suspensions.” Practical options include precipitation using salts such as sodium chloride, centrifugation with resuspension in a smaller volume, or evaporation of the solvent in small-volume cases where the energy cost is acceptable. This can be done with a rotary evaporator or by distillation in a fume hood equipped with a HEPA filter (for non-fibrous nanomaterials only). For any in-house treatment of a new type of nanomaterial, the effectiveness of the method must be analytically validated. Absence of nanoscale fractions should be confirmed using established techniques such as electron microscopy, dynamic light scattering, or single-particle mass spectrometry. Some nanomaterials are highly persistent and cannot be easily degraded. Examples include non-porous titanium dioxide (with some exceptions[57,58]), silica, cerium dioxide nanoparticles, and fullerenes[3,59,60]. For instance, carbon nanotubes (CNTs) have been estimated to have a half-life of 80 years under ambient conditions even in the presence of horseradish peroxidase, one of the rare enzymes capable of catalyzing their degradation[61]. Nanocrystals of CNTs and fullerenes have been found to persist in ice core melt samples for more than 10,000 years[65]. While most carbonaceous nanomaterials combust above 800 °C,[48] certain CNTs and other nanoparticles such as cerium dioxide can survive temperatures up to 1000 °C[3,62]. These conditions are not met in typical municipal waste incineration plants, which operate at ~600–750 °C. As a result, nanowaste containing such materials, or other nanomaterials with unknown decomposition thresholds, must be treated in specialized high-temperature furnaces operating at >1000 °C, typically 1200–1300 °C[33]. This destroys most substances and reduces the risk of toxic byproducts such as dioxins, though certain nanomaterials may still survive the process[53,63]. From a sustainability perspective, aqueous liquid nanowaste requires energy-intensive water removal before incineration. Some water, however, can be advantageous for high-thermal-load chemical waste incineration plants, as evaporation cools the furnace. Applying the “4R” principles (reduce, reuse, repair, recycle) to nanowaste remains particularly challenging. As of 2024, reuse and recycling are only feasible in rare cases and are generally not cost-effective in research laboratories, which typically produce diverse small quantities of untested nanomaterials. Moreover, unlike regular chemical waste such as organic solvents, which burn exothermically and allow partial energy recovery, nanowaste requires higher combustion temperatures to destroy its inert nanomaterial content[33,48,62]. Neutralizing nanowaste containing persistent nanomaterials therefore remains highly energy-intensive and costly. In the long term, avoiding the generation of such persistent nanowaste should be a priority. In our laboratories, the amounts of nanowaste are generally too small for effective in-house treatment. Instead, nanowaste is separated into subcategories such as aqueous and organic waste (**Figure 2, Table 1**) and collected by a waste treatment company. Depending on its physical form (liquid or solid), heavy metal content, pH, and content of halogenated solvents or other hazardous substances, the company applies treatments such as neutralization, precipitation, filtration, and drying. Ultimately, if labeled as nanowaste, the materials are incinerated at 1200-1300 °C[37]. Hazardous fumes are filtered, and the ashes are disposed of in landfills[63].

Specific rules for flammable nanowaste

Special attention is required for flammable nanowaste that can generate explosive atmospheres. Loose, flammable nanoparticle powders are particularly risky because they may cause dust explosions. In Europe, such situations fall under the ATEX norms (French: ATmosphères EXplosibles), which regulate explosive atmospheres in both gases/vapors and dusts. ATEX distinguishes three zones for gases and vapors (zones 0–2, with 0 meaning an explosive atmosphere is always present and 2 meaning it is rarely present) and three zones for dust (zones 20–22, with 20 indicating constant risk and 22 indicating rare risk). Discussing the full ATEX regulations across different countries, especially for explosive dusts, is beyond the scope of this article. The key point for laboratories is that fire and explosion protection requires strict limits on the storage capacity of highly flammable nanowaste[36]. In typical research environments, flammable liquids should only be stored in bottles of up to 3 L, and total volumes at the workplace should not exceed 15 L. Smaller quantities of flammable nanowaste can be kept in a non-combustible, well-ventilated storage cabinet. For larger volumes (>100–1000 L), ventilated fireproof storage cabinets with retention trays must be used, while ensuring compliance with the laboratory's approved storage limits.

Details on labeling nanowaste

Internationally, two regulations, GHS and ADR, apply to labeling nanowaste. The GHS is relevant for researchers who directly work with and store nanowaste in the laboratory and adhering to the ADR is the responsibility of the person, usually the local safety officer, who organizes the transport of nanowaste to the waste treatment company. The ADR labels consist of a set of globally harmonized pictograms and UN codes that must be well visible during transport on the outer packaging (for example, the cardboard box, barrel, or bin) at all times (**Figure 3c and Figure 5**, part within blue dotted lines). No specific waste UN codes or pictograms exist for nanomaterials, but the existing pictograms and UN codes can warn of the different hazards posed by the waste[34]. The absence of a nano-specific pictogram remains an unresolved issue. Existing toxicity pictograms do not warn downstream handlers of nanospecific risks such as aerosolization, and therefore, a dedicated pictogram would be valuable. Until such a symbol is officially adopted, we recommend applying the precautionary principle by using existing toxic pictograms in combination with explicit "nanowaste" labeling, so that downstream personnel are alerted to nanospecific hazards and the need for respirator use.

The UN code 3291 (clinical waste, unspecified, not otherwise specified (n.o.s.)) can serve for solid nanowaste mixed with non-sterile biohazardous material. The UN codes 3288 (toxic solid, inorganic, n.o.s.) or 2811 (toxic solid, organic, n.o.s.) principally cover non-biohazardous solid nanowaste that contains primarily inorganic or organic nanowaste. If the primary hazard of the solid nanowaste is not its biohazard or (potential) toxicity but (also) its corrosiveness, flammability, or oxidative nature, then the UN codes 1325, 2926, 2928, 2930, 3086, 3179, 3180, or 3290 come into question.

Liquid nanowaste is usually labeled depending on the solvent present in excess. For liquid nanowaste suspended in water, the UN code 3287 (toxic liquid, inorganic, n.o.s.) comes into question. The UN codes 1992 or 2929 can serve for liquid nanowaste suspended in organic solvents, which are typically toxic and flammable. Depending on the primary hazard of the liquid waste, as for the solid waste discussed above, the most important UN codes that must also be considered are 2810, 2927, 3287, 3289, 3381-4, 3387-3390, 3488, or 3489. Finally, additional national regulations may apply in addition to the GHS and ADR regulations. In Switzerland, for example, another six-digit waste code is required for transport. While there are no official codes for nanowaste, a Swiss governmental recommendation is to use for not otherwise classifiable nanowaste the code 16 03 03 for inorganic waste and 16 03 05 for organic waste (**Figure 5**, bottom two lines)[37,41]. As this guideline mainly addresses researchers working in the laboratory, we have focused on explaining the basics of labeling nanowaste for storage according to the GHS.

On the permeability of protective gloves

Appropriate glove use is a critical element of safe nanowaste handling. For nanomaterials with known lower hazards, single-gloving is generally sufficient, while double-gloving is recommended when handling nanomaterials of unknown or higher hazard potential[4,64,65]. The glove material must be impermeable to the solvents used, with a sufficiently long penetration (breakthrough) time. This information can usually be obtained from the solvent's SDS or from glove–chemical compatibility charts[44,66].

The most commonly available disposable laboratory gloves are made of polyvinyl chloride (vinyl), natural rubber (latex), or nitrile butadiene rubber (nitrile). These materials offer good abrasion, cut, and puncture resistance and are expected to provide several hours of protection against nanomaterial penetration. However, their breakthrough times for many organic solvents are very short, typically only a few minutes. For example, ethanol penetrates vinyl gloves in ~1 min, latex gloves in ~2 min, and nitrile gloves in ~8 min[67]. For more hazardous solvents such as benzene or chloroform, penetration times are even shorter, e.g., <6 min and ~4 min, respectively, for nitrile gloves[71]. While glove penetration by nanomaterials themselves is expected to occur only slowly, the primary risk arises from solvents that may transport nanomaterials into or through the glove material. Therefore, solvent compatibility must always be considered jointly with nanowaste hazards. Thus, vinyl, latex, and nitrile gloves primarily protect against incidental splashes and must be replaced immediately (vinyl and latex) or within minutes (nitrile) after contact with organic solvents, depending on the chemical. When working directly with nanowaste contaminated with hazardous organic solvents, thicker barrier polymer gloves, such as ethylene vinyl alcohol (EVOH) or fluorocarbon (Viton®), provide more reliable protection[44,66]. In all cases, glove choice should be guided by a risk assessment considering both the nanomaterial and the solvent. Gloves must be replaced immediately if contaminated, and double-gloving offers an additional safeguard when handling unknown or high-hazard nanowaste.

Case studies

Disclaimer: These case studies are inspired by real-life examples from research laboratories in Switzerland working with nanomaterials. The characters are entirely fictional, and any resemblance to actual persons or events is coincidental. We have attempted to describe the following procedures as practically as possible to allow other laboratories to adapt them quickly and, if not, at least spark a constructive discussion. The procedures will need updating in light of new findings. The treatment of nanowaste and the corresponding legal requirements differ from country to country and institution to institution, and no universal rule currently applies. Therefore, these case studies may not be transferable to certain countries or laboratories, and priority should always be given to the national and institutional environmental health & safety guidelines, especially when handling spill containment or unknown samples. Most importantly, the following aspects should always be considered: a) Is it reasonable to perform the manipulations? b) Is the person trained to handle the chemicals, and are the working conditions met for a safe process?

1. Orphaned samples disposal

Case: **In a research laboratory specializing in synthesizing and characterizing gold nanoparticles, Ph.D. student Martin must clean out the cold room. Martin finds an old cardboard box with clear 200 mL Schott bottles containing orange-red liquid sealed with heavily corroded caps. The label on the box says, "NP stock 03/2015 CA". What should Martin do?**

Answer: **As the bottles' contents are unknown, Martin should avoid opening them and only touch them wearing gloves, goggles, and a laboratory coat. An educated guess about their content can be made by looking up the names of the laboratory members in 2015 with the initials 'C.A.'. If the owner cannot be identified and contacted, it might be possible to determine the contents of the bottles with the (former) supervisor of the laboratory. If the substance remains unknown despite all investigations, it should be treated as such. It will be isolated from other waste and considered unknown waste containing nanoparticles. This information will be given to the institutional safety officer and the company handling the waste.**

If a cross-check of the historical information allows a reasonable estimate of the family of compounds composing the unknown waste, it needs to be treated with caution, taking preventive safety measures and in agreement with the laboratory manager and the safety officer. In the present case, the red content of the bottles is, based on the research activities of the lab and the routinely used abbreviation 'NP' for 'nanoparticles, strongly indicative of an aqueous or ethanolic suspension of gold nanoparticles. As the caps are corroded, there may also be, irrespective of the label on the bottle, corrosive aqua regia in the bottles, for example, because the former owner tried to dissolve gold nanoparticles in the bottles. Aqua regia can generate toxic, explosive fumes and cause a pressure buildup. The bottles should be gently (to avoid bursting bottles) transferred into a secondary container such as a large chemically inert bucket with a lid (to prevent spills and the spreading of fumes during transport) and carefully carried and placed into an empty and well-ventilated fume hood without ignition sources. An all-round absorbent such as Chemizorb® should be placed within reach for potential spills. Only the institutional safety officer, equipped with full PPE and appropriate shielding, may carefully attempt to open the bottles in the fume hood to release possible pressure and conduct a preliminary pH test using disposable strips. If the pH is close to neutral, the bottles likely contain gold nanoparticles. This can be confirmed by measuring the particle size distribution of a water-diluted subsample in a parafilm-sealed disposable cuvette by dynamic light scattering. Dilution will also clarify if the liquid is miscible with water. The identified water-miscible (likely gold) nanoparticle suspension can be discarded in an aqueous nanowaste container.

If the liquid in the bottles was highly acidic and under pressure, chances are high that the bottles contain aqua regia or another mix of acids and oxidizers. The contents of the bottles can then be slowly and carefully poured on ice for dilution, with constant temperature monitoring, and the resulting liquid can be neutralized (to be confirmed with pH strips) using a concentrated sodium hydroxide solution. The final solution can further be checked for the presence of nanoparticles using dynamic light scattering, as described above. Without detectable nanoparticles, the solution can be disposed of in a liquid aqueous chemical waste collection container.

2. *TEM grid disposal*

Case: Professor Smith has kept ~200 transmission electron microscopy (TEM) grids containing nanomaterial-exposed, resin-embedded cell sections from a published study. Sample preparation involved 0.3 M sodium cacodylate buffer, 2% osmium tetroxide, and staining with 0.02 M lead citrate and ferrocyanide. These reagents introduce arsenic, lead, cyanide, and osmium tetroxide, all highly toxic. Concerned, Prof. Smith asks the safety officer for disposal guidance.

Answer: The safety officer first determines the waste category using the institute's nanowaste decision matrix (**Figure 2**). The samples contain nanomaterials and hazardous chemicals (arsenic, lead, cyanide), but the cells are no longer biohazardous, having been chemically fixed and resin-embedded. Thus, they qualify as solid nanowaste with hazardous chemicals. Because the nanomaterials are embedded in a polymer matrix, release risk is reduced, but unknown leaching rates justify applying the precautionary principle: the grids should still be treated as solid nanowaste and hazardous chemical waste. The toxic reagents must be considered individually[1,68]:

- Osmium tetroxide is no longer present; during sample preparation, it has reacted to OsO_2, which has negligible acute toxicity but possible long-term effects.
- Ferrocyanide is a stable, food-grade iron–cyanide complex, not a major concern[69].
- Sodium cacodylate and lead citrate remain critical: ECHA classifies sodium cacodylate as "very toxic to aquatic life with long-lasting effects, and suspected of causing cancer," and lead citrate as "may damage the unborn child."

A conservative, worst-case calculation estimates maximum reagent content per grid: ~1.0 ng OsO_2, ~0.01 ng sodium cacodylate, and ~0.4 ng lead citrate. For 200 grids disposed into 1 kg of trash, final concentrations would be ~0.2 µg kg^{-1} (OsO_2), 0.02 µg kg^{-1} (sodium cacodylate), and 0.1 µg kg^{-1} (lead citrate). These values are lower than typical environmental levels (e.g., OsO_2 in sediments: 10–300 µg kg^{-1})[70], and, when compared to acute toxicity data (EC_{50}: 4 mg kg^{-1} for sodium cacodylate in mice; 100 mg kg^{-1} for lead citrate in rats), yield safe risk quotients[1] (<0.01 even with a safety factor of 100). Despite the low hazard based on quantity, the precautionary principle applies because nanoparticles are present, and sodium cacodylate and lead citrate have serious toxicological profiles. Therefore, the TEM grids must be disposed of as solid nanowaste with hazardous chemicals, not household trash. Final disposal should be coordinated with the institutional safety officer to ensure compliance with local hazardous waste regulations.

When transmission electron microscopy grids used for nanomaterial characterization are discarded, they can represent a small but concentrated nanowaste source. To evaluate potential environmental risks, a first-tier calculation using the risk quotient (RQ)[71] can be applied, following established environmental risk assessment practice:

RQ = PEC / PNEC

(Risk Quotient = Predicted Environmental Concentration divided by Predicted No-Effect Concentration)

If RQ < 1, the material is considered to present a low level of concern; if RQ ≥ 1, the material should be treated as hazardous until further data are available.

3. *Pilot-scale nanoparticle disposal*

Case: Senior scientist John is conducting nanoagrochemical field trials and produces 100 L batches of aqueous silica nanomaterial suspensions (~20 g silica L^{-1}, ~80 nm). One batch is faulty due to a bad ammonia reagent, yielding an unacceptably broad particle size distribution that must be discarded. Up-concentration by centrifugation is impractical at this scale. John asks how to safely dispose of the 100 L batch.

Answer: Consulting the institutional nanowaste decision matrix (**Figure 2**), John notes that bulk silica is non-toxic and the main hazard arises from nanoscale properties. He identifies two options:

- Scenario 1: Discard the suspension directly as aqueous nanowaste.
- Scenario 2: Treat in-house to eliminate nanospecific properties, then dispose of it as regular aqueous chemical waste.

Scenario 1 (direct disposal): Because the batch exceeds 50 kg (the legal definition of small-scale disposal[41]), extra checks and coordination with the safety officer are required. John evaluates chemical compatibility to avoid exothermic reactions when mixed with other waste. He confirms the silica nanoparticles are inert[57,58]and unlikely to react violently. From the synthesis yield, he expects <1% byproducts, likely residual tetraethoxysilane and ammonia. SDS data indicate tetraethoxysilane is not problematic at trace levels, but ammonia could be. The suspension's pH is 7.8, indicating only slight alkalinity, attributable to residual ammonia. Since the central nanowaste container is strongly acidic (pH 2), mixing could generate heat; John therefore avoids this risk by decanting the suspension into fresh 10 L waste containers. Wearing full PPE (lab coat, gloves, goggles, FFP3 respirator), he prepares the containers for waste collection. Because of the volume, the safety officer completes additional steps:

- a) adds the mandatory transport labels ("special waste / Sonderabfälle / déchets spéciaux / rifiuti speciali"),
- b) applies the Swiss transport waste code "16 03 03" (inorganic waste containing hazardous substances)[37],
- c) attaches in addition to the black-and-white GHS pictograms for storage precautionary ADR symbols ("Toxic substances" and "Miscellaneous dangerous substances and articles"),
- d) completes the official consignment note with weight and ID number.

Scenario 2 (in-house treatment): Swiss guidelines[37] recommend on-site neutralization where feasible. John opts to dissolve the silica nanoparticles by raising the pH. Literature shows silica dissolves rapidly at pH >10.7[57,72], with silica nanoparticles (pKa ~2–4)[73] having a half-life of ~66 d at pH 7[57] (if synthesized *via* tetraethoxysilane hydrolysis). John carefully increases the suspension to pH 10.8 by slowly adding NaOH pellets under continuous stirring, monitoring pH, temperature, and concentration. Once the suspension becomes transparent and stable at pH 10.8, he verifies nanoparticle absence by dynamic light scattering (no scattering signal) and TEM (no residual particles). With nanospecific properties removed, the waste can safely be discarded as common aqueous basic chemical waste.

4. Nanoparticle spill

Case: On a Friday evening, Master's student Jane is cleaning up her bench space. She needs to discard a strongly alkaline aqueous carbon nanotube (CNT) stock suspension. Wanting to finish quickly, she adds a large amount of concentrated hydrochloric acid all at once to neutralize it. The violent reaction causes the suspension to boil, and ~500 mL spill out of the Erlenmeyer flask into the fume hood, onto her gloves, lab coat, and the floor. She calls the safety officer for help.

Answer: The safety officer immediately highlights the danger of fibrous nanomaterials and instructs everyone to leave the area. Jane removes her contaminated PPE and disposes of it in a white solid nanowaste bucket. Because her sweater sleeves were soaked, she removes the garment and rinses her arms thoroughly under running water for 15 minutes. With no visible skin reaction, no immediate medical treatment is required, but the sweater is irreversibly contaminated and must be discarded as solid nanowaste (laundering is not an option due to the risk of cross-contamination).

If the spill had involved larger quantities (>500 mL) or particularly toxic components, the university's spill intervention team would be called. In this case, the small volume allows Jane, her supervisor, and the safety officer to handle it directly (note: this is strongly dependent on local regulation. The responsibility may differ for each country and institution). The main hazards are residual hydrochloric acid and possible CNT aerosolization due to boiling. While the risk of aerosolization is low when CNTs are in suspension, it is not negligible.

All three involved persons wear appropriate PPE: FFP3 respirators, heavy-duty nitrile gloves (cat. III, EN 388/374-certified, >300 mm long, >0.4 mm thick), disposable nonwoven lab coats or chemical aprons, and safety goggles. They use wet paper wipes to soak up the bulk of the suspension, then clean the contaminated surfaces thoroughly with detergent and water. All used wipes are immediately discarded into the solid nanowaste bucket, which is sealed after use. The contaminated PPE, including the disposable lab coats, is also disposed of in the same way. Everyone then washes hands and face thoroughly with soap and water.

Jane files an accident report and is advised to monitor her health for any skin changes over the following week, reporting to her doctor and the safety officer if needed. As a precaution against delayed CNT aerosolization, the safety officer locks the laboratory over the weekend, allowing any airborne particles to settle. On Monday morning, they wet-mop all surfaces and the floor again while wearing full PPE, disposing of all cleaning materials as solid nanowaste.