High Accuracy printed electronics down to µm size, for Organic Large Area Electronics (OLAE) Thin Film Transistor (TFT) and Display Applications

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Prepared by: Susanne Resch, Clemens Wolf & Matiss Reinfelds (BNN)

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[1] https://cordis.europa.eu/project/id/646296
[2] https://cordis.europa.eu/project/id/646155/de
[3] https://cordis.europa.eu/project/id/814401/
[4] https://www.nanosafetycluster.eu/

2 DOCUMENT CONTROL

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v1.0	Document creation	N.a.	17.02.2023	BNN
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3 EXECUTIVE SUMMARY

This report outlines the findings within the nanosafety assessment of printed organic electronics, more specifically, ink formulation development and processing. First, a brief introduction to nanosafety in industrial and research laboratories is provided, followed by a literature review on possible exposure scenarios to various nanomaterials relevant to the research performed in this work package (by all HI-ACCURACY partners). Inhalation and dermal exposure are the focal points of this review. Results from on-site measurements of (i) particle number concentration and (ii) volatile organic hydrocarbons (e.g., solvents) in the research laboratories of one of the project partners are presented. Additionally, a tool for the selection of alternative (more sustainable) solvents for printed electronics is described, followed by safe work procedure and best practice guidelines.

It could be established that the particle number concentration during the various printing processes is at a very low level, as are volatile organic hydrocarbons. At the same time, comprehensive literature review revealed a lack of availability for high-quality measurement data in regard to worker exposure to nanomaterials in R&D laboratories. Thus, in the here presented recommendations we encourage industries to perform such measurements and provide the data publicly to be available and accessible to further drive the knowledge on safety of nanomaterials.

4 CONTENTS

5 INTRODUCTION

Inks take a central role in the area of printed organic electronics. Researchers are continuously elaborating to find optimal ink formulations for various applications. Silver nanoparticle inks are already established as prime options for production of conductive layers (conductors). Nonetheless, at the same time various choices depending on project specifications are to be made. These include for example which exact nanoparticles are used (phys-chem specification), which solvents and additives are used and which printing technology is exploited. The selections and choices further translate into other layers of electric circuits being developed and include material selection and defining processing conditions. In case of thin film transistors (TFT), the semiconductor and dielectric (insulator) layers need to be produced. In this work package inks for both of these layers (semiconducting and dielectric) were formulated and tested, including various coating techniques. For each of these layers, work with nanomaterials can be envisioned, thus in the following report the relevant nanosafety topics are addressed. Additionally, solvent selection for ink formulations is a crucial step and poses not only scientific, but also environmental and safety challenges. To better meet the growing demand for more sustainable solvent selection in the field of printed electronics, an online tool is also described.

After a brief introduction about safety aspects of industrial processes involving nanomaterials, the current knowledge on possible exposure scenarios, relevant to the activities performed in this work package, is summarised.

6 NANOSAFETY ASSESSMENT

Per the current definition, manufactured particles, where 50 % or more of the particles in at least one dimension are in the size range between 1 to 100 nm in their number size distribution, are considered as engineered nanomaterials[5,6]. Regarding regulatory frameworks for nanomaterials, the same measures and regulations which are concerning chemicals are applied. However, information and data availability regarding risks of nanomaterials are much scarcer than for chemicals. Hence general precaution should be applied, especially in settings of industrial and large-scale production to also ensure occupational safety (1). In respect of exposure limits there are no set boundary values in place yet, although some suggestions have been brought up (2) and an increasing effort to standardise and regulate nanosafety is emerging (3). While the knowledge on the effects of nanomaterials on human health is not broad, first evidence has shown health implications in animal studies (4). The gravity of the situation becomes especially evident in regard of nanomaterial penetration into the human body. It has been shown that an inverse size-risk relationship is at play. The smaller the particle the more likely it is to cross blood-organ barriers and translocate even further to secondary-target organs (5-8). However, size is not the only factor determining the intra-body mobility, but also the physical properties play a role (8), which are also highly relevant for the pathogenic potential of the respective material. Hence, according to the European Agency for Safety and Health at Work, the general principle for manufactured nanomaterials should be to keep the level of exposure as low as possible, to ensure a low risk even if information on enhanced hazard level would emerge. They further suggest to assume a higher risk for nanomaterials consisting of the same material as its coarser sister materials. To evaluate risk of nanomaterials where data is only scarcely available, the need for predictive assessment methods is enhanced (9), leading to the development of tools such as the Stoffenmanager nano (10). In addition to threats for health, safety considerations warrant the inclusion of other potential injury causing hazards of more imminent nature, such as explosiveness and flammability[7][3]. Regarding occupational safety it is important to assess and monitor possible exposure routes (e.g., inhalation, skin contact, ingestion) and find suitable ways to avoid exposure and limit hazard contact (e.g., substitution of hazard, suitable technical working environment, personal protective equipment, organisational measures including safe work procedures (SWP) and best practices (BP)), not only for immediate handlers but also the broader environment (e.g., consider leakages). In case of hazard exposure there should be plans and operating procedures in place that can be followed.

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[5] https://echa.europa.eu/regulations/nanomaterials

[6] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:275:0038:0040:EN:PDF

[7] https://oshwiki.osha.europa.eu/en/themes/manufactured-nanomaterials-workplace-risks-and-how-manage-them

6.1 EXPOSURE TO NANOMATERIALS

Four major source domains have been identified, within which the vast majority of exposure situations for manufactured nanomaterials occurs (11):

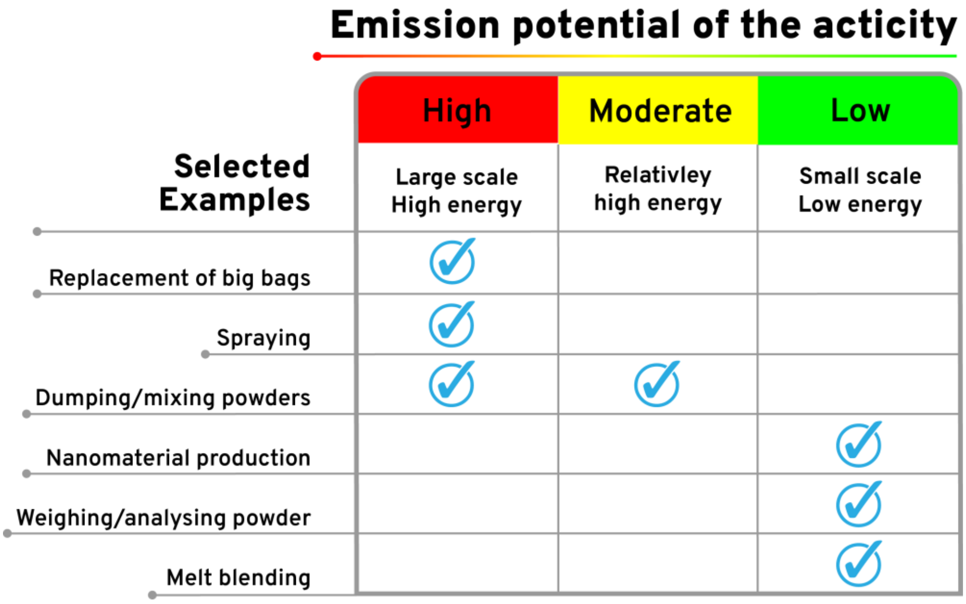
- **Production phase**
  Emissions during the synthesis of nanomaterials (such as release from reactors and leaks through seals and connections)
- **Bulk material handling**
  Handling and transfer of bulk nanomaterial powder (such as emptying bags or scooping)
- **Dispersion of nanoparticles**
  Dispersion of intermediates with highly concentrated nanoparticles (above 25%) or the use of products with relatively low concentrations (below 5%)
- **Fracturing and abrasion at work sites**
  Activities that result in the fracturing and abrasion of end products containing manufactured nanoparticles

These domains serve as a practical tool to initiate the evaluation process to further ensure the safe use of nanomaterials within specific operations in occupational settings. The two common ways of entry/exposure for all these domains are inhalation and dermal uptake. While these exposure routes are potentially occurring in all domains, each process in which nanomaterials are used requires individual evaluation of the likelihood of exposure.

For example, the likelihood of exposure to airborne nanomaterials depending on the performed activity was assessed by Bekker and colleagues by employing 46 measurement surveys with 18 different exposure situations as a basis (12). The activities were categorised in three groups:

- large scale, high energy
- medium energy
- low energy, low scale

Generally, the first category (large scale, high energy) has the largest exposure potential, while the last (low energy, low scale) presents with the lowest potential. For example, replacement of big bags with powdered substance has high emission potential, while weighing small amounts of powder in R&D laboratory settings has a low emission potential (see also, Figure 1). Nevertheless, to obtain large impact on the emission potential the specifics of the respective substance used have to be considered (e.g., if the nanomaterial is embedded into the product, such as in resin used for injection moulding, it will probably have a low emission potential).



Emission potential of the acticity

Selected Examples	High Large scale High energy	Moderate Relativley high energy	Low Small scale Low energy
Replacement of big bags	✓		
Spraying	✓		
Dumping/mixing powders	✓	✓	
Nanomaterial production			✓
Weighing/analysing powder			✓
Melt blending			✓

Figure 1: The emission potential of nanomaterials depends on the type of activity they are used in, as well as the properties of the nanomaterial itself (adapted from Bekker et al. (13)).

However, the same type of activity can lead to a significant variability of exposure, as measurements of mechanical dumping have demonstrated. The powder particle number concentration was found to vary between 0 and 100 000 (cm^3) (12). Thus, when evaluating exposure potential to nanomaterials during a particular process, the contextual situation should always be considered.

Dermal exposure can be the result of direct contact between skin and or deposition from air. However, the latter not being a significant dermal exposure pathway. The most commonly occurring dermal exposure results from skin contact with contaminated surfaces (13). Exposure via inhalation, commonly coincides with additionally increased possibility of dermal and ingestion exposure.

Hurley and coworkers performed a systematic literature review on measured inhalation or dermal exposure to various classes of nanomaterials (14). In Table 1, a summary of various laboratory processes involving nanomaterials relevant to this work package in HI-ACCURACY (pure element metals and metal oxides/their mixtures) is presented, with an estimation on exposure.

Table 1: Exposure to nanomaterials (pure element metals and metal oxides/mixtures) in various laboratory processes (adapted from Basinas et al. (14)).

Process		Pure element metals		TiO_2		Other metal oxides and mixtures	
		Inhalation	Dermal	Inhalation	Dermal	Inhalation	Dermal
Synthesis	Reaction	Yes	Yes	Yes	Yes	No	No
	Work up	Unclear	Unclear	Yes	Yes	Yes	Yes
Handling and transfer	Liquid	--	--	Unclear	Yes	Unclear	Unclear
	Powder	Yes	Yes	Yes	Yes	Yes	Yes
Testing and characterisation		Yes	Yes	--	--	--	--
Weighing and mixing		Unclear	Unclear	Yes	Yes	Unclear	Unclear
Packing		Yes	Yes	Yes	Yes	Yes	Yes
Spraying and finishing related processes		Yes	Yes	Unclear	Yes	Yes	Yes
Cleaning and maintenance		Yes	Yes	Yes	Unclear	Yes	Yes

It is important to point out, that operational conditions play a major role in determining whether exposure occurs or not. For example, inhalation exposure during synthesis of TiO_2 could be prevented by simply closing the fume hood in which the reactor is operating. Status of the reactor doors (open/closed) or presence of leakages increase exposure probability, also when analysing synthesis of “other metal oxides” and “pure element metals”. While inhalation exposure was suggested to be unlikely as long as reactor doors are closed for metal oxides, it is possible if they would be open; for pure element metals it was determined that inhalation was possible even if reactor doors are closed. Overall, the likeliness of the exposure increases if manual handling of nanomaterials is performed. Importantly, for TiO_2 and other metal oxides it has been demonstrated that inhalation exposure is likely even if local exposure controls are in place. This was proven to be ameliorated by using a glove box when working with TiO_2, which minimised the likelihood of inhalation exposure. Additionally, potential surface contamination, which can lead to subsequential dermal exposure, was significantly reduced if the processes were performed in an enclosed systems (14).

The authors of the study concluded that the form and route of exposure to nanomaterials depends more on the activity performed, and less on the nanomaterial itself. Importantly, presence of local exposure control alone is not enough to protect workers from being exposed to nanomaterials. Furthermore, various local exposure controls seem to be more efficient for large/industrial scale processes. Authors of the study speculated, that the reason for this might be advanced experience, training and hazard awareness for workers in large scale production workspaces compared to small scale laboratories. Meanwhile, small and pilot scale processes are often performed in workspaces where other, sometimes unrelated processes are conducted, increasing the overall probability of workers exposure to nanomaterials (14).

Brouwer and colleagues developed a helpful flowchart which can aid in significantly reducing dermal exposure among workers (13).

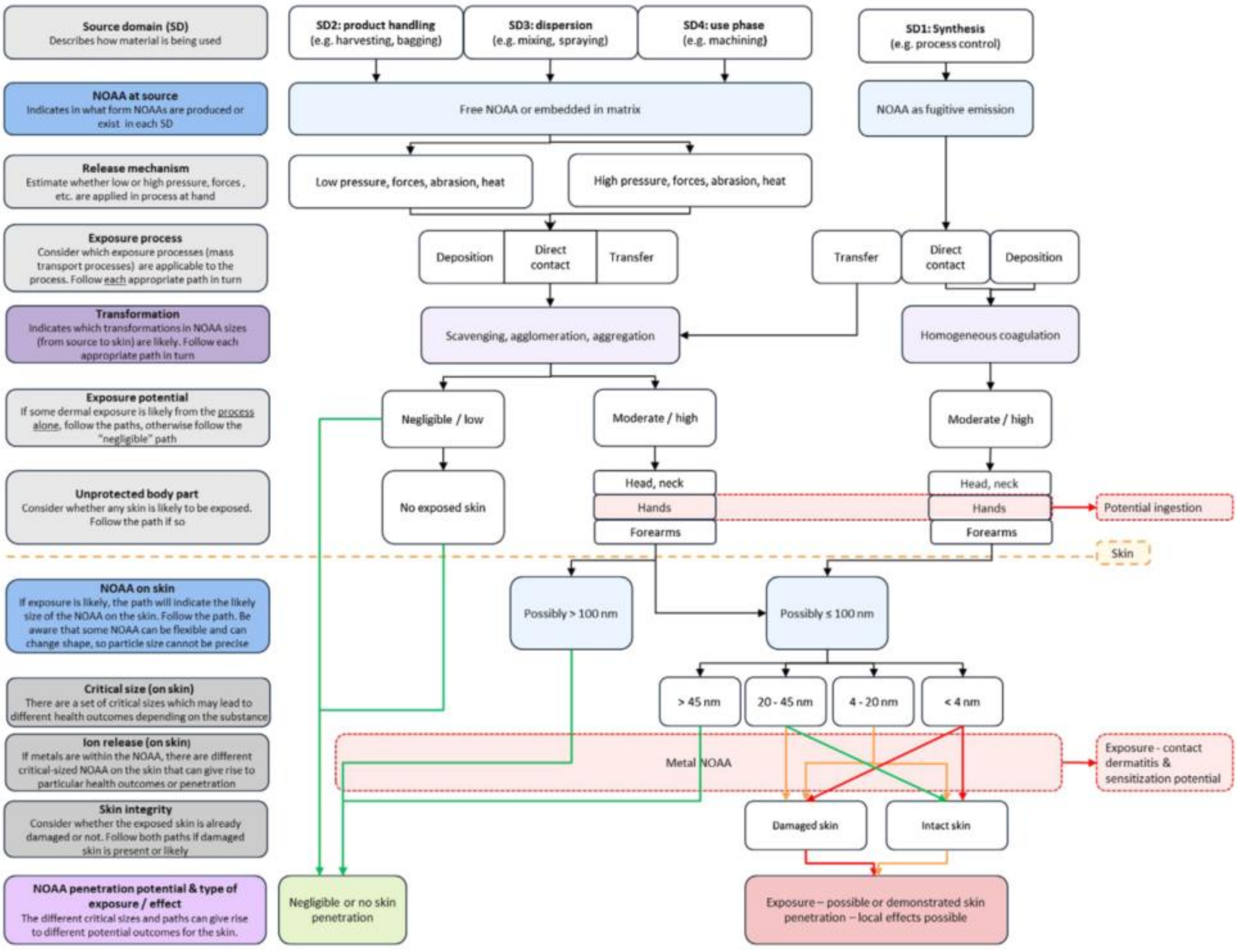


Figure 2. Proposed scheme for screening for potential risks associate with dermal exposure to insoluble (non-flexible) NOAA – reproduced from Brouwer et al. (13) with permission. ©Elsevier.

Finally, it is worth noting, that in this systematic review publications related to the keywords "Nanomaterial", "Exposure" and "Workplace" published from 2000 till 2015 were analysed. Only 107 papers fulfilled the expected quality criteria and were included in the study (14). Consequently, the limited availability of experimental data on exposure to nanomaterials in the workplace, underscores the imperative for further research in this area.

In the section 7. Results, the issued measurements carried out by the "Österreichische Staubbekämpfungsstelle" (ÖSBS, Austrian Dust Control Agency) for HI-ACCURACY can be found.

6.2 SAFE WORK PROCEDURES

An additional tool to ensure safety of industrial processes, are safe work procedures (SWP). These procedures are typically prepared for specific processes or tasks to ensure that employees understand and follow safety protocols to minimise risks and prevent accidents (15). Potential risks are not only associated with nanosafety, but include chemical exposure, electrical hazards, equipment operation, and more. Therefore, it is advisable to prepare SWPs for specific processes or tasks. At the beginning of a SWP development, risk assessment must be performed. When performing this task, it is worth to consider the nine general principles of prevention defined in the European Council directive (89/391/EEC) and if possible, make changes for the procedures accordingly:

1) avoiding risks

2) evaluating risks which cannot be avoided

3) combating risks at the source

4) adapting the work to the individual, especially in regard to the design of work places, the choice of work equipment and the choice of working and production methods

5) adapting to technical progress

6) replacing dangerous by non-dangerous or less dangerous options

7) developing a coherent overall prevention policy, which covers technology, organization of work, working conditions, social relationships and the influence of factors related to the working environment

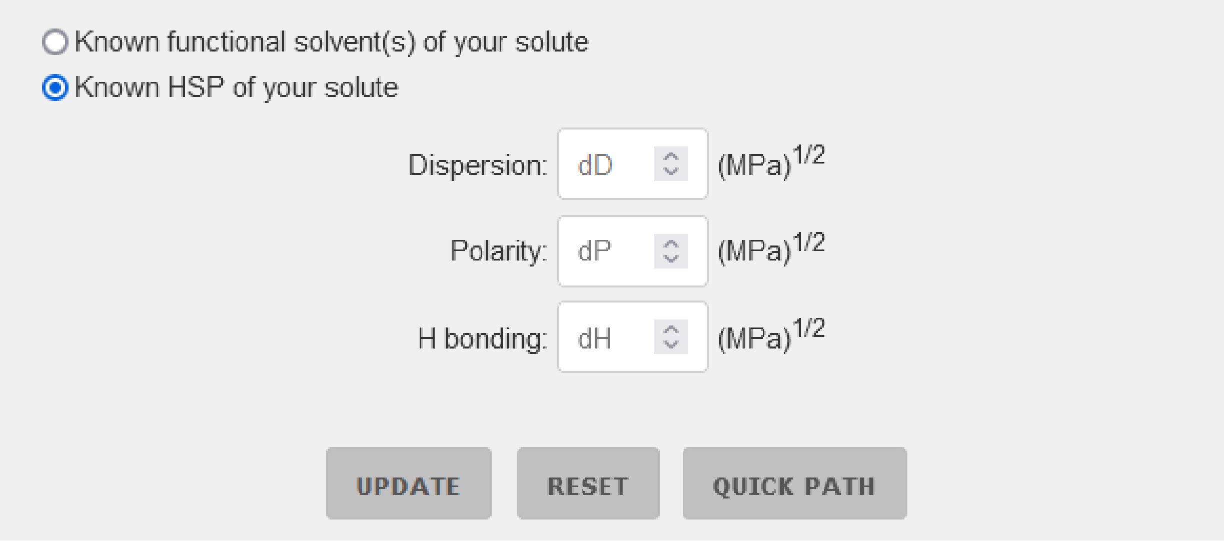
8) giving collective protective measures priority over individual protective measures

9) giving appropriate instructions to workers

Our recommendations for how to develop ideal SWPs and how to ensure their effective function are given in the section 10. Recommendations.

6.3 SUSTAINABILITY CONSIDERATIONS: SELECTION OF GREEN SOLVENTS

A broad range of solvents are used for ink formulations, including water and other green choices. Obviously, the array of solvents which can be used will depend on other components of the ink. Finding a suitable green solvent can be challenging when a layer of unpolar organic polymers needs to be printed (16). Nonetheless, the inks used in the process often present with major safety (17, 18) and/or sustainability concerns (19). Hence, efficient replacement of critical solvents is warranted. The decision process for solvent replacement can be supported by use of various tools such as those developed by AstraZeneca (20), Pfizer (21), GlaxoSmithKline (22, 23) and Sanofi (24). When it comes to printing inks, solubility is not the sole consideration; ink-substrate wetting, ink-film formation, and solute-film drying during the printing/coating procedure also play significant roles. In line with this, Edman and coworkers have recently released a free online tool[8] to support users in identifying green solvents for printed electronics (25). It is based on the Hansen solubility parameters, which allow for numerical estimation of the famous “like-dissolves-like" principle (26). As an input for the tool, the currently used solvent (also naming multiple solvents is possible and increases chances of finding a good match) or the known Hansen solubility parameters (dispersion, polarity and H-bonding) are submitted (see Figure 3).



○ Known functional solvent(s) of your solute

● Known HSP of your solute

Figure 3: Interface for the entry of Hansen solubility parameters to search for better alternatives for solvents using the “Green Solvent Selection Tool” (https://green-solvent-tool.herokuapp.com/).

The tool promptly suggests alternatives ranked in a table based on Ra (the effective separation between two solvents in the 3D Hansen solubility space). For example, if the toxic solvent ethylene glycol is used as the original solvent, one of the suggested alternatives is the non-toxic glycerol (Figure 4).

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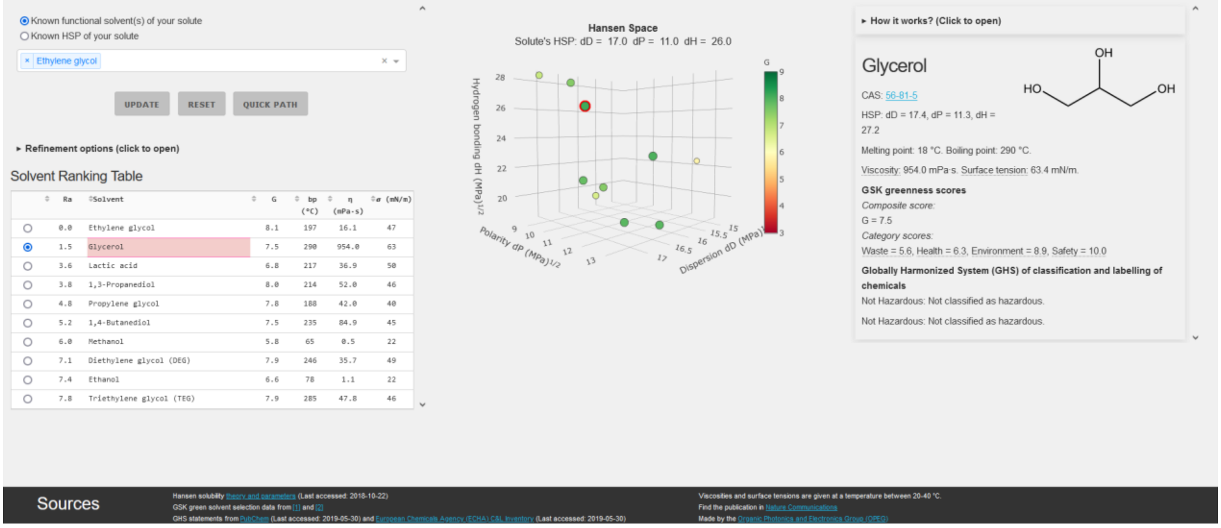
[8] https://green-solvent-tool.herokuapp.com/



● Known functional solvent(s) of your solute
○ Known HSP of your solute

Ethylene glycol

Solvent Ranking Table

	Ra	Solvent	G	bp (°C)	η (mPa·s)	σ (mN/m)
○	0.0	Ethylene glycol	8.1	197	16.1	47
●	1.5	Glycerol	7.5	290	954.0	63
○	3.6	Lactic acid	6.8	217	36.9	50
○	3.8	1,3-Propanediol	8.0	214	52.0	46
○	4.8	Propylene glycol	7.8	188	42.0	40
○	5.2	1,4-Butanediol	7.5	235	84.9	45
○	6.0	Methanol	5.8	65	0.5	22
○	7.1	Diethylene glycol (DEG)	7.9	246	35.7	49
○	7.4	Ethanol	6.6	78	1.1	22
○	7.8	Triethylene glycol (TEG)	7.9	285	47.8	46

Solute's HSP: dD = 17.0 dP = 11.0 dH = 26.0

Glycerol

CAS: 56-81-5

HSP: dD = 17.4, dP = 11.3, dH = 27.2

Melting point: 18 °C. Boiling point: 290 °C.

Viscosity: 954.0 mPa·s. Surface tension: 63.4 mN/m.

GSK greenness scores

Composite score:
G = 7.5
Category scores:
Waste = 5.6, Health = 6.3, Environment = 8.9, Safety = 10.0

Globally Harmonized System (GHS) of classification and labelling of chemicals

Not Hazardous: Not classified as hazardous.

Not Hazardous: Not classified as hazardous.

Sources

Hansen solubility theory and parameters (Last accessed: 2018-10-22)
GSK green solvent selection data from [1] and [2]
GHS statements from PubChem (Last accessed: 2019-05-30) and European Chemicals Agency (ECHA) C&L Inventory (Last accessed: 2019-05-30)

Viscosities and surface tensions are given at a temperature between 20-40 °C.
Find the publication in Nature Communications
Made by the Organic Photonics and Electronics Group (OPEG)

Figure 4: Exemplary use of the “Green Solvent Selection Tool” (https://green-solvent-tool.herokuapp.com/) using ethylene glycol as a test solvent.

Naturally, any newly chosen solvent should be capable of dissolving the respective substance. The probability of another solvent dissolving the same given substance is increasing with lower Ra values. For example, Ra value of glycerol to ethylene glycol is 1.5, while it is 16.1 for 1-octanol. In addition to their ranking according to Ra, properties of the various solvents (sustainability score (G), boiling point (bp), viscosity (η) and surface tension (σ)) is provided. If an alternative solvent is selected from the list, more information about it can be easily accessed (such as, chemical structure, physical properties, specific classification and labelling according to the Globally Harmonised System (GHS)). To refine the output alternatives the enhanced search option allows for setting ranges of properties (bp, η, σ) to ensure proper function of the ink in the printing process. Additionally, distinct hazardous substances based on their label can be excluded and relevant categories selected, which feed into the G value calculation. These include waste management options, health and environment impact and safety issues.

7 RESULTS

7.1 MEASUREMENTS REGARDING EXPOSURE TO NANOPARTICLES IN HI-ACCURACY

To assess exposure levels to nanoparticles during printing processes within HI-ACCURACY, the “Österreichische Staubbekämpfungsstelle” (ÖSBS, Austrian Dust Control Agency) was commissioned to carry out workplace measurements. To that end, determination of the particle number concentration of ultrafine aerosol particles and nanoparticles (including volatile organic hydrocarbons (VOC)) was carried out. Sampling was performed for ESJET and ink jet printing systems (both under fume hood). In the respective laboratory a supply and exhaust air system, as also conditioning, are installed. Silver nanoparticle inks were used for the printing experiments during measurement sampling.

Currently, no legally binding limits for nanoparticles in Europe are in place. The only data available for comparison are results of previous concentration measurements at workplaces or processes. Table 2 contains a brief tabular summary of previous ÖSBS measurements that can be used as reference.

Table 2: Reference measurements of particle concentration of nanomaterials performed by the ÖSBS in the past.

Nanotechnology industry	Process specification	Particle concentrations [Quantity / cm³]
Production and processing of carbon nanotubes (CNT)	Production in reactor	14.800
	Manual manipulation of the powder material	7.200
	Processing in the extruder	61.700
Metal powder production	Production	10.000
Research Laboratory	Production	1.700
	Organic material processing	2.000
Nano painting	Background	8.600
	Processing	32.700
Cushion coating	4.800	Background
	Processing	7.300

Exposure to ultrafine particles and nanoparticles was assessed using ***CPC 3007*** from TSI and ***DiSCmini*** (Diffusion Size Classifier) from the company Matter aerosol. Before performing actual measurements, sampling systems were examined using a HEPA filter. Specifications for sampling procedures of background and active printing processing measurements are listed in table 3, alongside the obtained particle concentrations. Concluding from the measurements the exposure during active processes is at a very low level as background levels were only insignificantly lower.

Table 3: ÖSBS measurement of particle concentration/size at different locations in the chemical laboratory of Johanneum Research (Weiz 2) in Weiz, Austria.

Location	Background/ active process	Vent in fume hood (on/off)	Sampling time	Particle Number Concentration (CPC 3007) N/cm³	Particle Number Concentration (DiSCmini) N/cm³	Size (DiSCmini) nm
laboratory	Background	-	09:55 – 10:05	560	1100	60
fume hood	Background	off	10:06 – 10:16	610	1030	67
fume hood	ESJET	on	10:16 – 10:31	820	1340	66
fume hood	ESJET	off	10:32 – 10:47	530	780	84
fume hood	no process	off	10:47 – 10:55	450	550	101
fume hood	no process	on	10:55 – 11:00	590	700	87
fume hood	Ink-JET (Ag)	on	11:31 – 11:46	1100	1300	66
fume hood	Ink-JET (Ag)	off	11:47 – 12:02	680	790	94

Additionally, volatile organic hydrocarbons (VOCs) concentration was determined and found to be present at only a very low level (see table 4).

Table 4: ÖSBS measurement of concentration of volatile organic hydrocarbons at different locations in the chemical laboratory of Johanneum Research (Weiz 2) and in the printing laboratory (Weiz 4) in Weiz, Austria.

Location	Background/ active process	Vent in fume hood (on/off)	Concentration [ppm]
laboratory	Background	-	< 1 ppm
fume hood	ESJET	on	< 1 ppm
fume hood	ESJET	off	6 ppm
fume hood	Background, no process	off	9 ppm
fume hood	Background, no process	on	2 ppm
fume hood	Ink-JET (Ag)	on	< 1 ppm
fume hood	Ink-JET (Ag)	off	3 ppm
Printing laboratory, Weiz 4, 2. OG	Background	-	< 1 ppm

8 DISCUSSION

8.1 CONTEXTUAL CONSIDERATIONS FOR MEASURED EXPOSURE LEVELS IN HI-ACCURACY

In a recent study, similar measurements as those presented in the section 7. Results were performed on printers for electronics using silver nanoparticle ink. The printer was placed in an acrylic exposure simulation chamber (Figure 4A). Using a dust monitor and a condensation particle counter, particle number concentrations were measured. This revealed, that higher exposure levels to nanoparticles were reached outside of the exposure simulation chamber, compared to inside (Figure 4B), while the level of nano-sized particles (<100 nm) detected was overall low (Figure 4C). The authors attributed this result to the high viscosity of the used silver nanoparticle ink. The conclusion of this study was that a no-risk concern level for printed electronics with silver nanoparticle ink can be reached (27).

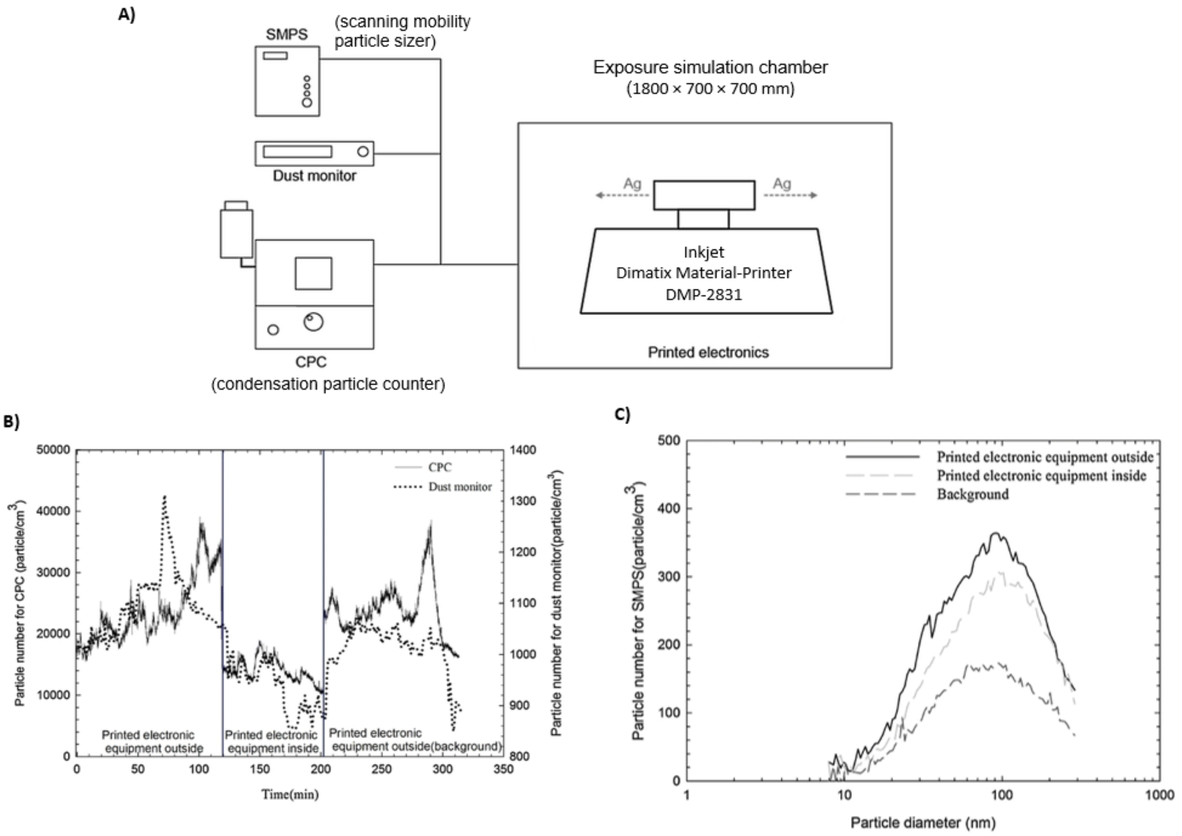


Figure 5: (A) Schematic diagram of exposure simulation chamber and the measurements performed using a printer for electronics utilising silver nanoparticle ink. Particle distribution and number concentration during operation were obtained. (B) Particle number was measured using dust monitor and condensation particle counter (CPC). (C) Particle number was measured using scanning mobility particle sizer (SMPS). Figures used and adopted (combined from two separate figures) under the terms and rights of CC BY 4.0 (http://creativecommons.org/licenses/by/4.0/) from Kim, E., et al (27).

In an earlier study from 2013, the exposure of workers in clean rooms for printed electronics was investigated. In this case roll-to-roll and roll-to-plate printing technology with silver nanoparticle inks (paste or formulations using organic solvents) were used. Measurements did not reveal significant exposure of workers to the silver nanoparticles. Authors instead highlighted the danger of exposure to organic solvents (especially in clean room conditions). However, airborne concentration for solvents used for the ink formulations (propylene glycol methyl ether acetate and ethylene glycol) were not determined (28).

9 CONCLUSIONS

Overall, we conclude that the exposure of workers to nanomaterials involved in producing and processing printed electronics is considerably low. We would like to highlight the low number of particle concentrations measured not only in the project specific tests, but also previously by others (27, 28). Nonetheless, to further improve the safety of workers involved not only should the exposure be monitored and controlled by specific personal and operational protective measures, but also regulated by instating SWPs. Recommendations for generating SWPs can be found in the following section 10. Recommendations. Alongside these recommendations, the overall recommendation is to also improve not only safety, but also sustainability of processes by choosing greener alternatives, supported by the “Green Solvent Selection Tool”[9].

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[9] https://green-solvent-tool.herokuapp.com/

10 RECOMMENDATIONS

10.1 SWP RECOMMENDATIONS

The effectiveness of SWPs is highly dependent on their inherent practicality and the employees’ compliance. To improve these parameters, it is recommended to practice effective communication by engaging with the workforce, providing thorough training and establishing clear roles and responsibilities. Additionally, a feedback system for employees to dynamically assess SWPs effectiveness is crucial, and should be taken seriously and considered for adaptation by responsible personnel. Further, an open dialogue regarding safety concerns, near misses and incidents, and utilising this feedback to enhance procedures will improve SWPs effectiveness and the compliance rate. All employees must have easy access to the most up-to-date SWPs and any implemented changes must be effectively communicated to the workforce. Additional steps to further foster a robust safety culture within the organisation include recognising and rewarding safe behaviour, while simultaneously conducting regular safety audits and inspections to ensure SWP compliance and pinpoint areas for improvement. Sustaining a strong safety culture at all levels is imperative to ensure that SWPs are not only developed but also rigorously implemented and adhered to throughout the organisation (15).

When preparing SWPs, the following general steps should be considered:

1. Listing the different processes, tasks or experiments which are regularly conducted. Employees who perform these tasks should be included in the generation of SWPs as they can provide valuable insights into potential hazards and practical safety measures.

2. For each process or task, the potential hazards need to be identified and listed (e.g., chemical exposure, electrical shock, burns, mechanical injuries, ergonomic strain)

3. Evaluate the potential of the identified hazards, including severity and likelihood, for example by using a risk assessment matrix. High-risk hazards must be prioritised.

4. Detailed, step-by-step, standardised procedure protocols should be established for each process or task. This should include information on how to safely set up, operate, and shut down equipment, handle chemicals, use personal protective equipment (PPE), and respond to emergencies.

5. All employees must be trained on how to operate according to SWPs relevant to their tasks. This training should be documented and repeated regularly, and immediately upon updates in the SWPs.

6. Necessary safety equipment, such as fire extinguishers, emergency eyewash stations, first-aid kits, and appropriate PPE, must be readily available and in good working condition and regularly maintained.

7. SWPs need to be regularly reviewed and adapted to reflect changes in processes, equipment or safety regulations. Employees who perform the tasks regularly should be consulted to improve procedures.

10.2 BEST PRACTICE RECOMMENDATIONS

Although nanomaterials are widely used in modern applications, they can still be considered as an emerging technology. Questions regarding their safety are currently addressed based on available data of the chemical elements or materials they consist of. However, due to their size, it is reasonable to expect that also their properties, influencing their safety, could be different. Thus, it is recommended to assume higher potential risks arising from a potential exposure of humans to these (hazardous) materials. That way safety can be ensured already before comprehensive data-based knowledge is gathered.

Individuals working with chemicals must be capable of responsibly handling chemicals and concerning materials to preserve overall safety. A safe work environment can be established if major attention towards these questions is established in all levels of organisations.

Further, expanding the amount of high-quality data regarding the exposure to nanoparticles in R&D processes (and more generally, during all stages of the life cycle of nanomaterials and nano-enabled products) will improve safety ultimately. Thus, we recommend research and production laboratories, especially industries and SMEs, to perform measurements in their facilities and make these data openly available. Such data can subsequently be used by the broader community.

10.3 SELECTING MORE SUSTAINABLE OPTIONS

Safety is inherently linked to sustainability, hence we recommend substituting chemicals, in this specific case solvents in the printing inks, by greener, more sustainable options. To aid in the decision several tools are available. Upon testing, based on information availability and usability, we recommend the use of the “Green Solvent Selection Tool”[10].

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[10] https://green-solvent-tool.herokuapp.com/

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