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Wearing face masks as a potential source for inhalation and oral uptake of inanimate toxins – A scoping review

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ABSTRACT

Background: From 2020 to 2023 many people around the world were forced to wear masks for large proportions of the day based on mandates and laws. We aimed to study the potential of face masks for the content and release of inanimate toxins.

Methods: A scoping review of 1003 studies was performed (database search in PubMed/MEDLINE, qualitative and quantitative evaluation).

Results: 24 studies were included (experimental time 17 min to 15 days) evaluating content and/or release in 631 masks (273 surgical, 228 textile and 130 N95 masks). Most studies (63%) showed alarming results with high micro- and nanoplastics (MPs and NPs) release and exceedances could also be evidenced for volatile organic compounds (VOCs), xylene, acrolein, per-/polyfluoroalkyl substances (PFAS), phthalates (including di(2-ethylhexyl)-phthalate, DEHP) and for Pb, Cd, Co, Cu, Sb and TiO_2.

Discussion: Of course, masks filter larger dirt and plastic particles and fibers from the air we breathe and have specific indications, but according to our data they also carry risks. Depending on the application, a risk-benefit analysis is necessary.

Conclusion: Undoubtedly, mask mandates during the SARS-CoV-2 pandemic have been generating an additional source of potentially harmful exposition to toxins with health threatening and carcinogenic properties at population level with almost zero distance to the airways.

1. Introduction

Since 2020 until 2023, triggered by the SARS-CoV2 pandemic and mandated by governments, wearing coverings of mouth and nose has become a new normal part of everyday life for many peoples around the world (Face covering policies during the COVID-19 pandemic, 2023). This is relevant, especially for health care professionals, who were mandated since the beginning of the pandemic based on WHO recommendations (World Health Organization (WHO), 2020), laws (Knobloch et al., 2023; Verordnung zum Schutz vor Neuinfizierungen mit dem Coronavirus SARS-CoV-2, 2023) and institutional obligations in hospitals and healthcare-groups (Helios führt allgemeine Maskenpflicht ein, 2020; Helios führt Maskenscanner in allen Kliniken ein, 2020) to wear face masks. Furthermore, in many countries children had been mandated to wear masks in schools for large proportions of the day (Ladhani, 2022; Thomson, 2022). The numerous commuters using public transport should also be mentioned (Face covering policies during the COVID-19 pandemic, 2023).

Available characterizations of facemasks reveal the presence of chemicals like hydrocarbons, phthalates, organo phosphate ester compounds, amides, paraffins, olefins, polyethylene terephthalate oligomers and microplastics (Kutralam-Muniasamy et al., 2022; Li et al., 2021a; Liu et al., 2022a; Muensterman et al., 2022). It is known from environmental research that the COVID-19 pandemic was exacerbated by

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environmental pollution, entailing (or bringing about) increased concerns. A recent comprehensive review on uptake, toxicity, and molecular targets of microplastics and nanoplastics impacting human health significantly mentioned face masks as a source of inhalation risk (Khan and Jia, 2023). Also, numerous environmental toxicology reviews (Chen et al., 2022; Ganesapillai et al., 2022) derive an indirect (environmental) health risk from wearing face masks due to the release of chemical additives (Aerts et al., 2020; Raval and Sangani, 2021) and (micro)plastic fibers (Li et al., 2022; Morgana et al., 2021; Shen et al., 2021). Face masks released contaminants (microplastics/fibers/chemical compounds) disturbing several ecosystems and affecting their biota (Masud et al., 2023; Oliveira et al., 2023). Those contaminants can induce multi-organ toxicity on a wide range of aquatic and terrestrial organisms. Fibres may cause localized responses as well as its additives and sorbed contaminants may result in genotoxicity, reproductive toxicity, carcinogenicity and mutagenicity (Gasperi et al., 2018; Torres-Agullo et al., 2021). Microplastics and microfibres released from face masks may also contribute to the dispersion of pathogens (Patrício Silva et al., 2021) and antibiotic resistance genes (ARG) in the environment, as the architecture of face masks (microscopic meshing) can provide a preferable base substrate for microbial communities, including antibiotic-resistant pathogens (Zhou et al., 2022). The ecotoxicological effects of face masks are not only related to the fragments released but also to the chemical additives that are present in their polymer matrix. Aquatic and soil organisms including vertrebrates may suffer from disturbances regarding their tissues and organs including oxidative stress, oxidative DNA damage, variations in immune functions, decreased viability, neurotoxicity, inhibited reproduction, decreased fecundity and retarded growth (Oliveira et al., 2023). Additionally, on a macroscopic level, there is a direct ingestion and entanglement risk for animals (Oliveira et al., 2023).

However, so far direct risks associated with using face masks and their repercussions on human health had only been explored from a scientific and not from a holistic perspective (Potluri and Needham, 2005). Potentially, face masks, that come into close contact with the consumer can pose an immediate threat to human health due to the release of toxicologically relevant substances and continuous exposure to them (Jin et al., 2021; Liu et al., 2022a). Humans inhale emissions from a mask at nearly zero distance and swallow water droplets originating from the moist dead space enriched with mask ingredients. In this regard – theoretically – wearing a mask may exert a higher risk of exposure than many other environmental sources (Chang et al., 2022). In this context, we underscore the phenomenon of predominantly oral breathing while wearing a mask (Kisielinski et al., 2021; Wyszyńska et al., 2022), in contrast to normal unimpeded breathing, which is largely via the nose, with greater filtration. Oral breathing increases the hazard of directly inhaling particles and toxins from the mask into the deeper airways (Everard et al., 1993; Heyder et al., 1986; ICRP, 1994).

Chemical toxic additives used in the manufacturing processes of masks, including plasticizers, phthalates, UV stabilizers, and bisphenol A have already been shown to leach and cause adverse health effects in humans (De-la-Torre et al., 2021). Children with less developed protective/conjugative pathways (Faustman et al., 2000) are particularly vulnerable to many of the face mask emissions. Some studies revealed no increased human health risk for skin (Estevan et al., 2022), whereas other scientific publications were able to show nano- (<1 µm) and microplastics (<3 mm) in nasal mucosa after mask use and deduced a health risk to the wearer (Klimek et al., 2020; Ma et al., 2021).

Interestingly, around the world, certain institutional regulatory actions were taken during the pandemic because face masks posed a considerable exposure risk (Azoulay et al., 2021; BfArM, 2020; Corona-Maske im Rückruf, 2020; Government of Canada, 2021; Habich, 2020; Information de sécurité - Action de sécurité de Santé publique - ANSM, 2021; La AEMPS informa de los resultados de la investigación efectuada sobre las mascarillas quirúrgicas tipo IIR con grafeno, 2021; Masken-Rückruf bei Müller, 2020; Mast et al., 2021; Maynard, 2021; Raval and Sangani, 2021).

By and large there is an increasing scientific interest focusing on the ingestion and inhalation risks from face masks, because of such an unprecedented use worldwide (2020–2023) implying long-term dermal contact, inhalation and ingestion exposure at population level. Nevertheless, overall knowledge on possible risks of wearing masks for humans is lacking. To our knowledge, since the beginning of the pandemic 2019, so far no comprehensive scientific review on this complex topic has been realised.

Inspired by scientific reports and the undisputed fact that masks are capable of causing inhalation of potentially toxic substances (Li et al., 2022; Mast et al., 2023; Masud et al., 2023; Palmieri et al., 2021) we decided to conduct a scoping review on this topic in order to evaluate reliable scientific data on toxic content and release from face masks. Moreover, we initially aimed for the assessment of the potential exceedances of toxin thresholds associated with face mask use.

2. Methods

2.1. Search and retrieval strategy

The PubMed/MEDLINE (NIH, national library of Medicine) database (PubMed, 2023) was searched till 31st December 2022. The specific search terms according to the criteria defined in the PICO scheme (Huang et al., 2006) were: ((face mask) OR (facemask) OR (surgical mask) OR (FFP1) OR (FFP2) OR (FFP3) OR (N95) OR (KF94) OR (KN95)) AND ((toxicity) OR (toxic) OR (environmental health)). To expand the amount of published data we reviewed citations from included articles to locate additional research. Additional records identified through other sources were also taken into consideration, if applicable.

2.2. Inclusion and exclusion criteria

The aim was to study the potential of protective face masks for the maximum content and release of inanimate toxins that may be inhaled or ingested under use. Thus, popular cloth masks, surgical masks/FFP1, N95/KN95/KF94/FFP2 and FFP3 masks were the field of interest. Only manufactured content of the face mask was taken into account. Other substances like natural exhaled breath constituents including CO_2 were disregarded. The main findings considered were the quantifiable content and release of clinically relevant, potential toxins from face masks.

Assuming the worst case scenario in use with release of substances when the mask is drenched, bent, crumpled and by air currents passing through the mask during breathing, not only mask tissue analyses but also washout tests in water and similar test set-ups, e.g. with vacuuming or breathing simulation experiments were taken into account. This was intended to represent everyday use in the general population under worst-case scenarios as part of a simplified risk assessment. However, we excluded studies only aiming for release of toxins from masks after disposal, simulating decomposition, e.g. in salty sea water including washing, digestion experiments etc. Case reports, case series, expert opinions and preprints were also excluded.

The qualitative inclusion criteria for studies were: valid reproducible presentation of the outcomes, comprehensible recruitment of evaluated masks, credibility of the results, transferability to other mask studies and results, clear focus and comparability with existing evidence.

The quantitative inclusion criteria were: Appropriate and precise methods, valid processing, valid measurement of outcomes, representative selection of evaluated masks, and sufficiently reproducible analytical methods.

2.3. Data extraction and analysis

Two independent researchers identified and screened the eligible studies (Fig. 1). The selected papers were checked by all authors for final eligibility. Study design, methodology, analytical and experimental method, primary and secondary outcomes and language have been evaluated. Exclusions and reasons have been documented. Concerning included studies the following data was extracted into tables: Author and year, method and type of study, sample size and mask types, outcomes/examined substances, content, release, main findings, and risks. Only the most relevant and toxic substances were included in the extraction tables. Studies on content and release have been presented in separate tables, respectively. Due to our toxicological approach, we focused on maximal content/release data on masks. Such approach is common in toxicological analyses with a worst case scenario. This enabled us to derive a risk estimation for members of the community. If not specified in the papers, the data representing exact maximal mask content/release of compounds was derived based on the data in the measurements of the original works and presented as the last column in the extraction tables. For example, on the basis of the data on leaching or exhaust vapour tests, etc.

2.4. Calculations and exceedance analysis

Due to the only basic arithmetic calculations in our study, the software Libre Office Calc (Calc | Libre office, 2023) was used. If not realised in the included publications, we additionally performed a comparative analysis of the content and release of the toxic substances from the face masks with reference to (most appropriate) threshold limits. Such limits e.g. for the ambient air, are given by national or international institutions and organisations. For example, data from the United States Environmental Protection Agency (USEPA) (US EPA, 2016a), data from the WHO (What are the WHO Air quality guidelines?, 2021), as well as from the German Federal Environment Agency (Luft, 2023) and the European Union (EU) target limits (EU, Air Quality, 2022) were taken into consideration. Similarly, textile content threshold values from international, high quality and standard organisations like the Oeko-Tex (Oeko-Tex® Service GmbH, 2023) were used. The calculated and extracted exceedance results were considered in the discussion section and were presented in separate tables. Text and tables were generated with Libre Office software (LibreOffice, 2023).

For the purpose of data comparison the results of the included studies have been standardized and converted to values per mask, if not primarily reported. For those calculations data from the primary studies were gathered. If the necessary parameters were not exhaustively specified in the primary studies (e.g. mask surface or weight), we used valid values stated in previous scientific publications. Average mask weight was estimated from studies that give the specific mask weight within the scope of their measurements (average weight of the mask without rubber bands and nose clip, and if applicable also without valve) (Fernández-Arribas et al., 2021). Thus, the disposable/textile/community mask

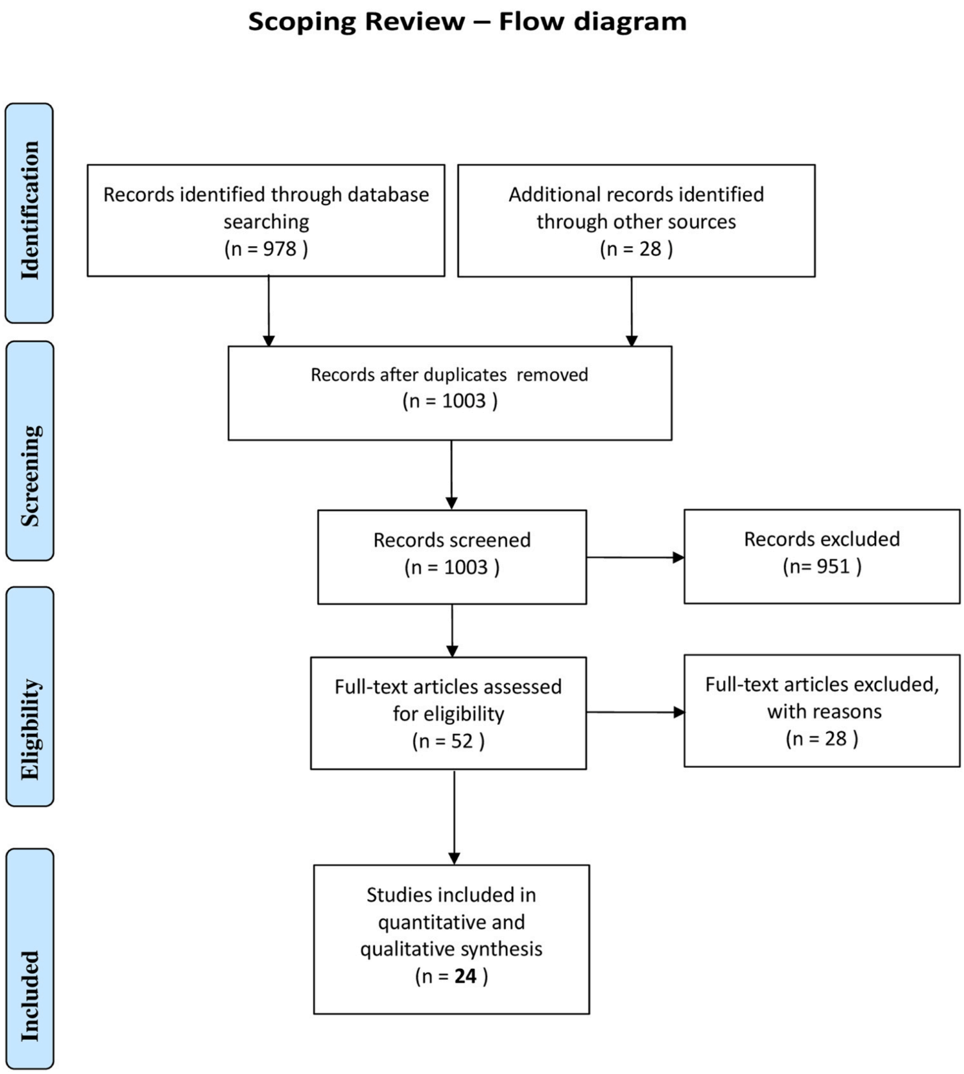

Fig. 1. Flow diagram of the scoping review according to PRISMA.

was set at 2.5 g (Xie et al., 2021, 2022), the surgical mask was set at 3 g, the FFP2/KN95 at 4 g and the FFP3 mask at 5 g (Fernández-Arribas et al., 2021). The average mask surface area was set at approximately 230 cm^2 (0.023 m^2) (Rengasamy et al., 2009), while assuming the surface area of a standard N95 respirator to be 175 cm^2 (0.0175 m^2) (Roberge et al., 2010). However, this assumption is not the worst case scenario, since some authors state larger surface areas in their primary evaluations (Zuri et al., 2022). For breathing calculations, we referred to the values from the USEPA calculating a breathing volume of 10 m^3/12 h (US EPA, 1989). However, taking into account the high variability in breathing patterns, we assumed an adult at rest to breathe approximately12–18 respirations per minute (mean 15), exchanging 0.5 litres – corresponding to approximately 0.5 m^3/h, thus we rounded up for a simple calculation as 1 m^3/2 h being in the normal range (Benchetrit, 2000). The exact calculation methods are mentioned continuously throughout our paper (e.g. by descriptions in the discussion, or as footnotes in the tables).

3. Results

3.1. General findings

Of the original 1003 results, 24 studies (2.4%) were finally included (Fig. 1). This is not an unusually low rate in reviews (Kisielinski et al., 2023a). The selection was strictly based on the inclusion and exclusion criteria and the applied quality assessment (see methods section, inclusion and exclusion criteria). Among the included papers eleven were published in 2021 and thirteen in 2022 representing very recent scientific interest in the mask toxin topic. The included papers, content/release was evaluated in 631 masks, among were 130 N95, 273 surgical, and 228 textile/disposable masks over an experimental period ranging from 17 min to 15 days. Altogether, among the included studies eleven measured the mask toxin content, twelve the mask toxin release and one both of them.

3.2. Analysed substance classes

Ten of the papers measured a microplastic (MP) release by face masks (Chen et al., 2021; Delgado-Gallardo et al., 2022; Dissanayake et al., 2021; Li et al., 2021a; Liang et al., 2022; Liu et al., 2022b; Ma et al., 2021; Meier et al., 2022; Sullivan et al., 2021; Zuri et al., 2022), representing 42% of the included papers. Also a nanoplastic (NP) release was documented by three of the included studies (Delgado-Gallardo et al., 2022; Ma et al., 2021; Sullivan et al., 2021).

Among the included studies, five measured volatile organic compounds (VOCs) related to face masks, thereof three the emission (Chang et al., 2022; Hui Li et al., 2022; Kerkeling et al., 2021) and two the content (Jin et al., 2021; Xie et al., 2021). Two studies measured the organophosphate esters (OPE) content in face masks and did an intake estimation (Fernández-Arribas et al., 2021; Xie et al., 2021). Only two studies measured the Polycyclic aromatic hydrocarbons (PAH) content in face masks (Jin et al., 2021; Xie et al., 2021). We found eight studies that measured the phthalates and phthalate esters (PAE) emissions and content in face masks (Fernández-Arribas et al., 2021; Jin et al., 2021; Liu et al., 2022b; Min et al., 2021; Vimalkumar et al., 2022; Wang et al., 2022; Xie et al., 2022; Zuri et al., 2022). There was only one study that evaluated the UV-filter and organophosphate flame retardants (OPFR) content in face masks (Xie et al., 2021). One study evaluated the per- and polyfluoroalkyl substances (PFAS) from masks and additionally did an exposure estimation (Muensterman et al., 2022). Seven studies investigated trace elements and heavy metals, five predominantly release (Delgado-Gallardo et al., 2022; Hui Li et al., 2022; Liu et al., 2022b; Meier et al., 2022; Sullivan et al., 2021) and two the content (Bussan et al., 2022; Verleysen et al., 2022) in face masks.

In the studies on the release of pollutants from face masks, the following methods were used: vacuum pump (Li et al., 2021a), air based Sheffield head breathing simulation (Meier et al., 2022), flow cell and micro chambers (Chang et al., 2022; Kerkeling et al., 2021) and filtered water release / leaching (Chang et al., 2022; Delgado-Gallardo et al., 2022; Dissanayake et al., 2021; Hui Li et al., 2022; Liang et al., 2022; Liu et al., 2022b; Ma et al., 2021; Meier et al., 2022; Sullivan et al., 2021; Zuri et al., 2022).

The evaluated toxic substances as well as our research question are summarised in Fig. 2.

3.3. Special findings

Interestingly, the N95 mask showed a higher content and release for MP/NP, OPEs, OPFRs, PAHs than other mask types.

In contrast, regarding VOCs, PAEs and heavy metals the surgical masks are responsible for higher levels and releases than N95 masks. As far as this is concerned, the textile masks are comparable to the surgical masks.

All relevant results concerning the evaluated studies on toxins in face masks (study type, aim, mask types, outcomes, findings, special risks, maximal face mask content/release), are summarised in the extraction Tables: Table 1 shows results on the face mask content and Table 2 on the release of toxins.

4. Discussion

The results of our review show that ingredients of mask manufacture/production play a key role in their potential toxic properties. We also found clear evidence that values of certain contents/emissions are alarmingly high in all scrutinized mask types (N95, surgical, textile) and may – in worst case scenarios – pose a health risk to the wearer, who inhales the toxic substances at nearly zero distance. In the following subheadings we discuss the origin, the release and risks of particular toxics and compare our results of the contents and releases from masks to the threshold limit values of air- or textile concentrations, if available, from international organisations and institutions.

4.1. Microfibers, micro- and nanoplastics (MPs and NPs)

4.1.1. MP and NP from masks – origin

Synthetic macromolecules with repeating units (plastic polymers) are the primary component of all types of face masks (Khan and Jia, 2023). This fact is responsible for the mask being a significant source of plastic fiber and particle release (Chen et al., 2021; Delgado-Gallardo et al., 2022; Dissanayake et al., 2021; Li et al., 2021a; Liang et al., 2022; Liu et al., 2022b; Ma et al., 2021; Meier et al., 2022; Sullivan et al., 2021; Zuri et al., 2022). Therefore, the mass consumption of face masks has generated a huge additional source of microplastics (MPs $<$5 mm) or even nanoplastics (NPs $<$1 μm) pollution (Aragaw, 2020; Fadare and Okoffo, 2020; Hasan et al., 2021; Huang et al., 2021a; Parashar and Hait, 2021). Mask manufacturing materials consist of specific polymers with polypropylene (PP) being the most widely used (Xu and Ren, 2021), although polyethylene (PE), polyamide (PA), polystyrene (PS), and polyethylene terephthalate (PET), or polyester (PES) also are commonly used in synthetic textiles (Ma et al., 2021; Potluri and Needham, 2005; Zuri et al., 2022). Especially, the nanofibers created from microfibers and fragments of melt-blown filters of facemasks (middle layers) contribute to the dust release and inhalation risk of MPs and NPs while wearing a mask (Khan and Jia, 2023). When producing these non-woven fabrics, high-speed hot air is applied to blow the thermoplastic polymer to a conveyor collector (Hutten, 2007). NPs and MPs are generated during the production process of these fine fibers, giving face masks the potential to act as a primary source of MPs (Liu et al., 2022b). While the surgical mask usually consists of three layers with one melt-blown fiber layer (Fadare and Okoffo, 2020), the FFP2/N95 mask has 5 layers,

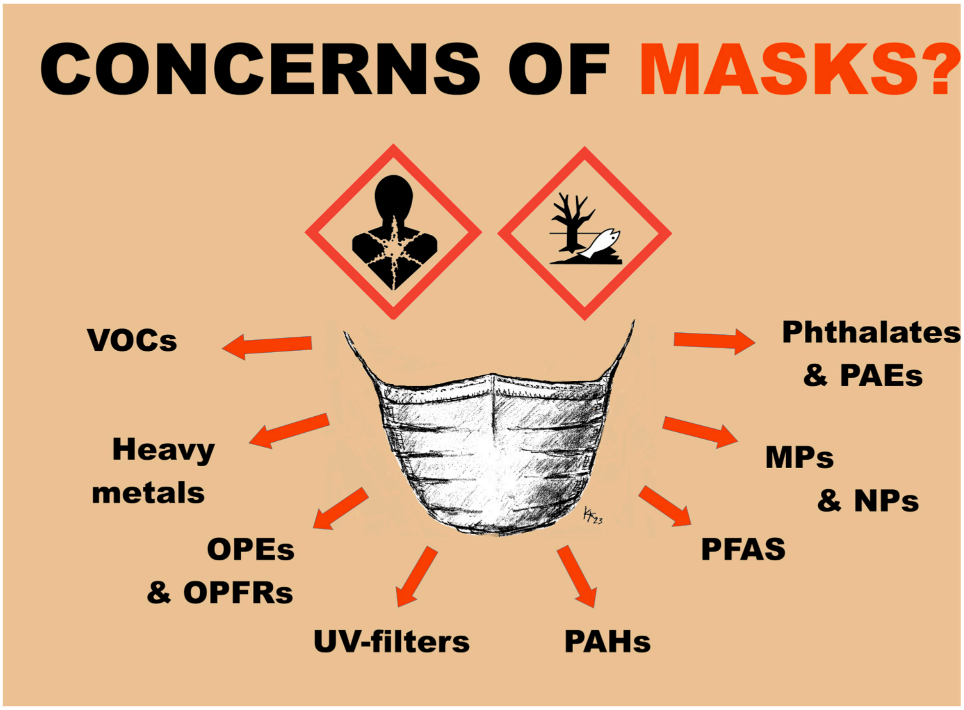

Fig. 2. Graphical representation summarising the toxic substance classes evaluated in the included studies and our research question regarding toxicity.

thereof two melt-blown fiber layers (Zuri et al., 2022).

4.1.2. MP and NP from masks – release and intake

Exposure to plastic particles has increased continuously in the modern world (Prata et al., 2019), but the obligations to wear masks around the world during the SARS-CoV-2 pandemic 2020–2023 (Face covering policies during the COVID-19 pandemic, 2023) has increased this exposure even further (Tesfaldet and Ndeh, 2022). Recent environmental studies have reported that plastic-based personal protective equipment (PPE) releases substantial amounts of NPs and MPs, to the environment (De-la-Torre et al., 2021; Fadare and Okoffo, 2020). The NPs and MPs released from face masks were detected even in marine organisms showing their broad distribution (Chen et al., 2021; Khan and Jia, 2023). Once released, these MPs and NPs (MPs, $<$ 5 mm, NPs, $<$ 1 μm) originating from masks pose a delayed indirect environmental health risk to humans regarding oral uptake and inhalation (Du et al., 2022).

But, according to the study results at hand, there exists also a significant direct immediate inhalation risk for the user, from the mask breathing zone into the airways (Chen et al., 2021; Delgado-Gallardo et al., 2022; Dissanayake et al., 2021; Li et al., 2021a; Liang et al., 2022; Liu et al., 2022b; Ma et al., 2021; Meier et al., 2022; Sullivan et al., 2021; Zuri et al., 2022), as already assumed by other papers (Du et al., 2022; Han and He, 2021; Khan and Jia, 2023; Kisielinski et al., 2021). The fact that MPs were also detected in the nasal mucus shortly after mask wearing (Klimek et al., 2020; Ma et al., 2021) gives evidence that MPs can be directly inhaled while wearing a mask. This additional inhalation risk was also laboratory proven by breathing simulations with diverse mask types (N95, surgical and other) by Li et al (Li et al., 2021a). However, this study was not conducted in super-clean laboratory (no contamination control measures were applied) thus it is not clear whether the control air in the blank measurements (no mask) does not correspond to the air already contaminated by mask handling. Therefore, the control values (without mask) in that study should be interpreted with caution, as they probably provide additional evidence for the release of plastics from masks.

Interestingly, the release of MPs and NPs is predominantly higher for the N95 type when compared to the surgical mask (Delgado-Gallardo et al., 2022; Dissanayake et al., 2021; Huang et al., 2021a; Liang et al., 2022; Ma et al., 2021; Zuri et al., 2022). This fact could be due to more layers including two melt-blown and thus higher overall plastic content and weight of the N95 mask. According to the literature, reusing a mask increases even the risk of microplastic release: regardless of whether a mask is new or used, the risk of inhaling spherical-type MPs and NPs released from the facemask remains significant (Huang et al., 2021a; Li et al., 2021a). Problematic is that mechanical stress, e.g. a beard under the mask or pulling the mask out of the pocket may contribute to mask's physical abrasion of microplastics (Khan and Jia, 2023).

In the evaluated literature we found a possible maximal release of MPs up to 5390 particles per mask within 24 h (Zuri et al., 2022) and a maximum mass loss of 0.831 mg/N95 mask (particles and fibers) during 24 h (Liang et al., 2022). Depending on the filters and analytic methods used, the release experiments describe different sizes of the mask debris. For released fibers we found a size range of 25 μm to 2.5 mm (Dissanayake et al., 2021; Meier et al., 2022; Sullivan et al., 2021) and an amount of 3152 fibers per surgical mask (Meier et al., 2022). For released particles we found a size range of 89 nm (Verleysen et al., 2022) to 500 μm (Sullivan et al., 2021), among many other dimensions (Chen et al., 2021; Delgado-Gallardo et al., 2022; Li et al., 2021a; Liang et al., 2022; Liu et al., 2022b; Ma et al., 2021; Zuri et al., 2022). Noteworthy, a study with precise analysis on silicon wafers and using scanning electronic microscopy (SEM) for exploration describes most of the particles involved smaller than 1 μm (Ma et al., 2021).

Surgical and N95 masks have been designed to be worn for very specific purposes such as in hospital surroundings and for a short period of time (Buzzin et al., 2022). If they are crumpled up in people's pockets where the friction and damp environment promotes significant fiber abrasion and worn for longer periods of time, a high microplastic release is possible, as shown by included papers (Chen et al., 2021; Li et al., 2021a; Liang et al., 2022).

However, it is interesting to compare the plastic release of masks while wearing them for a period of time, e.g. 2 h with average breathing of $1\ m^3$ to known MP concentrations in ambient air given as n/m^3. For example, the mask-independent average concentration of airborne MPs

Table 1

Extraction tables of the included experimental and analytical studies on mask content of toxins (characteristics and main findings). Maximal content was used for comparison and standardisation, if necessary own calculations were performed (see footnote and materials & methods section).

Author and year	Type of study, method	Aim	Mask Types	Outcomes	Findings	Special risks mentioned	Maximal face mask content*
Bussan 2022	Experimental and analytical study, ICP-MS, saliva leaching (6h) and breathing experiments (15min).	**Determining concentration of trace elements** measured by Inductively Coupled Plasma Mass Spectrometry ICP-MS) in leachates and breathing release.	24 masks: 21 surgical and 3 KN95	12 trace elements: Cr, Mn, Ni, Cu, Zn, As, Se, Mo, Cd, Sb, Tl, and Pb (^{206}Pb, ^{207}Pb, and ^{208}Pb)	Detectable concentration levels for **Cu, Sb, Pb and Zn.** **Cu** detected in most of the **surgical masks (**2.24 to **410 µg/g**). **Sb** was detected **in both surgical and KN95 masks,** (0.97 to **90.18 µg/g**) with KN95>surgical. **Pb** was detected **in surgical and KN95 masks** (0.15 to **13.33 µg/g**). **Noticeably, Pb was detected in 76% of black colored masks.** **Zn in surgical masks:** 15.93 to **56.80 µg**.	**Sb** is a **possible carcinogen.** **Sb** in amounts greater than 8.87 mg/m^3 can cause **pneumoconiosis, also chronic bronchitis, chronic emphysema, inactive tuberculosis, pleural adhesions, and respiratory irritation.** Inhaled and ingested **Pb** can cause **severe brain damage, reproductive system damage** and **death.** **Excess of Zn** can cause **lethargy** and **respiratory tract problems** such as **metal fume fever (MFF).**	**Cu: 1230 µg (surgical)** **Sb: 360.7 µg (KN95)** **Pb: 39.9 µg (surgical)** **Zn:170.4 µg (surgical)**
Fernández-Arribas 2021	Experimental-analytical in vitro study (6h), electrospray 4h simulation of mask wearing, ionisation mass spectrometry, chemical organic trace analysis.	**Estimatig** the **Organo-phosphate ester (OPE) content (ng/mask)** for 16 substances, additional inhalation estimation while testing with two paper-mache dummy heads representing an adult human's head (indoors and outdoors).	20 masks, surg. (8), KN95 (3), FFP2 (3), FFP3 (2), and reusable face masks (4)	12 OPEs: TCEP, TCIPP, THP, TEHP, IDPP, TEP, TPP, DCP, TnBP, TPHP, TPPO, TDClPP, TCP, T2IPPP.	**Highest OPE mean concentrations obtained for KN95 masks (11.6 µg/mask) and the lowest for surgical masks (0.24 µg/mask**). TEP, TPHP, TnBP, TEHP and TClPP being the most common OPEs at the highest concentrations. **The highest inhalation percentages were for TnBP (between 1 and 13%) and TDClPP (between 6 and 9%).** Comparing indoor to outdoor use, no differences found. Face mask is not considered to be dangerous for citizens regarding exposure to OPEs. **Human exposure to OPEs via indoor air inhalation is doubled by the use of a KN95 mask per day.**	**OPEs** are associated with **asthma and allergies.** **TnBP** is observed to disrupt **endocrine** and **reproductive functions**, **nervous system development** and is **suspected carcinogen**. **TDClPP** is associated with **decline of semen quality**.	**ΣOPE: 20.4 µg (KN95)** **ΣOPE: 0.717 µg (surgical)** **ΣOPE: 27.7 µg (FFP3)** **TnBP 44.9 ng (N95)** **TnBP 657 ng (surgical)** **TDClPP 23.5 ng (N95)** **TDClPP 10.4 ng (surgical)**
Jin 2021	Analytical and experimental study (1h), behind mask breathing-zone VOC-analysis, GC−MS, HPLC−FLD.	Estimating the increased **human exposure to volatile organic compounds (VOCs)** through wearing surgical masks.	60 surgical	11 Organic compounds: Formaldehyde, Acetaldehyde, Acrolein, Glyoxal, Methylglyoxal, Furfural, Hexanal, Octanal, Decanal, Benzaldehyde, p-Tolualdehyde 16 polycyclic aromatic hydrocarbons (PAH): Naphthalene, Acenaphthene, Acenaphthylene, Fluorene. Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benz[a]anthracene, Chrysene, Benzo[b]fluoranthene, Benzo[k]fluoranthene, Benzo[a]pyrene (equivalent calculations), Dibenz[a,h]anthracene, Benzo[ghi]perylene, Indeno[1,2,3-cd]pyrene 6 Phthalate esters: DMP, DEP, DPP, BBP, DBP, DEHP	**VOC concentrations in the breathing zone of the mask were positively correlated with the levels of VOC residues in the masks.** **Surgical masks from around the world are loaded with semivolatile and volatile organic compounds (VOCs), including alkanes, polycyclic aromatic hydrocarbons (PAHs), phthalate esters, and reactive carbonyls at ng to µg/mask levels.** **Naphthalene** was the most abundant mask-borne PAH, accounting for over 80% of total PAH levels. **Acrolein, a mutagenic carbonyl,** was detected **in most of the mask samples**, and **DEHP, an androgen antagonis**t, was detected **in one-third** of the samples, exceeding the inhalation reference concentration (RfC; a daily inhalation exposure concentration below which yields no appreciable risk) for acrolein (0.02 µg/m^3) set by EPA. Furthermore, wearing the mask containing the highest level of acrolein residues (0.64 µg/mask) increased acrolein concentrations in the /m^3 behind-mask breathing zone to over 0.5 µg and remained above the RfC for 1 h. DEP and DBP, both of which are highly volatile, accounted for over 85% of the total detected phthalate content	**Alarmingly, wearing surgical mask increased the VOC amount in the breathing zone by a factor of ~5, whereas wearing highly polluted masks further increased the total VOC.** **VOCa are respiratory irritants and suspected or known carcinogens. Acrolein and glyoxal are both highly mutagenic and strong irritants to the skin, eyes, and nasal passages. Acrolein is a well-known lung cancer causing agent.** **PAHs are 1B carcinogens. Epidemiological studies have shown the elevated risk of bladder, lung, skin, and gastrointestinal cancer and other chronic health effects, including cataracts, jaundice, and kidney and liver damage. Dermal contact with naphthalene can cause skin redness and inflammation, and inhalation of excess naphthalene is associated with hemolysis.** **Phthalate exposure is associated with asthma, obesity, impaired reproductive development, endocrine disruption, and infertility. DEHP is known as an androgen antagonist and has been demonstrated to have a lasting effect on male reproductive function and carcinogenicity.** Masks containing more residue VOCs lead to significantly higher exposure levels and associated disease risks to the wearer, which should warrant the attention of the general public and regulatory agencies.	**ΣVOC 36.8 µg/mask** **Acrolein 637 ng/mask (0.5 µg/m^3 in the mask breathing zone)** **Glyoxal 862 ng/mask** **Σ PAH 5563 ng/mask (Naphthalene 80%)** **Naphthalene 5296 ng/mask** **Σ Phthalates 2305 ng/mask (DEP+DEB >85% phthalates)** **DEHP 1450 ng/mask**
Hui Li 2022	Analytical and experimental study. Leachates (24h), GFAAS, ICP-OES, FESEM-EDX, GC-MS.	**Identifying and quantifying the major chemicals** released from face masks **including the facemasks' fibers.**	100 surgical masks	Microfiber degradation, 3 heavy metals: Pb, Cd, Cr, 7 VOCs (4-methylheptane, 2,4 dimethylhept-1-ene, Heptacosane, Heneicosane, Octadecane, Octacosane, Pyridine-3-carboxamide)	**pH-dependent degradation of microfibers. Pb (3.238% ppb), Cd (0.672 ppb) and Cr (0.786 ppb)** were found. Additionally, **2,4-dimethylhept-1-ene and 4-methylheptane** were identified as **the VOCs.**	The experiments indicate a **pH-related degraded material.** **VOC emissions** can vary over the lifespan of the polymer because **polymers deteriorate due to several factors such as thermal stress and** **UV exposure**, even under normal circumstances. **Pb, Cr, and Cd** hold **high potential to harm human health and the environment.**	**Pb 69.36 ± 0.535 ng (surgical)** **Cd 3.343 ± 0.009 ng (surgical)** **Cr 84.01 ± 6.538 ng (surgical)**

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Table 1 (*continued*)

Author and year	Type of study, method	Aim	Mask Types	Outcomes	Findings	Special risks mentioned	Maximal face mask content*
Y. Liu 2022	Analytical study. Non-targeted analysis method with GC-Orbitrap HRMS, Full scan MS, GC–MS.	**Explore the unknown volatile chemicals in medical masks.**	60 medical masks, thereof: 5 N95, 25 surgical, 30 medical, thereof 20 children masks,	Volatile substances	69 volatile substances were identified in 60 masks, **alkanes, esters, benzenes, and alcohols were the top four groups of substances identified in masks and accounted for 34.8%, 15.9%, 10.1%, and 7.2% of the total substances, respectively**. In addition, ketones, ethers, phenolics, amides, and other substances were identified. **12 high-risk volatile chemicals in medical masks were: 1,4-Dichlorobenzene, toluene, xylenes (p, m, o), ethylene oxide, ethylbenzene, caprolactam, N, N-dimethylacetamide, N, N-dimethylformamide. N-methylpyrrolidone, dimethyl glutarate.**	Some of **volatile chemicals** were **considered carcinogenic.** For example, **ethylene oxide** was classified as group 1 carcinogens (carcinogenic to humans) by the International Agency for Research on Cancer (IARC, 2020). **1,4-dichlorobenzene and ethylbenzene** were classified as group 2B carcinogen (possibly carcinogenic to humans). **Toluene, and xylene** were categorized as **group 3 carcinogens** (not classifiable as to their carcinogenicity to humans). Some substances were restricted in textile related regulations. For example, **1,4-dichlorobenzene, N, N-dimethylacetamide, and N, N-dimethylformamide** were **restricted** by the International Environmental Textile Association Oeko-Tex Standard 100. The latter two were also listed in the RSL list of the American Apparel and Footwear Association. **N-Methylpyrrolidone** was **restricted** by REACH regulations. Other substances, such as **dimethyl glutarate**, can **irritate the human eye, respiratory system, and skin.**	**Caprolactam 205.2 µg (N95)** **Caprolactam 153.9 µg (surgical)** **Ethylene 20.8 µg (N95)** **Ethylene 15.6 µg (surgical)** **N-methylpyrrolidon 25.6 µg (N95)** **N-methylpyrrolidon 19.2 µg (N95)**
Min 2021	Analytical study. Analysis with DCBI-MS LC-MS.	To establish a **rapid screening of the phthalate esters (PAEs)** in face masks.	Surgical (3), N95 (2), activated charcoal (2)	13 PAEs: DMEP, DEP, DAP), DPhP, BBP), DBP, DBEP, DPP, DHXP, DEHP, DNOP, DINP, DDP.	**DAP, BBP, DBP, DPP, DHXP and DE HP were detected in all masks** with an overall detection rate of 100%. The highest values were found for DHXP. The **maximal content values for surgical masks were: DAP 54.1, BBP 32.4, DBP 34.7, DPP 65.8, DHXP 168.7 and DEHP 34.8 µg/m^2 mask surface.** **For N95 masks the maximal content values were: DAP 18.2, BBP 38.8, DBP 6.8, DPP 12.5, DHXP 201.3, DEHP 19.3 µg/m^2 mask surface.**	**Some PAEs such as DHXP** were detected in a **concentration of more than 0.9 µg/g or 200 µg/m^2**, which is a **safety issue for susceptible population,** such as the elderly, children, pregnant women. **Phthalates (PAEs) from masks will enter the human body directly from the respiratory system** thus potentially threatening human health. **PAEs** are known as **endocrine disruptors** that can have **adverse effects on human hormonal balance and development, some PAEs and their metabolites are suspected to be human carcinogenic.**	**DAP 1.2443 ± 0.0368 µg (surgical)** **DAP 0.3185 ± 0.01225 µg (N95)** **BBP 0.7452 ± 0.0345 µg (surgical)** **BBP 0.679 ± 0.028 µg (N95)** **DBP 1.5134 ± 0.046 µg (surgical)** **DBP 0.119 ± 0.007 µg (N95)** **DPP 1.5134 ± 0.0414 µg (surgical)** **DPP 0.21875 ± 0.01225 µg (N95)** **DHXP 3.8801 ± 0.0897 µg (surgical)** **DHXP 3.5 ± 0.05425 µg (N95)** **DEHP 1.0396 ± 0.0437 µg (surgical)** **DEHP 0.33775 ± 0.0175 µg** (N95)
Muenster-man 2022	Analytical study, LC-qTOF, GC-MS, PIGE. Additional human exposure and risk estimates, landfill contamination estimation with leachates.	To **characterize per- and polyfluoroalkyl substances (PFAS) associated with different types of facemasks.**	9 masks: 1 N95, 6 cloth, 1 other, 1 surgical	50 target and 4886 suspect nonvolatile PFAS by LC-qTOF	**Total fluorine** was quantifiable in 5 of 9 facemasks and **ranged up to 40,000 nmol F/cm^2**. **Summed PFAS** concentrations **ranged from 15 to 2900 µg/m^2**. The surgical and N95 masks gave the lowest measured total PFAS. Of the nonvolatile PFAS, perfluoroalkyl carboxylates (PFCAs) gave the highest detection frequency, followed by fluorotelomer-based PFAS, and perfluoroalkyl sulfonates (PFSAs). Nonvolatile PFAS suspect screening revealed tentative identification of only three PFAS. **Fluorotelomer alcohol (FTOH), was estimated to be the dominant exposure route**, accounting for over 40% (children) and 50% (adults) of total median exposure to PFAS in facemasks. **High physical activity increased inhalation exposure estimates to over 70% (children), 700% (women), and 400% (men) more than the summed ingestion and dermal exposure routes.**	**In the estimates of human exposure wearing masks treated with high levels of PFAS for extended periods of time can be a notable source of exposure and have the potential to pose a health risk.**	**Σ Flourine 1.747862 ± 0.786531 ng/cloth mask** **Σ PFAS: 1.058 ± 0.368 µg/surgical** **Σ PFAS: 0.2625 µg/N95** **Σ PFAS: 20.93 ± 4.37 µg/cloth mask** **Σ PFAS: 66.7 µg/special cloth mask** **volatile PFAS 5.75 ± 0.391 µg/cloth mask** **volatile PFAS 27.6 µg/special cloth mask**

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Table 1 (*continued*)

Author and year	Type of study, method	Aim	Mask Types	Outcomes	Findings	Special risks mentioned	Maximal face mask content*
Verleysen 2022	Analytical study and estimation of the fraction of TiO_2 particles at the fiber surface. STEM-EDX analysis, ICP-OES, TEM imaging and analysis.	To evaluate whether the **TiO_2 particles** in face masks possibly present a health risk, their amounts, their properties and their localization were analysed.	Textile masks (12)	Size, morphology and agglomeration state of TiO_2 particles	STEM-EDX analysis on sections of a variety of single use and reusable face masks visualized **agglomerated near-spherical TiO_2 particles in non-woven fabrics, polyester, polyamide and bi-component fibers**. Median sizes of constituent particles ranged from 89 to 184 nm, implying an important fraction of nano-sized particles (< 100 nm). The total **TiO_2 mass** determined by ICP-OES **ranged from 791 to 152,345 µg per mask**.	The estimated **TiO_2 mass** at the fiber surface ranged from 17 to 4394 µg, and **systematically exceeded the estimated acceptable exposure level to TiO_2 by inhalation (3.6 µg).** In animal experiments, **toxic effects were reported when TiO_2 particles were inhaled, as well as when they were ingested orally.** In 2017, the Risk Assessment Committee (RAC) of the European Chemical Agency (ECHA) reviewed the **carcinogenic potential of TiO_2** and proposed to classify Titanium dioxide as **Carc. 2, H351** (suspected human carcinogen) by inhalation.	**Particle size 89-184 nm** **TiO_2 2386 ± 286 µg (single use textile mask)** **TiO_2 152,345 ± 18,281 µg (reusable community mask)**
Vimalkumar 2022	Analytical and experimental study. Analysis with GC-MS, additionally inhalation exposure assessment for 24-h (loss of analytes measured). Correlation analysis of plasticisers composition.	To determine the **occurrence of plasticizers in facemasks.**	66 textile masks	Nine phthalate diesters: DMP, DEP, DBP, DiBP, BbzP, DCHP, DnHP, DEHP, DNOP. four adipates; DEA, DBA, DiBA, DEHA. and TnBP, and DBS.	**DEHP, DBP, BBzP, and DEHA were found at mean concentrations > 500 ng/g**, whereas **DBS** was **the most predominant plasticizer,** with an overall median concentration of **> 3200 ng/g.** Among nine **phthalate diesters** measured **(mean ±SD in ng/g, DiBP 405 ± 399, DBP 620 ± 497, and DEHP 732 ± 1060** were found **in all facemask samples.** BBzP was found in 67% of the samples analysed, at a mean concentration of 598 ± 1050 ng/g. At detection frequencies of between 21% and 61% at concentrations in ng/g, DMP 34, DEP 276, DnHP 14, and DnOP 210 were found. Among **non-phthalate plasticizers, dibutyl sebacate (median: 3390 ng/g) and di(2-ethylhexyl)adipate (352 ng/g)** were found at **notable concentrations. Inhalation exposure to** select **phthalate and non-phthalate plasticizers** from the use of facemasks was estimated to **range from 0.1 to 3.1 and 3.5 to 151 ng/kg-bw/d, respectively.** DBP, DiBP, and BBzP were significantly correlated (Spearman's r = 0.253–0.599, p< 0.05). Also DiBA, DEHA, and DBS were significantly correlated with each other (Spearman's r = 0.674–0.748, p < 0.01).	**Several plasticizers are used in combination in face masks. Little is known about the toxicity of non-phthalate plasticizers. Non-phthalates plasticizer exposure for children was higher than for adults.** Face masks are not a significant source of human exposure to phthalates, but **exposure to non-phthalate plasticizers from face masks is "notable".**	**Disposable textile masks:** **DEP 5.85 µg** **DiBP 6.325 µg** **DBP 5.025 µg** **DEHP 19.175 µg** **BBzP 13.75 µg** **DBA 4.725 µg** **DEHA 14.15 µg**
Wang 2022	Experimental and analytical study, Pyrolysis-GC/MS analysis of mask material. PAEs sampling (24 h), with volume of 4 m^3. One volunteer used mask for 4.7 h and urine samples collected before and after and analysed with LC-MS.	To **assess and quantify phthalate esters (PAEs)** in face mask materials and evaluate associated inhalation **exposure risk.**	Surgical (12), N95 (4)	2 Polymers: PP and PET, 8 PAEs: DMP, DEP, DnBP, DiBP, BBzP, DEHP, DCHP, DNOP.	Mask samples were identified to be made of **polypropylene (PP)**, with polyethylene **terephthalate (PET). PAE detection** frequency (DF) was the highest for **DMP (88%), followed by DnBP (75%), DEP (69%)**, DiBP (50%) and DEHP (44%). DEHP and DiBP were higher and detected in all of the N95/P1/P2 masks but in only ~30% of the 3-layer surgical masks. Mass loss (%) of PAEs on the masks during the course was calculated as from 12% to 82%. The highest loss was observed from DEP (60 – 82%), **No obvious increase was observed for the urinary concentration of any phthalate metabolite.**	Although the **exposure may not be a concern during a single mask wearing event** for an individual, such unprecedented use of face masks worldwide means **long-term exposure at the population level**. This require a **particular attention for frontline workers** who may need to wear face masks more frequently and for longer periods of time.	**Σ PAE 1700 ± 140 ng (surgical mask)** **Σ PAE 5200 ± 800 ng (N95)** **DEP 98 ± 60 ng (N95)** **DEP 41 ± 32 ng (surgical)** **DnBP 57 ± 32 ng (surgical)** **DnBP 510 ± 630 ng (N95)** **DiBP 140 ± 54 ng (N95)** **DEHP 750 ± 270 ng (N95)**

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Table 1 (*continued*)

Author and year	Type of study, method	Aim	Mask Types	Outcomes	Findings	Special risks mentioned	Maximal face mask content*
Xie 2021	Analytical study, GC-MS, estimation of SVOCs exposure.	To explore the **occurrence and health risks of the semi-volatile organic compounds (SVOCs) exposure** from face masks.	53 masks (16 N95, 1KN90, 36 textile masks), including 25 children masks	Three categories of 31 SVOCs 14 polycyclic aromatic hydrocarbons (PAHs): naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(a)pyrene, indeno(1,2,3-cd) pyrene, dibenz(a,h)anthracene, benzo(g,h,i)perylene 4 organophosphate flame retardants (OPFRs): TnBP, 2-ethylhexyl diphenyl phosphate, tris (2-chloroethyl) phosphate, triphenyl phosphate 13 UV-filters: benzothiazole, oxybenzone, octocrylene, 2-methylbenzothiazole, benzophenone, octyl salicylate, 2-(2-hydroxy-5-methyl-phenyl)benzotriazole, octyl methoxycinnamate, 2-(3-t-butyl-2-hydroxy-5-methylphenyl)5-chlorobenzotriazole, 2-(2-Hydroxy-5-tert-octylphenyl)benzotriazole, 2,4-di-t-butyl-6-(5-chloro-2Hbenzotriazole-2-yl)phenol, 2-(2H-benzotriazole-2yl)4,6-di-t-pentylphenol, octocrylene, 2[3,5-bis(1-methyl-1-phenylethyl)-2-hydroxyphenyl]benzotriazole, hexamethylbenzene	**26 compounds were detected (10 PAHs, 12 UV-filters and 4 OPFRs)**. The total concentrations of the SVOCs ranged from 8.83 to 9200 ng/g, with a median value of 263 ng/g. **The PAHs, UV-filters and OPFRs were detected in 90.6%, 96.2% and 92.5% of the mask samples,** respectively. **N95 masks have significantly higher concentrations of PAHs and OPFRs than the surgical mask.** The detection frequencies of individual compound for the **OPFRs were found to be generally higher** than those for the PAHs and UV-filters. For the UV-filters content, no significant difference was observed between the two types of masks. **The median values of the exposures for the OPFRs, PAHs and UV-filters from the 53 face masks were 0.63, 0.98 and 0.99 ng/kg bw/d.** The median values of total concentrations of the OPFRs and PAHs in the KN95 masks were 224 and 57.1 ng/g, significantly higher than those in the disposable masks with values of 63.4 and 26.7 ng/g. While for the UV-filters content, no significant difference was observed between the two types of masks.	**Face mask can be a potential source of SVOCs exposure to humans. The cumulative carcinogenic risks (CCRs) for 39 masks exceeded the safe level for the carcinogenic risks, which accounted for 73.6% of the whole mask samples.**	**Σ SVOC 29 µg/mask** **Σ UV-filters 3.43 µg/mask** **Naphthalene 10.206 µg (N95)** **Phenanthrene 0.101 µg (N95)** **anthracene 0.126 µg (N95)** **fluoranthene 0.287 µg (N95)** **2-(3-t-butyl-2-hydroxy-5-methylphenyl)5-chlorobenzotriazole 0.305 µg (N95)** **tributyl phosphate (TnBP) 4.104 µg (N95)** **benzothiazole 22.444 µg (N95)** **benzophenone 49.978 µg (N95)** **2-ethylhexyl diphenyl phosphate 0.161 µg (KN90)** **disposable textile masks:** **triphenyl phosphate 14.4039 µg** **2-(2-Hydroxy-5-tert-octylphenyl)benzotriazole 0.013 µg** **2-(2H-benzotriazole-2yl)4,6-di-t-pentylphenol 0.063 µg** **pyrene 0.056 µg** **benzo(a)anthracene 0.042 µg** **chrysene 0.054 µg** **benzo(a)pyrene 3.046 µg** **benzo(g,h,i)perylene 0.023 µg** **tris (2-chloroethyl) phosphate 0.092 µg** **fluorene 0.114 µg**
Xie 2022	Analytical study, GC-MS, estimation of phthalate exposure.	To analyse **levels of phthalates** in face masks and to estimate **daily intake (EDI).**	56 masks (16 N95, 1KN90, 1KF94, 38 textile masks), including 16 children masks	12 phthalates: DMP, DEP, DiBP, DBP, DMEP, DPP, DHXP, DCHP, DEHP, DphP, DNOP, DNP. Three deuterated compounds were used as surrogates, DiBP-d4, DMP-d4, DEP-d4.	**11 phthalates** were determined **ranging from 115 ng/g to 37,700 ng/g** with a median level of 1950 ng/g. **Estimated daily intakes (EDIs) ranged from 3.71 to 639 639 ng/kg-bw/day**, and the EDIs of the phthalates from masks **for toddlers were approximately 4–5 times higher** than those for adults. Regarding phthalates, masks seem to have only **additional influence on daily intake rate.**	**89.3% of the mask samples exhibited potential carcinogenic effects to humans. Phthalate exposure** is reported to **affect testosterone and semen parameters as well as fetal growth** and have **reproductive toxicity.** Bis(2-ethylhexyl)phthalate (DEHP) was also found to be associated with penile birth defects and other effects related to androgen disruption.	**ΣPhthalates 191.64 µg (textile mask)** **DBP 9.66 µg (textile mask)** **DBP 1.60 µg (N95)** **DEHP 186.59 µg (textile mask)** **DEHP 26.91 µg (N95)** **DiBP 3.00 µg (N95)** **DiBP 2.84 µg (textile mask)**

Legend: Bold= Important facts, red= results with hazardous content in relation to limit values (see discussion section).

Abbreviations: BBP= butyl benzyl phthalate, BBzP= butylbenzyl phthalate, BMPP= bis(4-methyl-2-pentyl) phthalate, BW= body weight, CBS= Dibutyl sebacate, DAP= diallyl phthalate, DBA= dibutyl adipate, DEA= diethyl adipate, DEHA= di(2-ethylhexyl)adipate, DiBa= di-isobutyl adipate, DCP= diphenylcresyl phosphate,

Legend of Table 1 (*continued*):

DBEP= bis(2-*n*-butoxyethyl) phthalate, DBP= dibutyl phthalate, DCBI-MS= desorption corona beam ionization mass spectrometry, DCHP= dicyclohexyl phthalate, DDP= didecyl phthalate, DEHP= bis(2-Ethylhexyl)phthalate, DEP= diethyl phthalate, DHXP= dihexyl phthalate, DiBP= di-isobutyl phthalate DNIP= diisononyl phthalate, DMP= di-methyl phthalate, DMEP= bis(2-methoxyethyl)phthalate, DnBP= di-n-butyl phthalate, DnHP= di-n-hexyl phthalate, DNOP= di-n-octyl phthalate, DNP= dinonyl phthalate, DPhP= diphenyl phthalate, DPP= diamyl phthalate EDI= estimated daily intake, EDX= energy dispersive X-ray spectroscopy, EPFR= environmentally persistent free radical, FEG-SEM= field emission gun scanning electron microscopy, FESEM= field-emission scanning electron microscopy, FFP= filter face piece, FID= flame ionization detector, FLD= fluorescence detection, FTIR= Fourier transform infrared spectroscopy, GC= Gas chromatography, GC-MS= gas chromatography-mass spectrometry, GFAAS= graphite furnace atomic absorption spectroscopy, HEHP= hexyl-2-ethylhexyl phthalate, HP= trihexyl phosphate, HPLC= high-performance liquid chromatography, HRMS= high-resolution mass spectrometry, ICP-MS= Inductively coupled plasma mass spectrometry, ICP-OES= Inductive Coupled Plasma-Optical Emission Spectrometry, IDPP= isodecyldiphenyl phosphate, LDIR= laser infrared imaging system, LC-MS=liquid chromatography–mass spectrometry, LC-qTOF= liquid chromatography quadrupole time-of-flight mass spectrometry, MP= microplastic (<3 mm), NP= nanoplastic (<1 µm), OPE=organophosphate ester, OPFRs= organophosphorus flame retardants, PAEs= phthalate esters, PA= polyamide, PAHs= polycyclic aromatic hydrocarbons, PES= polyester, PET= polyethylene terephthalate, PFAS= Per- and Polyfluoroalkyl Substances, PIGE= particle-induced gamma emission, PP= polypropylene, PTR-QiTOF= protontransfer-reaction quadrupole-interface time-of-flight mass spectrometry, ROS= reactive oxygen species, SEM= scanning electron microscope, STEM= scanning transmission electron microscopy, SVOCs= semi-volatile organic compounds, T2IPPP= tris(2-isopropylphenyl) phosphate, TCEP= tris (2-chloroethyl) phosphate, TCIPP= tris(2-chloroisopropyl) phosphate, TCP= tricresyl phosphate, TD= thermal Desorption. TDClPP= tris(1,3-dichloro-2-propyl) phosphate, TEHP= tris(2-ethylhexyl) phosphate, TEP= triethyl phosphate, THP= trihexyl phosphate, TnBP= tri-n-butyl phosphate, TPHP= triphenyl phosphate, TPP= tripropyl phosphate, TPPO= triphenylphosphine oxide, TVOC= total VOC, UPLC-MS = ultra-high-performance liquid chromatography coupled to mass spectrometer, VOC= volatile organic compounds.

Footnote: *If maximal values are not given in the original publications, means and standard deviations are used. If required parameters not given in the studies values have been calculated (see materials & methods), with estimated weight of masks: disposable/textile community 2.5 g (Xie et al., 2021, 2022), surgical 3 g, N95 4 g (Fernández-Arribas et al., 2021), the average surgical/disposable/textile mask surface area was set as approximately 230 cm^2 (0.023 m^2) (Rengasamy et al., 2009) assuming the surface area of a standard N95 respirator to be 175 cm^2 (0.0175 m^2) (Roberge et al., 2010).

in the United States of America (USA) is being described in 2019 as high as 5.6 n/m^3 (outdoor) and 12.6 n/m^3 (indoor) and > 59% were MPs with the size of < 50 µm (Gaston et al., 2020). In Shanghai, China, the airborne MP concentration was maximum 4.18 and on average 1.42 ± 1.42 with a size range of 23–5000 µm (Liu et al., 2019). An analytic study in Paris 2017 evaluated the indoor air concentrations of 0.4–59.4 n/m^3 with 33.3% containing polymers. Outdoor fiber concentration was 0.3–1.5 n/m^3 with presence of numerous inhalable MPs below 50 µm (Dris et al., 2017).

In contrast to MPs, to date, there is no information regarding the amount or concentration of airborne NPs (Yee et al., 2021).

According to the data in our extraction tables (Table 2) and assuming a case scenario with wearing a mask appropriately for 4 h while breathing on average a total of 2 m^3 air, the mentioned average concentration of airborne MP values (USA, China, France) would be highly exceeded during mask use and breathing through (Ma et al., 2021). Under a worst case assumption, that the mask MP release during 4 h would be as high as in the analytical experiments by Ma et al. (2021), the subject wearing a mask 4 h would inhale up to 2200 n/m^3, exceeding the environmental airborne MP content of outdoor air in the USA by a factor of approximately 400 and in China and Paris even by a factor of approximately 1500. Regarding the MP concentrations in indoor air in Paris, the mask would be responsible for a 37-fold increase of the microplastic particles. Moreover, the mask release of microplastic would be shifted to extremely higher concentrations of smaller MP particles (and even NPs) than known in the environment (Delgado-Gallardo et al., 2022; Liu et al., 2022b; Ma et al., 2021).

Cox et al. have estimated that the intake of MPs by humans via food and inhalation ranges between 203 and 312 particles per day (Cox et al., 2019). Our results indicate that wearing masks may substantially increase that daily inhalation of MPs by a factor of 10 to 22 (Table 2) under assumptions of release with wearing time between 1 h and 4 h (Ma et al., 2021; Meier et al., 2022). But in other worst case release scenarios (wearing time for >4 h) the daily inhalation of MPs would even increase by a higher factor (Table 2) (Li et al., 2021a; Zuri et al., 2022).

Interestingly, the estimated daily intake (EDI) values of MPs via street dust ingestion ranges from 0.6 to 4.0 for children and from 0.3 to 2.0 particles per day for adults in Tehran, Iran (Dehghani et al., 2017). Nevertheless, in some heavily polluted areas, such as Asaluyeh County, Iran, higher EDI values of MPs for children and adults were 0.7–103.3 and 0.3–51.7 particles/d, respectively (Abbasi et al., 2023; Huang et al., 2021a).

Consequently, our results indicate that wearing masks may increase such values of inhalation of MPs by a high factor. With possible maximal mask MP release during breathing of 3090 particles/mask in only 2 h (Li et al., 2021a) and a maximal possible MP leaching of 5390 particles/mask in 24 h (Zuri et al., 2022) (Table 2) the estimated daily intakes mentioned above (even those in heavily polluted regions) might be highly exceeded while wearing a mask by a factor of 30 or more, assuming a worst case scenario (Li et al., 2021a; Meier et al., 2022) (Table 2, Fig. 3).

This can be directly relevant for the wearing person. And if popular mass mask use is established like it was during the pandemic, this is also relevant for all the people due to the increase of overall release of particles with an additional environmental exposition to fine and ultra-fine particles even without using the mask personally (Khan and Jia, 2023; Li et al., 2022; Masud et al., 2023; Morgana et al., 2021; Oliveira et al., 2023; Shen et al., 2021). Thus, for the individual even when not wearing a mask, the primary environmental air pollution is influenced by mask usage proportion in the populace and the particle release by all masks, especially when indoors. Of course, the internal direct particle release by the mask – i.e. the deep inhalation of such particles while using one – is the main risk, and the possible increase in particle concentration due to the many masks used, e.g. in crowded classrooms, malls etc. is added to this. Always, depending on the actual intention of the face mask application, a risk-benefit analysis is necessary. For example, mask use may be plausible, when the release of particles by the mask including breathing them is lower than the potential particle burden by breathing without the mask. In extreme situations, i.e. when working with extreme dust exposure, smoke etc., masks certainly make sense, but this does not apply to everyday life; common people are not constantly walking behind a grinding machine or in a burning area. Unfortunately, particularly for real-life conditions such risk-benefit-assessments do not exist and too few reliable data are available on the masḱs efficiency in protecting the general populace against air pollutants. Regarding the benefits of masks as a filter against ubiquitous pollutants including $PM_{2.5}$ hardly any clinical studies have tested how effective face masks are against everyday air pollution, or how people use them. It is hard to predict individual risks because people's exposures and health statuses vary widely (Huang and Morawska, 2019). Notably, the theoretical mask efficiency is reduced by real world conditions: In case of leakage, owing to defect or poor fit, affecting 1% of the mask area, the filtration efficiency is reduced by 50%; if the gap is 2% of the mask area, efficiency is reduced by 75% (Drewnick et al., 2021). Moreover, the real filtration

Table 2

Extraction tables of the included experimental and analytical studies on mask release of toxins (characteristics and main findings). Maximal release was used for comparison and standardisation, if necessary own calculations were performed (see footnote and materials & methods section).

Author and year	Type of study, method	Aim	Mask Types	Outcomes	Findings	Special risks mentioned	Maximal face mask release *
Chang 2022	Analytical study, flow-cell-experiment (surgical 6h, N95 12h), PTR-QiTOF.	**Highly time-resolved and nontargeted measurements of volatile organic compounds (VOCs) emitted** from face masks.	11 masks: 7 surg., 4 N95	9 VOCs: Methanol-d, propyne, propene, 1-butene and 2-butene, 1-pentene and 2-pentene and 3-methyl-1-pentene/4-methyl-1-pentene	**Typical thermoplastic materials used for filtration fibers were found (e.g. 1-butene and 2-butene, 1-pentene and 2-pentene, 3-methyl-1-pentene and 4-methyl-1-pentene).** **High concentrations of VOCs** emitted from **surgical masks** (predominant mask type) were all **concentrated in the initial 1h with >1000 µg/m^3 and then dropped** rapidly to an acceptable level after a process of naturally airing out. Surgical masks generally had higher TVOC concentrations than N95 respirators, especially in the first 2 h. **Higher emissions** from a surgical mask for children are likely due to their **colourful cartoon patterns**. Despite the lowest emissions, the **N95** respirator with an active carbon layer required 6 h to remove the **toxic methano**l (52% of N95 total VOC emissions).	**Diverse VOC species emitted, some of which are toxic (e.g. methanol).** **As an acutely toxic VOC, short-term exposure of healthcare workers to methanol by inhalation may result in dizziness, blurred vision, and headache.** **Great health concern since the emitted total VOC concentration exceeds the WHO guideline of Level 4 for TVOCs (only temporary exposure is acceptable).** **Humans can inhale VOC emissions from the mask at zero distance. In this regard, mask wearing may exert a higher risk of VOC exposure than many environmental sources.**	**average TVOC (6h) 445 µg/m^3 (surgical, adult)** **average TVOC (6h) 839 µg/m^3 (surgical, children)** **average TVOC (12h) 406 µg/m^3 (N95)** **average TVOC (12h) 91 µg/m^3 (N95 with active carbon layer)** **specific VOC release:** **Propene >40 µg/m^3 (surg., 40 min)** **Propene <10 µg/m^3 approx. 8 (N95, 40 min)** **Methanol-d 48.23 µg/m^3 (N95)**
Chen 2021	Experimental and analytical: 24 h filtered water release experiment, microplastics retained on the filter (0.8 µm pore size) were examined under stereo-microscope, Raman spectra analysis.	To **evaluate** the **ability** of **new and used masks** of different types **to release microplastics.**	18 masks: 7 surg., 2 N95, 5 medical, 4 disposable-textile	MP release capacity, characteristics of released MP (shape, color, and size), four size categories (<100 µm, 100–500µm, 500–1000 µm, 1000–2000 µm and >2000 µm).	**Released MPs** were **either fibrous or fragmentary**. **Medium size (100–500 µm)** microplastics were predominant both in fibers and fragments. **Fiber**s were predominant, accounting for more than **70%** of the total released microplastic. Average **amount of microplastics** released was 183.00 ± 78.42 particles/piece while microplastics release from used DFMs was 1246.62 ± 403.50 particles/piece in 24 h. **Microplastics released from used ones increased significantly than the new ones from 6.0 to 8.1 times**. N95 released more MPs than surgical.	**Microplastics released from used ones increased significantly than the new ones.** Large amount of fibers carried by the fabric material of the masks themselves, but also because of the process of use that would further promote the **production and release of**	**MP 222.17 ± 98.79 / new N95 mask (24h)** **MP 1478.00 ± 265.80 / used N95 mask (24h)**
Delgado-Gallardo 2022	Analytical and experimental; water leaching (4h) and separation of particles, 0-1 and 0.02 µm pore size inorganic membranes were used to retain and subsequently analyze nanoparticles (>20 nm). Optical Microscopy, FEG-SEM with Energy-Dispersive Spectroscopy, Elemental characterisation of particles, LC−MS analysis, ICP-MS Elemental Analysis for heavy metals.	To study the **release of micro- and nanopollutants** into the environment from medical masks.	Surgical (3) and N95 (3) masks	Micro- and naoparticles, 11 heavy metals (As, Cd, Cr, Co, Cu, Mo, Ni Pb, Sb, Ti, and Hg), organic contaminants	FFP2 and surgical masks release **MP, NP and fiber**, most likely made from polypropylene, **in the micro- and nanoscale**. **FFP2 emit more fibers than surgical masks** (significant amounts of additional microplastic particles). **Chemical elements found in particles were 3.65% of As, 3.47% of Cd, 3.73% of Cu, 4.71% of Hg, 3.96% of Ni, 5.65% of Pb, and 4.92% of Sn.** **Masks emit heavy metals** (antimony up to 2.41 µg/L and copper up to 4.68 µg/L). Polar leachable organic species related to **plastic additives and contaminants**, polyamide-66 monomer and oligomers (nylon-66 synthesis), surfactant molecules, and PEG.	**The presence of particles containing heavy metals in the masks is of particular concern.** These results **claim for stricter regulations to be put in place**. Also, a complete **investigation must be done to clarify the extent of the risks and the potential impacts** of the fibers and particles released. The presence of particles containing heavy metals in the masks is of particular concern as it is unknown how strongly they are bonded to the mask fibers.	**Cd 0.001 µg (surgical)** **Co 0.003 µg (N95)** **Cr 0.029 µg (N95)** **Cu 4.676 µg (surgical)** **Mo 0.019 µg (N95)** **Ni 0.025 µg (surgical)** **Pb 0.052 µg (surgical)** **Sb 2.413 µg (N95)** **Ti 0.083 µg (surgical)** **V 0.002 µg surgical**

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Table 2 (*continued*)

Author and year	**Type of study, method**	**Aim**	**Mask Types**	**Outcomes**	**Findings**	**Special risks mentioned**	**Maximal face mask release ***
Dissanayake 2021	Experimental in-vitro analytical study, FTIR, water based leaching (48 h), 0.45 µm nitrocellulose filter, digital. microscopy (400x).	Preliminary **quantification of number of bigger (light microscopic) microplastic fibers released** by different face masks to aqueous medium.	13 masks: 3 surgical 3 KF94 3 KF-AD 4 FFP1	Fiber count and composition	>**84% polypropylene (outer layer)**, and **polystyrene. (inner layer). Microplastic <3mm with fibers less 1mm: Surgical masks released higher number (>100).**	**Microplastics are carriers of biofilm and pathogenic microorganisms.**	**81 ± 7 MP fibers (KF-AD)** **147 ± 18 MP fibers (KF94)** **169 ± 31 MP fibers (surgical)** **143 ± 16 MP fibers (FFP1)**
Kerkeling 2021	Analytical study, emission measurements in a micro-chamber thermal extractor at 40°C: 17-170 min, TD, GC, MS, FID.	**Investigations** into **volatile organic compound (VOC) emissions** from polymer fleeces used in particle filtering half masks, evaluation against the German hygienic guide values and provide an **initial, tentative toxicological evaluation**.	47 masks: 31 FFP2, and 16 KN95	Aromatics, Siloxanes, Terpenes, Caprolactam, Aldehydes, Alkanes, Alcohols, Esters, Amin, Phthalates	**All masks** showed emission of **xylene.** in most cases, aromatic compounds such as **Toluene and other alkylated benzenes and a variety of different alkanes.** **In 94 % of samples,** up to 24 **additional aromatic compounds** were found. 17 % of samples showed terpenes, **53 % emitted aldehydes, 77 % exhibited caprolactam and 98 % released siloxanes. Exponential decline of VOC levels. emission rate declines rapidly over the first few hours and emissions seem to stabilize at 16 mg/m^3.** Half of the measured emissions are inhaled while the other half is exhaled.	**All masks exceeded the TVOC hygienic guidance value level 5 of 10 mg/m^3. Emissions reach a constant level after an initial decrease.** The user might already be exposed to individual VOCs in indoor air, which would increase the total VOC intake.	**Total VOCs 403 mg/m^3 (N95)** **Xylene 12 mg/m^3 (N95)**
Hui Li 2022	Analytical and experimental study. Water, HNO_3 and NaOH based leachates (24h), GFAAS, ICP-OES, FESEM-EDX, GC-MS.	**Identifying and quantifying the major chemicals** released from face masks **including the facemasks' fibers.**	100 surgical masks	Microfiber degradation, 3 heavy metals: Pb, Cd, Cr, 7 VOCs (4-methylheptane, 2,4 dimethylhept-1-ene, Heptacosane, Heneicosane, Octadecane, Octacosane, Pyridine-3-carboxamide	**pH-dependent degradation of microfibers. Pb (3.238% ppb), Cd (0.672 ppb) and Cr (0.786 ppb)** were found. Additionally, **2,4-dimethylhept-1-ene and 4-methylheptane** were identified as **the VOCs.**	The experiments indicate a **pH-related degraded material.** **VOC emissions** can vary over the lifespan of the polymer because **polymers deteriorate due to several factors such as thermal stress and UV exposure**, even under normal circumstances. **Pb, Cr, and Cd** hold **high potential to harm human health and the environment.**	**Pb 2.322 ± 0.138 ng (surgical)** **Cd 0.672 ± 0.009 ng (surgical)** **Cr 0.747 ± 0.071 ng (surgical)**
L. Li 2021	Experimental, with 2h (up to 720h) breathing simulation with vacuum pump (collection of filtrated microplastic), microscopic analysis with Raman spectroscopy, FTIR, LDIR.	**Investigating microplastic inhalation risk**. Microplastic inhalation caused by reusing masks that underwent various treatment processes was also tested.	7 masks: 1 N95, 2 surgical, 4 other types	Microplastic and particles 20-500µm	**Inhaled microplastics were mostly fiber-like and spherical types, 20 µm to 500 µm, over 90% of the identified particles are 20–100 µm.** When suction time was 2 h, the spherical-type particles observed with the N95, surgical-A, cotton, fashion, nonwoven, surgical-B, and activated carbon masks, and without a mask were 1695, 1808, 2241, 3110, 2152, 3090, 2212, and 3918, respectively). The amount of fiber-like microplastics was determined to be 25, 38, 92, 69, 47, 112, 153, and 172 particles after the continuous use of N95, surgical-A, cotton, fashion, nonwoven, surgical-B, and activated carbon masks, and in the blank case, respectively, based on 2 h of simulated respiration. Mask disinfection processes led to varying extents of microplastic inner structure damage, increasing the risk of microplastic inhalation.	**Wearing masks poses microplastic inhalation risk, reusing masks increases the risk.** This study was not conducted in super-clean laboratory, no contamination control measures were applied, thus it is not clear whether the control air in the blank measurements (no mask) does not correspond to the air already contaminated by mask handling.	**>90% of face mask particles 20-100 µm** **Spherical-type particles:** **1695 MP (N95, 2h)** **3090 MP (surgical, 2h)** **Fiber-like particles:** **25 (N95, 2h)** **112 (surgical, 2h)**

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Table 2 (*continued*)

Author and year	Type of study, method	Aim	Mask Types	Outcomes	Findings	Special risks mentioned	Maximal face mask release *
Liang 2022	Analytical and experimental study. Deionized, filtered water based 24h to 168h release experiment (0.45 µm cellulose ester membrane filter), optical microscope, Raman microscope.	To identify the **microplastics released and measure their quantities,** also **analysing microplastic release kinetics.**	12 medical masks, thereof 4 N95, 4 medical 4 surgical	Microplastics: length, shape, and colour. release kinetics: mass loss of mask, microplastic release change over time.	**Microplastics of 100–500 µm and of <100 µm were released in large quantities and at rapid rates.** Fiber and transparent microplastics accounted for a large proportion and **their daily release proportion increased with time.** **Polypropylene microplastics fibers and debris were released.** **N95 masks** released **801 ± 71 to 2667 ± 97 microplastic particles (piece/24 h), surgical masks** released **1136 ± 87 to 2343 ± 168 microplastic particles (piece/24 h),** and normal medical masks **released 1034 ± 119 to 2547 ± 185 microplastic particles (piece/ 24h).** The mass loss ranged from 0.293 ± 0.03 to 0.831 ± 0.035 mg/piece/ 24h. The percentage mass loss of masks in this study ranged from 0.006% to 0.019%. The cumulative release quantities increased from 1034 ± 119–2457 ± 135 particles/piece on the first day to 1737 ± 82 to 4270 ± 185 particles/piece on the seventh day. **Microplastics release was rapid with the increase in release quantity on the first day.** The Elovich equation described the release kinetics of microplastics well.	**Wearing masks poses risks of microplastic inhalation and ingestion.** **Plastic pollution from face masks has become a major environmental and health concern (indirectly and directly).**	**MP (24h) 0.831 ± 0.035 mg / N95** **MP (24h) 2667 ± 97 particles / N95** **MP (24h) 2343 ± 168 particles / surgical** **MP 2547 ± 185 particles / medical**
Z. Liu 2022	Experimental in-vitro analytical study with filtered deionized water leaching (15d), stereo-microscope analysis, SEM, FTIR, GC-SM and ICP-OES and cell culture toxicological measurements (24h).	**Verifying** the **release of chemical compounds** and **generation of environmental persistent free radicals (EPFRs)** after exposing face masks to water, and assess the toxicity of the leachate.	8 masks: 6 surg., 2 N95	MP release, non-organic and organic chemical substances, EPFRs, Viability of mc3t3e1cell	**MP´s being fibrous (80.3-97.4%), rarer particle (<10%), consisting of polypropylene >89.2%, range of 76-276 items/L (blue and transparent). Abundance of MP´s 40-75µm (37.1-47.6%).** Metals as **Co (8.0µg/L), Cu (8.3 µg/L), Ni (2.8µg/L), Sr (14.4µg/L), Ti (9.2µg/L) and Zn (17.7µg/L)** detected in all samples **Cd (1.3µg/L), Cr (0.8µg/L), Mn (2.9µg/L) and Pb (1.3µg/L)**, presented in the surgical masks. **Organics**, such as **acetophenone (6.8 µg/L), 2,4-Di-tert-butylphenol - DTBP (3.8µg/L), benzothiazole (9.2µg/L), bisphenol-A (3.2µg/L), phthalide (4.1µg/L)**, but also tributyl acetylcitrate and benzaldehyde detected. **Environmentally persistent free radicals (EPFRs)** generated in the leachates with characteristic **g-factors in a range of 2.003–2.004 G**, identified as mixture of carbon- and oxygen-centered radicals (superoxide radical and methyl radical). **Viability of mc3t3e1cell** was **significantly decreased** after exposing to leachate (**excessive oxidative stress to the test cells**).	**Contact allergy to Cr, Ni and Co** is the most common metal allergy (1–3%). **Cd, Co, Cr and Pb** was reported to have potential **carcinogenic risk.** Multiple **metal–metal interactions** of, e.g. Cd, Cu, Ni, and Zn, may contribute to a **higher toxicity in a mixture.** **EPFR´s cause cytotoxicity and oxidative stress.** By inducing r**eactive oxygen species (ROS)** and overloaded ROS may induce oxidative stress, further causing cardiopulmonary dysfunction and chronic respiratory diseases.	**Co 4.0 µg (surgical)** **Cu 4.15 µg (surgical)** **Ni 1.4 µg (surgical)** **Sr 7.2 µg (surgical)** **Ti 4.6 µg (surgical)** **Zn 8.85 µg (surgical)** **Cd 0.65 µg (surgical)** **Cr 0.4 µg (surgical)** **Mn 1.45 µg (surgical)** **Pb 0.65 µg (surgical)** **Acetophenone 3.4 µg/L** **2,4-Di-tert-butylphenol - DTBP 1.9 µg** **Benzothiazole 4.6 µg** **Bisphenol-A 1.6 µg** **Phthalide 2.05 µg** **g-factors 1.002 G**

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Table 2 (*continued*)

Author and year	Type of study, method	Aim	Mask Types	Outcomes	Findings	Special risks mentioned	Maximal face mask release *
Ma 2021	Experimental in-vitro and in-vivo qualitative and quantitative analytical study, filtered water leaching (4h) analysed on silicon wafer with SEM, FTIR but also retention of MPs in human nasal mucus after wearing a mask for 1-2h with fluorescence microscope of nasal rinsings.	**Quantify** and characterise face mask **released particles** and **evaluate** their **potential for accumulation** in humans.	8 surg. and 2 N95 masks (10)	Microparticles-(MPs) and Nanoparticles (NPs)	**>1,000,000,000 of NPs and MPs were released from** each **surgical or N95** face mask, mostly irregularly-shaped particles sized from 5 nm to 600 µm. **Most of them <1 µm. N95 masks release more and smaller NPs than surgical masks ($p < 0.05$). MPs were detected in the nasal mucus of mask wearers. Higher breathing frequency resulted in a larger number of particles detected in the nasal mucus ($p<0.05$).**	**MPs >1 µm occupied only a minor fraction of the particles, ranging from 1.3 to 4.4×10^3 per mask. Most particles in the masks were nano scale sized<1 µm.** **PM$_{2.5}$ (Particulate matter < 2.5 µm) is well-known for generating adverse effects in humans.** **PM$_{0.1}$ (<0.1 µm) have even more harmful effects such as alveolar inflammation and exacerbation of pre-existing cardiopulmonary diseases.**	**6×10^9 NPs (N95 > surgical, 4h)** **4.4×10^3 MPs (N95, 4h)** **2.9×10^3 MPs (surgical, 4h)**
Meier 2022	Experimental in-vitro qualitative and quantitative analytical study. Air based extraction with Sheffield heads(12.0µm Nuclepore filter membrane) debris extraction (1h and 8h), deionized filtered water based liquid fiber and particle (0.4µm Nuclepore filter membrane) extraction (45min), optical analysis (NanoSight LM20), ICP-MS. Cell culture (48h).	To quantify the **debris release (fibers and particles) and metals** from a textile-based facemask in comparison to a surgical mask and a reference cotton textile using both liquid and air extraction, **possible adverse effects** on cell culture.	Surgical masks (2), textile based face masks (5)	fiber and particle release, metal content (Cr, Co, Cu, Fe, Pb, Mn, Ni, Ag, Zn).	**Release of 740 particles per surgical mask (SM) in breathing simulation** (air based extraction 8h), of which 404 with 0.3 µm. **Under liquid extractions, SM released up to 1030 ± 115 fibers g^{-1} textile, corresponding to 3152 ± 352 fibers per mask.** The sum metal content of calibrated elements (Cr, Co, Cu, Fe, Pb, Mn, Ni, Ag, Zn) was 43 ± 2 µg g^{-1} for SM. Several metals including copper (up to 40.8 ± 0.9 µg g^{-1}) and iron (up to 7.0 ± 0.3 µg g^{-1}). Mask debris show no acute in vitro cytotoxicity to human lung cells	The in vitro **acute cytotoxicity assessment does not allow prediction of possible long-term exposure effects** (long-term toxicity assessment on in vitro and in vivo lung exposure models).	**ΣFibers 3152 ± 352 (surgical, average)** **Σmetal release: 131.6 ± 6.1 µg (surgical)** **Σmetal release: 211.7 ± 39,7 µg (coated cotton)** **Cu 125.5 ± 3.06 µg (surgical)** **Fe 92.61 ± 10.6 µg (coated cotton)**
Sullivan 2021	Experimental in-vitro qualitative and quantitative analytical study, water based leaching (4h) analysed with FTIR, SEM-EDX, light microscopy, ICP-MS and LC-MS.	To identify and characterize various **released pollutants (heavy metals),** emitted/leached from face masks including **micro (<1 mm) and nano-particles (0.1–1 µm).**	Textile masks (7)	Micro and nano-fibers and particles (MP´s and NP´s), heavy metals: Cd, Co, Cu, Pb, Sb, and Ti	Significant amount of **grain-sized particles** measured between **360 nm-500 µm, micro- and nano-scale corresponding to MP and NP. Polymeric fibers (25 µm to 2.5 mm) found.** Fibrous particles had high percentage of carbon, the grains contained high percentages of Si and oxygen. Polar organic species pollutants: **Polyamide-66, polyamide-6** and various oligomers of polyamide (PA) found, also **polyethylene glycol** (PEG) derivatives and **aromatic amines**.Heavy metals: **Cd (1.92 µg/L), Co (0.59 µg/L), Cu (4.17 µg/L), Pb (6.79 µg/L), Sb (393 µg/L) and Ti (0.64 µg/L)** found in masks.	Even **low exposures to Pb** can lead to **neurological damage** and be detrimental to **foetal development. MPs and NPs** exhibit **cytotoxic and genotoxic effects including neurotoxicity and oxidative stress.**	**Cd 0.48 µg (textile mask)** **Cu 1.04 µg (textile mask)** **Co 0.14 µg (textile mask)** **Pb 1.69 µg (textile mask)** **Sb 98.3 µg (textile mask)** **Ti 0.16 µg (textile mask)**
Zuri 2022	Analytical and experimental study, migration water experiment, (24h), collection with 20 µm nylon filters, Stereo-microscope, µ-FTIR, UPLC-MS.	To evaluate the **migration of microplastics (MP) and phthalates.** Migration was evaluated according to the conditions stated in EU Regulation No 10/2011 on plastic materials and articles intended to come into contact with food.	3 FFP2, 1 surgical	MP-morphological analysis (shape, dimension, particle count), 11 phthalates: DMP (dimethyl phthalate), DEP (diethyl phthalate), BBP (butylbenzyl phthalate), DBP (dibutyl phthalate), DPP (dipropyl phthalate), BMPP (bis(4-methyl-2-pentyl) phthalate), DnHP (di-hexyl phthalate), HEHP (hexyl-2-ethylhexyl phthalate), DEHP (diethylhexyl phthalate), DNOP (di-n-octyl phthalate) and DNP (di-nnonyl phthalate)	All masks released particles in form of fibers and fragments. **Polypropylene (PP) and polyamide (PA)** were released **as fragments**, while both **PP and polyester (PES)** were released **as fibers**. **Each mask could potentially release from 2040 to 4716 MP/mask.** Additionally, **phthalates including DBP, BBP, DNOP, and DEHP were also released.**	**MP** affect biota and also represent a **health hazard for humans,** specifically a **risk of MP inhalation through breathing.** Additionally, MP could carry other potentially harmful compounds and heavy metals that can be introduced in the human body. **Concerning phthalates DEHP has been identified as an endocrine disruptor, BBP is classified as a reproductive toxicant.**	**5390 MP (FFP2, 24h)** **4716 MP (surgical, 24h)** **Σ Phtalates 35 µg (FFP2)** **Σ Phtalates 25.3 µg (surgical)** **DBP 21.1 µg/FFP2** **BBP 13.6 µg /surgical** **DNOP 4,96 µg/FFP2** **DEHP 4.59 µg/FFP2**

Legend of Table 2 (*continued*):

Legend: Bold= Important facts, red= results with hazardous release in relation to limit values (see discussion section).

Abbreviations: BBP= butyl benzyl phthalate, BMPP= bis(4-methyl-2-pentyl) phthalate, DBP= dibutyl phthalate, DEP= di-ethyl phthalate, DEHP= bis(2-Ethylhexyl) phthalate, DMP= di-methyl phthalate, DnHP= di-n-hexyl phthalate, DNOP= di-n-octyl phthalate, DNP= dinonyl phthalate, DPP= diamyl phthalate, DTBP= 2,4-Di-tert-butylphenol, EDX= energy dispersive X-ray spectroscopy, EPFR= environmentally persistent free radical, FEG-SEM= field emission gun scanning electron microscopy, FESEM= field-emission scanning electron microscopy, FFP= filter face piece, FID= flame ionization detector, FTIR= Fourier transform infrared spectroscopy, GC= Gas chromatography, GC-MS= gas chromatography-mass spectrometry, GFAAS= graphite furnace atomic absorption spectroscopy, HEHP= hexyl-2-ethylhexyl phthalate, ICP-MS= Inductively coupled plasma mass spectrometry, ICP-OES= Inductive Coupled Plasma-Optical Emission Spectrometry, LDIR= laser infrared imaging system, LC-MS=liquid chromatography–mass spectrometry, MP= microplastic (<3 mm), NP= nanoplastic (<1 μm), PES= polyester, PP= polypropylene, PTR-QiTOF= protontransfer-reaction quadrupole-interface time-of-flight mass spectrometry, ROS= reactive oxygen species, SEM= scanning electron microscope, TD= thermal Desorption, TVOC= total VOC, UPLC-MS = ultra-high-performance liquid chromatography coupled to mass spectrometer, VOC= volatile organic compounds

Footnote: *If maximal values are not given in the original publications, means and standard deviations are used. If required parameters not given in the studies values have been calculated (see materials & methods), with estimated weight of masks: disposable/textile community 2.5 g (Xie et al., 2021, 2022), surgical 3 g, N95 4 g (Fernández-Arribas et al., 2021), the average surgical/disposable/textile mask surface area was set as approximately 230 cm^2 (0.023 m^2) (Rengasamy et al., 2009) assuming the surface area of a standard N95 respirator to be 175 cm^2 (0.0175 m^2) (Roberge et al., 2010).

efficiency is significantly lower than the theoretical laboratory filtration efficiency – by 12.4% and 46.3% for surgical and N95 masks, respectively (Shah et al., 2021). National and international standards for bacterial filtration efficiency (BFE) have been existing since decades for medical masks, e.g. the EU-EN 14683, or the USA-ASTM F2101, and they are the prerequisites for general approval. In the case of N95, a 95% filtering capacity for fine particles up to at least 0.3 μm exists (NIOSH, 2020). Thus, even without a consideration of above mentioned real-world conditions, from a strict normative perspective, significant filtering with N95 masks of particles of less than 0.3 μm which also belong to the $PM_{2.5}$ fraction, appears questionable.

Indeed, in a real world scenario regarding the environmental microplastic burden and face masks, there is a mathematical challenge with lots of variables. Undoubtedly, further research is needed to clarify the significance and interaction of the numerous variables. Until then, to ensure human safety, our analysis should urge caution with mask use at least in the general populace. As the risk of wearing a mask must be lower than not wearing one we have ensured a preliminary toxicological risk assessment, using worst-case consideration which is necessary in such a protective approach (Directorate-General for Health and Consumers, 2013).

4.1.3. Limits for MPs (NPs)

A regulatory standard for MP and NP release from medical masks is not established so far.

In contrast, efforts by major public health and environmental organizations around the world to reduce the dangers posed by particulate matter are intensifying (US EPA, 2016b).

MPs are categorized according to their diameter into particles > 10 μm, particles < 10 μm (PM_{10}), particles < 2.5 μm ($PM_{2.5}$), and ultra-fine particles < 0.1 μm (Kelly and Fussell, 2012). The large particles > 10 μm are assumed to collide with the upper airways upon respiration, whereas PM_{10} can enter the bronchioles, and $PM_{2.5}$ and ultra-fine particles can penetrate the alveoli (Kelly and Fussell, 2012; Prata et al., 2019; Wieland et al., 2022). The shape of MPs influence their toxicity by modifying interactions with cells and tissues (shape-specific toxicity) (Allegri et al., 2016; Wieland et al., 2022). Moreover, the surface charge of micro-particles can affect their toxicity (particles

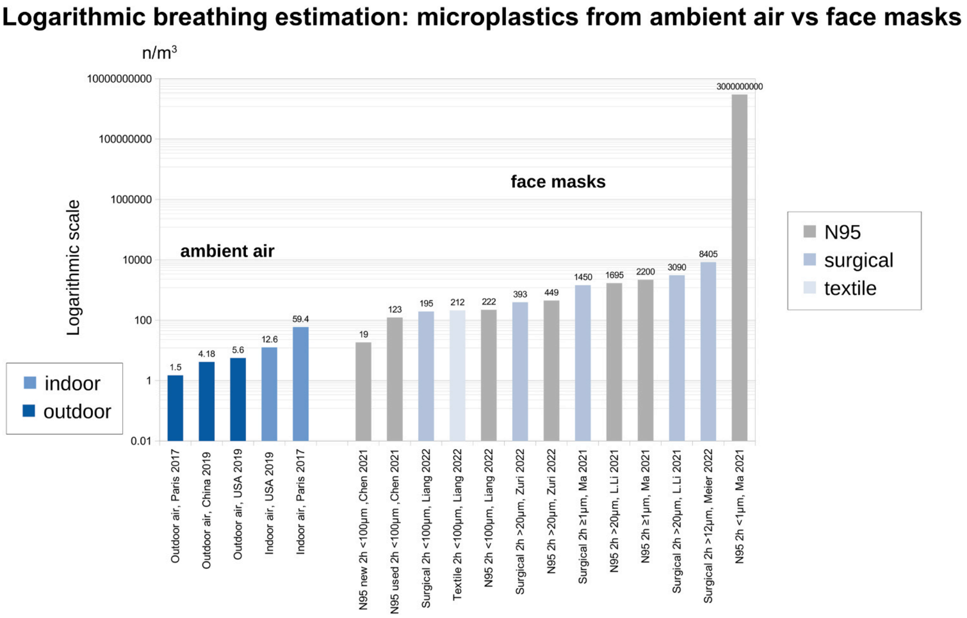

Fig. 3. Worst case microplastic (MP) release scenario from diverse face masks during 2 h compared to pre-pandemic ambient air values (n particles per m^3 air). Graph with logarithmic scale due to very large differences between ambient air and face mask situation for the breathing user. Legend: Microplastic content of ambient air taken from Liu 2019 (Liu et al., 2019), Gaston 2020 (Gaston et al., 2020) and Dris 2017 (Dris et al., 2017). Calculated worst case microplastic particle release from masks referring to the mentioned studies (Table 2) (Chen et al., 2021; Li et al., 2021a; Liang et al., 2022; Ma et al., 2021; Meier et al., 2022; Zuri et al., 2022), normalised to 1 m^3 (assuming simplification that 2 h face mask wearing corresponds to approximately 1 m^3 breathing and particle release is linear). Please note: Only Ma used ultrafine particle filtering methods and SEM (Ma et al., 2021).

Table 3A
Exemplary limit threshold exceedance for microplastics, MP ($PM_{2.5}$) in worst case scenario while wearing a mask.

Publication	Mask type	Outcome	Result*	AQG WHO (2021) threshold value**	Factor of exceedance
Liang et al. (2022); Ma et al. (2021)	**N95**	MP ($PM_{2.5}$) release	**41.55 μg/m^3** (72 min use)	5 μg/m^3 ($PM_{2.5}$) *annual average*	**8.31**
Liang et al. (2022); Ma et al. (2021)	**surgical**	MP ($PM_{2.5}$) release	**33.9 μg/m^3** (72 min use)	5 μg/m^3 ($PM_{2.5}$) *annual average*	**6.78**
Liang et al. (2022); Ma et al. (2021)	**N95**	MP ($PM_{2.5}$) release	**41.55 μg/m^3** (72 min use)	15 μg/m^3 ($PM_{2.5}$) *3 to 4 days (24 h) per year.*	**2.77**
Liang et al. (2022); Ma et al. (2021)	**surgical**	MP ($PM_{2.5}$) release	**33.9 μg/m^3** (72 min use)	15 μg/m^3 ($PM_{2.5}$) *3 to 4 days (24 h) per year.*	**2.26**

Legend: MP= Microplastic, $PM_{2.5}$ = Particulate matter (≤2.5 μm), WHO= World Health Organisation.
Footnotes: **calculated from 831 μg/24 h (N95) and 678 μm/24 h (surgical) (*Liang et al., 2022*). Particles are assumed to be predominantly less or equal to 2.5 μm (*Ma et al., 2021*). Breathing air is estimated to be 10 m^3 in 12 h according to USEPA (*US EPA, 1989*). Particle release in the first 24 h is estimated to be linear (34.63 μg/h and 28.25 μg/h for N95 and surgical mask, respectively) (*Liang et al., 2022*).*
**for further details see discussion section, limits for MP/NP.

potential, electrostatic interactions of MPs with cells and tissues including adhesion) (Peltonen and Hirvonen, 2008; Silva et al., 2014; Wieland et al., 2022).

MP adsorption of molecules, leaching of softeners and microorganisms can additionally modify their toxicity. The MPs may act as a carrier of adsorbed toxins or pathogenic bacteria and fungi (Buzzin et al., 2022) enlarging their potential to impact human health (Sun et al., 2021; Wieland et al., 2022).

Concerning microplastic particles, being a relatively new and modern environmental harm, only few official limits exist (Rahman et al., 2021). For example, the updated WHO Air Quality Guidelines (AQG) state that annual average concentrations of $PM_{2.5}$ should not exceed 5 μg/m^3, while 24-hour average exposures should not exceed 15 μg/m^3 more than 3 to 4 days per year (World Health Organization (WHO), 2021).

According to our data (Table 2) those thresholds appear to be exceeded while wearing a mask in a worst case scenario. A release of 34.63 μg MP per hour per mask (N95) may be possible (Liang et al., 2022). Considering that only a few reliable studies with adequate fine particle filtering (e.g. silicon waver) and analytical methods (e.g. SEM) exist on mask-released particles (Ma et al., 2021), only these can be used to estimate the exact size of the released smaller particles. In fact, Ma et al. detected very small particles being predominantly < 1 μm – equivalent to at least $PM_{2.5}$ (Kelly and Fussell, 2012; Ma et al., 2021). Thus, we can assume for the worst case scenario, that wearing face masks, particularly N95 masks, may lead to highly exceeding the WHO $PM_{2.5}$ guidelines for 24-hour average exposure of 15 μg/m^3 (Table 3A). Also the annual average concentrations of 5 μg/m^3 $PM_{2.5}$ could have been exceeded, e.g. during mask wearing enforced by law during 2020–2023 with regular and/or daily use of masks in many countries (Face covering policies during the COVID-19 pandemic, 2023). None of the existing medical mask standards, including the ASTM standards (F1862, F2100, F2101, F2299) and NIOSH regulation (42 CFR 84), which are adopted by the FDA in regulating medical face masks and surgical respirators in the U.S (U.S. Food and Drug Administration FDA, 2023), regulate respirable debris such as micro(nano)plastics that may be present in these products. ISO standards (ISO 22609, 16900), EU standards (EN 140, 143, 149, 14683) and Chinese standards (GB 19083, 2626; GB/T 32610, 38880; YY 0469; YY/T 0969) on masks and respirators give no information pertinent to the particular type of microplastic related hazard. However, according to our data those appeared necessary for many in their daily life and work, particularly during the pandemic. Thus, questions must be raised over this apparent regulatory gap concerning the long-term use safety of face masks (Han and He, 2021).

4.1.4. MP and NP risks

The toxicology of fibers and particles is becoming more and more important as the modern world contains ever more artificial objects (Donaldson and Seaton, 2012; Riediker et al., 2019). Noteworthy is the fact that plastic particles released in the course of medical treatment and application of implants have been known since decades to be responsible for undesirable reactions in diverse tissues (Kisielinski et al., 2003a, 2003b, 2004; Klinge and Klosterhalfen, 2018; Klosterhalfen et al., 2005). But above all, the breathing of microplastics has become more and more a health risk concern (Gasperi et al., 2018). MPs found in nasal mucus following mask use (Klimek et al., 2020; Ma et al., 2021) and complaints of throat irritation or discomfort in the respiratory tract by children, the elderly adult, or other sensitive individuals after using face masks are alerting signs of respectable amounts of respirable debris inhaled from masks and respirators (Howie et al., 1986; Prata, 2018). There is very recent evidence of MPs isolated in lower airway of European citizens examined in 2021, a time with rigid mask mandates and a year after they had been introduced during the pandemic (Baeza-Martínez et al., 2022). The involved subjects came from regions, where face mask mandates were enforced by law and widely followed (Face covering policies during the COVID-19 pandemic, 2023). Another scientist team could show resembling results in a similar investigation period with microplastic particles in all parts of the lungs containing predominantly polypropylene and polyethylene (Jenner et al., 2022), which are the most common components of the face mask (Zuri et al., 2022). Thus, a correlation of mask wearing and the recently detected high amounts of MP in human lungs appears conclusive (Khan and Jia, 2023; Klimek et al., 2020; Ma et al., 2021). Generally, it can be concluded that face masks contribute to direct microplastic inhalation risk (Khan and Jia, 2023) and therefore expose the mask user immediately to health risks (Almeida and de Souza, 2021; Gasperi et al., 2018; Kutralam-Muniasamy et al., 2023; Prata et al., 2020). Special consideration must be given to the fact that due to increased breathing resistance wearing a mask can cause substantial damage to nasal airflow (Kisielinski et al., 2021; Lee and Wang, 2011). Due to the presence of the mask, people have a natural tendency to breathe through the open mouth which means less breathing resistance bypassing the nasal airflow (Kisielinski et al., 2021; Wyszyńska et al., 2022). Usually under natural nose breathing (Thomas, 2013) particles impact further up the respiratory airways depositing in a size-dependent manner from the nasal passages to the larger bronchioles. The nose effectively filters foreign particles that enter the nasal cavity dependent on particle size and air flow rate with filtration efficiency decreasing with smaller particle size. Therefore, usually only smaller particles (<1–3 μm) diffuse deep into the lung tissue, depositing in the alveoli by a number of mechanisms including diffusion, sedimentation, and electrostatic effects. This relationship (particle size-depth of diffusion and deposition) is constant across humans (Heyder et al., 1986; Thomas, 2013). Most humans incline to revert to oral breathing during mask wearing (Kisielinski et al., 2021; Wyszyńska et al., 2022). This significantly increases the amount and size of particles that may be directly inhaled into the bronchi and lungs due to bypassing the filtration of the nasal cavity (ICRP, 1994). In a human study using a radiolabelled aerosol, scientists found a huge increase in deposition in the lungs (+37%) when breathing through the mouth compared to the nose (75% vs. 38%) for particle diameters averaging 4.4 μm (range 3.8–5.1 μm) (Everard et al., 1993). Thus, taking into account the nearly zero distance to the airways and the predominant mouth breathing, the particle release from masks and their appearance in the mask breathing zone, appear to be worse (predominant mouth breathing) than similar particle presence in normal air in the no mask condition (predominant nose breathing). This seems comparable to the difference between active and passive cigarette smoking, with higher risk for active smokers due to frequent inhalation of particles directly at nearly zero distance through mouth breathing (Barnoya and Glantz, 2005). In this respect, the use of room air limit values in the evaluation of (predominantly oral) respiration from the mask breathing zone (with the particles released there) does not seem entirely appropriate for comparison. Noteworthy is, that inhaled ultra-fine particles can penetrate the alveoli where they can enter the bloodstream (Wieland et al., 2022). In addition, scientific reports exist on microplastics in human blood with evidence of origin from masks used worldwide (Kannan and Vimalkumar, 2021; Leslie et al., 2022).

MPs exposure can cause toxicity through oxidative stress, inflammatory lesions and there is a potentiality of metabolic disturbances, neurotoxicity, and increased cancer risk in humans (Rahman et al., 2021).

According to the WHO, air pollution (including MPs and NPs) is the second highest risk factor for noncommunicable diseases (World Health Organization, 2019).

For the long term exposure, there is clear evidence that both $PM_{2.5}$ and PM_{10} were associated with increased mortality from all causes: cardiovascular disease, respiratory disease and lung cancer. And the associations even remained below the former 2005 WHO guideline exposure level of 10 $\mu g/m^3$ for $PM_{2.5}$ (Chen and Hoek, 2020; WHO, 2005).

Moreover, even the short-term exposure to particulate matter with aerodynamic diameters less or equal than 10 and 2.5 μm (PM_{10}, $PM_{2.5}$) are positively associated with increased cardiovascular, respiratory, and cerebrovascular mortality (Orellano et al., 2020).

The toxic effects of micro- and nanoplastics comprise inflammation with disruption of immune function (increased IL1-q, IL-1ß, IL-6, IL-8, IL-10) oxidative stress and apoptosis (increased ROS, ER stress), as well as disturbance of metabolic homeostasis (altered channel function of K^+-channels, blocking of vesicle transport, dysbiosis, intestinal barrier function disturbance, absorption disturbance, impairment of energy metabolism), neurotoxicity (AChE activation), reproductive toxicity and DNA-damage (DNA breaks) (Lai et al., 2022; Sangkham et al., 2022; Yee et al., 2021).

The COVID-19 pandemic has increased face mask pollution, and the release of nanofibers from face masks has been reported to inhibit even reproduction and growth (Kwak and An, 2021). NP and MP exposure also damages the seminiferous tubules, causing apoptosis in spermatogenic cells and lowering sperm motility and concentration, increasing the frequency of sperm abnormalities (Li et al., 2021b).

But there exists even more harm due to inhaled mask debris: Face mask microfibers and particles may serve as an important vehicle for harmful contaminants (Delgado-Gallardo et al., 2022; Kutralam-Muniasamy et al., 2022; Sun et al., 2021). The plastics usually contain chemicals from raw monomers and various types of additives to improve their properties. MP particles have been demonstrated to be very important carriers for the transformation and accumulation of the toxic PAHs (see referring section) (Sun et al., 2021). In addition, plastics also absorb chemicals from their surroundings (Campanale et al., 2020; Sun et al., 2021; Yee et al., 2021) including heavy metals (Delgado-Gallardo et al., 2022) as well as microorganisms (Sangkham et al., 2022). Moreover, a microorganism growth on and in masks is scientifically proven (Buzzin et al., 2022; Kisielinski and Wojtasik, 2022; Kisielinski et al., 2023b).

All these mechanisms can potentiate the adverse effects of MP and NP released from masks.

Finally, a significant role of MPs and NPs in exacerbating the COVID-19 pandemic has been discussed, as plastic particles that loaded the virus into the air increased the half-life of the virus and facilitated the transmission of the virus to humans through the Trojan horse effect: Increased transmission and, consequently, more cases of COVID-19 will lead to rising production and use of surgical masks, an acknowledged source of MPs and NPs (Khan and Jia, 2023). The findings of Fögen 2022 (Fögen, 2022) using data from the USA which show that mask use correlates with an increased mortality and case fatality rate of COVID-19 could be due to these processes. This phenomenon could also explain the elevated face mask related mortality found by Spira (Spira, 2022) in the EU. Possibly the respiratory overload with NPs and MPs due to N95 masks (Chen et al., 2021; Delgado-Gallardo et al., 2022; Dissanayake et al., 2021; Li et al., 2021a; Liang et al., 2022; Liu et al., 2022b; Ma et al., 2021; Meier et al., 2022; Sullivan et al., 2021; Zuri et al., 2022) could be responsible to the measured nasal blockage, postnasal discharge as well as to impairment in mucociliary clearance function while using a medical mask (Cengiz and Can, 2022). Thus, an impaired self-cleaning of the mucous membranes may favour infections and be responsible for the opposite effect – more rather than fewer respiratory infections – under face mask use at the population level (Fögen, 2022; Spira, 2022). Correspondingly, higher respiratory infection rates have been observed in Germany (Tenenbaum et al., 2022) and USA (Ma, 2022), where mask mandates for long periods were enforced by law (Face covering policies during the COVID-19 pandemic, 2023). Additionally, COVID-19 rates have been able to expand swiftly especially during Ommicron (New COVID-19 Cases Worldwide, 2023) even in societies where mask use was assiduously followed — as in Korea, Taiwan, Hong Kong and Singapore (Fearnley and Wu, 2022).

Noteworthy is also the problem regarding nanoparticles: Females are particularly more vulnerable to NP toxicity, and this may affect reproductivity and fetal development (Brohi et al., 2017). Additionally, various types of NPs have negative impacts on male germ cells (Brohi et al., 2017). Moreover, NPs as an environmental hazard are able to cause allergic asthma, pleural, interstitial lung disease and even sarcoma (Bonner, 2010; Hansen et al., 2006).

4.2. Organic compounds and organic contaminants: volatile organic compounds (VOCs) in general, including total VOCs (TVOCs)

4.2.1. VOCs from masks – origin

Volatile organic compounds (VOCs) are relatively small organic compounds, usually containing five to 20 carbon atoms, showing generally a molecular weight in the range of 50 to 200 Dalton (Rowan, 2011). In conjunction with face masks, they are regarded as residues, probably originating from the fossil fuel-based petrochemicals used in the manufacturing of the plastic polymer filtering material (Jin et al., 2021; Xie et al., 2021). The long-chain organic molecules contained in the face mask polymers can liberate the VOCs when in use (Hui Li et al., 2022). Since face masks' inner layers are mostly polypropylene and polyethylene polymers, aliphatic compounds are produced when they degrade due to oxidation reactions (Hui Li et al., 2022). Studies have shown that the degradation of e.g. polyethylene (one of the main mask contents) liberates several VOCs (e.g. the aliphatic compounds 4-methylheptane, octadecane, tetracosane and 2, 4-dimethylhept-1-ene) (Hui Li et al., 2022). The solvent spinning process of the face mask fiber polymer uses a large amount of organic solvents and e.g. methanol is the dominant organic solvent currently used in the commercial production of cellulose acetate and triacetate fibers, which are widely used as the particle-retentive filters of a N95 mask. Thus, methanol accounts for 52% of total VOC emissions in N95 respirators (Chang et al., 2022). Examples for commonly detected other VOCs in face masks are butene, pentene, propene and propyne (Chang et al., 2022), acrolein, glyoxal and decanal (Jin et al., 2021), xylene, toluene, benzene, caprolactam and aldehydes (Kerkeling et al., 2021) as well as methylheptane (Hui Li et al., 2022).

4.2.2. VOCs – release/intake

Results from the included studies show that VOC concentrations in the mask breathing zone were positively correlated with the levels of VOC residues in the masks (Jin et al., 2021). VOCs are divided in very volatile organic compounds (VVOCs) and semi-volatile organic compounds (SVOC) with different release characteristics (Shrubsole et al., 2019). According to the available data, the amount of possible intake of VOCs by inhalation while wearing masks is alarming. The total VOC release in the first minutes of mask use can go up to concentrations of 403 mg/m^3 for N95 masks during the first 17 min (Kerkeling et al., 2021). Total face mask VOC emission exceeds concentrations of 1000 µg/m^3 in the first hour and reaches on average 445 µg/m^3 in a surgical mask and 406 µg/m^3 in a N95 respirator during the following 6 h (Chang et al., 2022). In children face masks these values are much higher, even 836 µg/m^3 (Chang et al., 2022), which is alarming compared to usual levels known from indoor air. Total VOC concentrations observed in indoor environments in diverse countries (including Europe, Japan, Australia, China) range on average between 44.3 and 415 µg/m^3 with maximal values of 3.36 mg/m^3 (Shrubsole et al., 2019). Interestingly, according to our data, face mask wearing of N95/FFP may exceed those indoor air concentration values by a factor of 971, and even compared to the maximum indoor air concentrations by a factor of 120 (Kerkeling et al., 2021).

4.2.3. Limits for VOCs

A regulatory standard for chemical residues in face masks is not established (Jin et al., 2021). However, VOC emissions from consumer products are regulated in many countries around the world (Salthammer, 2022; US EPA, 2015a). Textile standards like the Standard 100 by Oeko-Tex defines accurate steps in the production and delivering of textiles which are not harmful to the health for consumers and include also limits for VOCs (Oeko-Tex® Standard 100, 2023). Standard definitions of VOCs in the air are determined even in European buildings (Shrubsole et al., 2019). There is mentioning of VOC in a guideline for air quality (World Health Organization, 2000) and concerning selected VOC-pollutants in an additional guide from the WHO (World Health Organization, 2010). Some countries present their indoor air quality (IAQ) values for VOCs as regulations (Tsai, 2019). For the European Union (EU), the European Community has prepared a target guideline value for TVOCs of 0.3 mg/m^3, where no individual VOC should exceed 10% of this target guideline (Fromme et al., 2019; Mølhave et al., 1997; Public Services and Procurement Canada, Government of Canada, 2002; Seifert, 1999; Tsai, 2019; Tuomi and Vainiotalo, 2016). However, the total VOC (TVOC) concept has evolved from the need to study mixtures and represents only a summation of individual VOCs (Jantunen et al., 1997). Thus, TVOC as a measure reveals little regarding the nature of the individual compounds, their concentrations and possible toxicity (Shrubsole et al., 2019). Therefore, TVOC is not a toxicologically based parameter and only suitable for a limited number of screening purposes (Salthammer, 2022).

For example, the German hygienic Indoor Guide Value for total VOC regards rates > 1 mg/m^3 as suspicious, > 3 mg/m^3 as questionable and > 10 mg/m^3 as unacceptable from a hygienic perspective due to health risks (Umweltbundesamt, 2007, 2013). It has been agreed upon that TVOC levels in indoor air should be kept as low as reasonably achievable, which is in accordance with the so-called ALARA-principle (Salthammer, 2022; Tuomi and Vainiotalo, 2016). Regarding the fact that inhalation of total VOCs (TVOCs) from the mask breathing zone may be very high in comparison to the environmental exposition (Kerkeling et al., 2021), it is interesting to compare maximal outcomes documented in the included studies with recommendations from those institutions (Umweltbundesamt, 2007, 2013). Disturbingly, in some of the included studies, TVOC-concentrations are exceeded by all N95 masks and being partially more than 40-fold (concentrations of 403 mg/m^3 for N95 masks during the first 17 min) (Kerkeling et al., 2021) than the unacceptable limit for hygienic air quality ($>$10 mg/m^3) (Umweltbundesamt, 2007, 2013). The Oeko-Tex Standard 100 limit of 0.5 mg/m^3 TVOCs may be exceeded 806-fold in the initial 17 min of N95 mask wearing (Kerkeling et al., 2021). With increasing mask wearing time, these concentrations decrease, but still exceed the Oeko-Tex concentration limits by a factor of 2 in the first hour under surgical masks and by a factor of 1.7 under children's masks up to the sixth hour of wearing time (Chang et al., 2022).

Also, in the experiments the mask released xylene concentrations were exceeded as well (Kerkeling et al., 2021), entered values which require immediate action according to, e.g. the German Federal Environmental Agency (Umweltbundesamt, 2007, 2013). Additionally, by using a mask under rest conditions, for 17 min with average breathing of 0.236 m^3 according to data from Kerkeling et al. (maximal xylene concentrations of 12 mg/m^3 with arithmetic average of 529 µg/m^3) (Kerkeling et al., 2021) the xylene concentration in mg/kg (calculation with assuming the mask weighing 4 g) would be on average 3 times higher (and in the worst case 70.8 times) higher than the Oeko-Tex Standard 100 limit value for textiles (10 mg/kg) (Oeko-Tex® Standard 100, 2023) Another particular VOC, acrolein, increased during the first 30 min of mask wearing to over 0.049 µg/m^3 in the behind-mask breathing zone of all tested masks (Jin et al., 2021), exceeding the inhalation reference concentration (RfC; a daily inhalation exposure concentration below which yields no appreciable risk) for acrolein (0.02 µg/m^3) set by EPA (US EPA, Acrolein, 2003; US EPA National Center for Environmental Assessment, 2003). Furthermore, wearing the mask containing the highest level of acrolein residues (0.64 µg/mask) increased acrolein concentrations in the behind-mask breathing zone to over 0.5 µg/m^3 and remained above the RfC for 1 h (Jin et al., 2021). Moreover, in evaluations with diverse face masks including N95 and textile masks, Xie et al. reported 73.6% of all mask samples exceeding a calculated cumulative carcinogenic risk (CCR) for semi-VOCs (Xie et al., 2021).

4.2.4. VOCs – risks

VOCs are respiratory irritants and suspected or known carcinogens (Jin et al., 2021). There is evidence that an average daily (8 h) TVOC exposure above 300 µg/m^3 range is associated with acute perceived discomfort as well as temporary symptoms of irritation in eyes and the respiratory system (Tuomi and Vainiotalo, 2016). When the average TVOC concentration exceeds 3000 µg/m^3 the number of complaints rises, while an average concentration above 25 mg/m^3 leads to an increase in the prevalence of irritating symptoms in eyes and the respiratory tract (Tuomi and Vainiotalo, 2016). Additionally, according to the WHO, health effects reported for VOC range from sensory irritation to behavioural, neurotoxic, hepatotoxic and genotoxic effects (World Health Organization, 2000). An exposure to a mixture of VOC as shown for face masks according to our results (TVOC, Table 2) (Chang et al., 2022; Hui Li et al., 2022; Jin et al., 2021; Kerkeling et al., 2021; Xie et al., 2021) may be an important trigger of the so-called Sick Building Syndrome (SBS) (World Health Organization, 2000). SBS-like symptoms have been linked to mask use in recent comprehensive reviews on adverse face mask effects (Kisielinski et al., 2021, 2023a). Possibly, some of the symptoms immediately occurring while wearing a mask may be caused by toxic chemicals released by the face mask.

According to a WHO paper, neurotoxicity, genotoxicity and carcinogenicity are expressed a long time after exposure to VOCs and it is assumed that there is no threshold concentration for an effect, therefore risk estimation is extended to very low concentrations (Jantunen et al., 1997) requiring the ALARA principle (Salthammer, 2022).

The US Environmental Protection Agency and Public Health England list the potential health effects of VOCs including irritation of the eyes and respiratory tract, allergies and asthma, central nervous system symptoms, liver and kidney damage, as well as cancer risks (Shrubsole et al., 2019). Some VOCs emitted from face masks have metabolic toxic properties (e.g. methanol with predominant toxic effects of its metabolites) with short-term exposure resulting in dizziness, blurred vision, and headache (Chang et al., 2022). Unfortunately, children in schools that are particularly vulnerable to many classes of such VOCs (Bayati et al., 2021) have been mandated to wear face masks for long periods during the SARS-CoV-2 pandemic (Ladhani, 2022; Thomson, 2022).

4.3. *Specific organic compounds: organophosphate esters (OPEs) and Organophosphate flame retardants (OPFRs)*

4.3.1. *OPEs and OPFRs from masks – origin*

Organophosphorus esters (OPEs) are a class of organic compounds containing phosphate conjugated to oxygen (Yang et al., 2022). OPEs, often used as plasticizers, are added to make the mask material softer and more flexible, while organophosphorus flame retardants (OPFRs a special kind of OPEs) are chemical additives to facemask components designed to prevent ignition (Fernández-Arribas et al., 2021; Xie et al., 2021). Face masks are produced with flame retardant properties and OPFRs are usually applied as such flame retardants during the mask tissue manufacturing process (Xie et al., 2022). More OPFRs are involved in the production of the N95 masks than other medical masks (Xie et al., 2021). The most common OPEs detected in medical masks are triethyl phosphate (TEP), triphenyl phosphate (TPHP), Tri-n-butyl phosphate (TnBP), tris(2-ethylhexyl) phosphate (TEHP), tris(1, 3-dichloro-2-propyl) phosphate (TDClPP) and tris(2-chloroisopropyl) phosphate (TCIPP) (Fernández-Arribas et al., 2021; Xie et al., 2021).

4.3.2. *OPEs and OPFRs from masks – release/intake*

Up to 92.5% of the mask samples contain OPFRs (Xie et al., 2021). The median values of total concentrations of the OPFRs in the KN95 masks were 224 ng/g (Xie et al., 2021). All masks analysed in the included studies presented an OPE contamination, with maximal values up to 27.7 μg/mask in the FFP3. The maximal OPE values for N95 masks was 20.4 μg and for surgical masks 0.717 μg (Fernández-Arribas et al., 2021). Interestingly, the higher OPE levels were found in N95 masks, while the lowest values were those of surgical masks. The estimated OPE inhalation percentages during the use of masks was around 10% according to Fernandes-Arribas et al., but the experimental tests did not consider the humidity present between the mask and the face when inhaling, and the higher exposure temperatures during summer-time or exercise (real world scenario). As these factors can affect a higher emission of plasticizers from the mask, those results could underestimate the real amounts of plasticizers that can be inhaled (Fernández-Arribas et al., 2021).

4.3.3. *Limits for OPEs and OPFRs*

There is no specific regulation for organic additives in face masks (Fernández-Arribas et al., 2021).

However, the United States Environmental Protection Agency (USEPA) updates regularly the oral reference dose (RfD) and oral cancer slope factors (SFO) of some OPEs (US EPA, 2015b).

Similarly, the European Union (EU) introduced regulations and criteria for the hazard classification and labelling of certain OPEs (Regulation (EC) No 1272/2008) (Regulation (EC) No 1272/2008, 2008).

For textiles the Oeko-Tex norm Standard 100 set limits for flame retardants content (Oeko-Tex® Standard 100, 2023).

Xie et al. and Fernandes-Arribas deduced no obvious risk for OPEs and OPFRS from face masks (Fernández-Arribas et al., 2021; Xie et al., 2021). However, it is important to note that OPE exposure also occur by other routes, such as indoor/outdoor inhalation, dust ingestion, dermal absorption, dietary intake and the sum of all these exposures (including mask use) can bring the values closer to (or even above) the established safety limits (Fernández-Arribas et al., 2021).

4.3.4. *OPEs and OPFRs– risks*

OPEs are associated with asthma and allergies, some harbour cancer risks (US EPA, 2015b).

OPFRS as well as OPEs are predominantly metabolised to diaryl and dialkyl phosphate esters (DAPs) in the human body (Yang et al., 2022) and there are many reported health risks associated with DAPs including infertility, DNA oxidative stress, kidney disease and in the case of pregnant women, behavioural developmental deficits comprising depression, attention problems, withdrawal from the offspring (Yang et al., 2022). Special OPEs, e.g. tri-n-butyl phosphate (TnBP) have been observed to disrupt endocrine and reproductive functions and nervous system development (He et al., 2020). Epidemiological studies have reported that exposure to tris(1,3-dichloro-2-propyl) phosphate (TDClPP) is associated with decline of semen quality (He et al., 2020). Therefore, Fernandez-Arribas et al. suggest that N95 masks are the least recommended to be used by the population when considering exposure to OPEs (Fernández-Arribas et al., 2021).

4.4. *Specific organic compounds: UV-filters*

4.4.1. *UV-filters from masks – origin*

Organic UV filters are a group of chemicals that due to their chemical structure are capable to absorb UV irradiation by their high degree of conjugation (Huang et al., 2021b). UV-filters are not only components in sunscreen products, but are also widely used in other products, e.g. plastics, textiles and also face masks in order to protect these from UV triggered photodegradation (Huang et al., 2021b). Examples for some simple popular UV-filters detected in face masks are: benzothiazole, oxybenzone, octocrylene, benzophenone, octyl salicylate, octyl methoxycinnamate and octocrylene (Xie et al., 2021).

4.4.2. *UV-filters from masks – release/intake*

UV-filters contribute most significantly the SVOCs exposure accounting for 40% (mean value) and have been detected in 96.2% of the mask samples (Xie et al., 2021). For the UV-filters content, no significant difference was found between different types of masks (Xie et al., 2021). The median value of the total levels of UV-filters in diverse masks calculated with data from an included study (Xie et al., 2021) is around 3.43 μg/mask (average mask weight 3.15 g) and the median calculated daily exposure dose for the UV-filters from face masks is 0.99 ng/kg bodyweight/day (Xie et al., 2021).

4.4.3. *Limits for UV-filters*

A regulatory standard for chemical residues in face masks is not established, however, around the world a total of 45 organic UV-filters are only permitted as additives in cosmetics with limits ranging from 2 to 20% (Huang et al., 2021b). For textiles the Oeko-Tex norm Standard 100 set limits for UV-filter content as well, being 0.1% (Oeko-Tex® Standard 100, 2023). In indoor dust samples from eastern China, the total concentration of four UV-filters ranged from 66.6 to 56,123 ng/g (Huang et al., 2021b).

Regarding the concentration of UV-filters in face masks from the included studies (Table 2) (Xie et al., 2021), the exposure while wearing a mask appears not significantly higher than from other high exposure sources like indoor dust (Huang et al., 2021b). However, the maximum concentrations of UV filters in masks of about 3.43 μg/g (Xie et al., 2021) should be viewed critically, particularly with regard to the Oeko-Tex limits of less than 0.1% (Oeko-Tex® Standard 100, 2023).

Additionally, regarding the fact that masks harbour the risk of inhaling a lot of microplastics originating from the mask tissue itself (37-fold increase of the microplastic particles inhaled compared to indoor air, see microplastic section above and Table 2, Fig. 3), face masks are undoubtedly able to enlarge the total daily exposure to UV-filters.

4.4.4. UV-filters– risks

UV-filters, being highly lipophilic tend to accumulate after dermal absorption, oral intake or inhalation in fatty tissues (Huang et al., 2021b). It is known from studies that UV-filters harbour potential endocrine disruption with negative effects on placenta, human embryos and human sperm. The possible toxic effects comprise men's infertility and sulphonated compounds of UV-filters have been reported to act as DNA alkylating agents (mutagens) and as genotoxic agents (Jesus et al., 2022). Additionally, there are reports of association of organic UV-filters with oxidative stress, obesity, including several diseases like diabetes, osteoarthritis, respiratory/allergic disease, breast cancer, polycystic ovary syndrome, decreased testosterone in adolescent boys and reduced estradiol, follicle-stimulating hormone and luteinizing hormone in healthy women and in pregnant women even effects on the next generation (Huang et al., 2021b).

4.5. Specific organic compounds: phthalates and phthalate esters (PAEs)

4.5.1. Phthalates and PAEs from masks – origin

Phthalates and Phthalate esters (PAEs) are low-molecular-weight organic compounds and commonly used as plasticizers, added to give the mask plastic material more softness, flexibility and durability (Jin et al., 2021; Min et al., 2021; Zuri et al., 2022).

4.5.2. Phthalates and PAEs from masks – release / intake

Since PAEs are not covalently bonded to the polymer and only combined with the plastic matrix by hydrogen bonds or van der Waals forces, PAEs can easily leak from the masks' material (Min et al., 2021). Interestingly, the surgical masks are responsible for higher levels and releases than N95 masks.

Xie et al., 2022 measured the total concentrations of the phthalates ranging up to a maximum of 37.7 μg /g contributing to 191.64 μg/mask (Xie et al., 2022). In their analytical study, Min et al. found some PAEs such as dihexyl phthalate (DHXP) more than 0.9 μg/g or 200 μg/m^2 (Min et al., 2021). The most frequent phthalates detected were DEXP, DEHP, DAP and BBP (Min et al., 2021).

According to our calculations based on the data of Vimalkumar et al. (Table 1), the maximum levels of known PAEs in textile masks were 5.85 μg for DEP, 6.325 μg for di-iso-butyl phthalate (DiBP), 5.025 μg for DBP, 19.175 μg for DEHP and 13.75 μg for butyl benzyl phthalate (BBzP) (Vimalkumar et al., 2022).

4.5.3. Limits for phthalates and PAEs

No regulations exist concerning phthalates and PAES in face masks (Fernández-Arribas et al., 2021; Jin et al., 2021; Liu et al., 2022a; Min et al., 2021; Wang et al., 2022; Xie et al., 2022, 2021; Zuri et al., 2022). The EU has prohibited placing goods with phthalate contents of more than 0.1% by weight of the material (sum of DEHP, DBP, BBP and DiBP) (Commission Regulation EU No. 126/2013, 2013). Several included studies point at possible exceedances of this limit in masks (Min et al., 2021; Vimalkumar et al., 2022; Xie et al., 2022; Zuri et al., 2022). Accordingly, Zuri et al., 2022 found total concentrations for phthalates of 35 μg/mask for FFP(N95) and 25.3 μg/mask for the surgical mask (Zuri et al., 2022).

In the analytical study by Xie et al., 2022, the total concentrations of the phthalates for a textile mask with 50 mask samples showed potential carcinogenic risks in the cumulated risk calculations (Xie et al., 2022). The maximum disposable textile mask concentration of DEHP (36.73 μg/g) in the mentioned study would exceed even the threshold limit for phthalate/plasticizer established by Oeko-Tex Standard 100 (0.01% of weight) by factor 367; for the N95 mask (6.3 μg/g), the exceedance would be a factor of 63 (Oeko-Tex® Standard 100, 2023; Xie et al., 2022).

4.5.4. Phthalates and PAEs – risks

Phthalate exposure is associated with asthma, obesity, impaired reproductive development, endocrine disruption, and infertility (Jin et al., 2021; Wang and Qian, 2021). Additionally, phthalates and PAEs are known as endocrine disruptors that can have adverse effects on human hormonal balance and development and harbour also a carcinogenic potential (Min et al., 2021; Wang and Qian, 2021). Thus, also the PAEs belong to the "three-causing" substances, being carcinogenic, teratogenic and mutagenic (Zuri et al., 2022).

Alarmingly, DEHP, which is a known androgen antagonist and has been demonstrated to have a lasting effect on male reproductive function and carcinogenicity was detected in one-third of the tested mask samples at concentrations as high as 1450 ng/mask by Jin et al (Jin et al., 2021). Phthalates, as endocrine-disrupting chemicals are detrimental to the reproductive, neurological, and developmental systems and children are at a higher level of exposure and more vulnerable to phthalates than adults (Wang and Qian, 2021).

4.6. Specific organic compounds: polycyclic aromatic hydrocarbons (PAHs)

4.6.1. PAHs from masks – origin

Polycyclic aromatic hydrocarbons (PAHs) belong to a class of hazardous organic substances that contain two or more fused aromatic hydrocarbon rings (Sun et al., 2021). In general, the PAHs are not intentionally added into the masks, but are existent in the raw materials commonly used as plasticizers or fillers (Xie et al., 2021). Thus, PAHs are ubiquitous in plastic ware manufactured from petroleum-derived materials and can remain in polymer-based plastics like face masks (Jin et al., 2021).

Examples for PAHs found in face masks are: naphthalene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(a)pyrene (Xie et al., 2021).

4.6.2. PAHs from masks – release / intake

In his analytical study Xie et al. detected the PAHs in 90.6% of the mask samples (Xie et al., 2021). Naphthalene was the most abundant mask-borne PAH (5296 ng/surgical mask), accounting for over 80% of total PAH levels (5563 ng/surgical mask) (Jin et al., 2021).

4.6.3. Limits for PAHs

Already in 2011, the Occupational Safety and Health Administration (OSHA) in 2011 set an 8–hour time-weighted average (TWA) limit of PAHs of 0.2 mg/m^3 in the air (Polycyclic Aromatic Hydrocarbons (PAHs), 2021). The ECHA CMRD Directive 2004/37/EC list and gives the advice on limiting the exposure to several PAHs that are cancerogenic as far as possible (Directive, 2004/37/EC, 2004).

However, the Oeko-Tex norm allows up to 10 mg/kg PAHs in textiles with plastic and synthetic fibers (Oeko-Tex® Standard 100, 2023).

4.6.4. PAHs – risks

Regarding PAHs, the unprecedented use of face masks worldwide during the SARS-CoV-2-pandemic by nearly all parts of the population (long-term exposure at the population level) (Face covering policies during the COVID-19 pandemic, 2023) could have pose a health risk.

PAHs are a typical class of "three-causing" substances (carcinogenic, teratogenic and mutagenic). As the number of rings in the molecular structure increases, the toxicity of PAHs becomes stronger (Sun et al., 2021). Evidence exists regarding adverse effects of PAHs, including carcinogenicity and teratogenicity, genotoxicity, reproductive- and endocrine-disrupting effects, immunotoxicity and neurotoxicity (Sun et al., 2021).

Benzo[*a*]pyrene is a well-known and extensively studied carcinogen, primarily responsible for lung cancer caused by cigarette smoke. It's also the leading cause of chimney sweep cancer, a tumor of the testicular membrane resulting from soot irritation containing benzo[*a*]pyrene (Bukowska et al., 2022; Sun et al., 2021). Therefore is noteworthy, that Xie et al. detected benzo[*a*]pyrene several times in substantial concentrations, even in masks for infants (Xie et al., 2021). Xie et al. summarized, that more than 70% of the masks tested "exceeded the safe level for the carcinogenic risks".

4.7. Specific organic compounds: per- and polyfluoroalkyl substances (PFAS)

4.7.1. PFAS from masks – origin

Poly- and perfluoroalkyl substances (PFASs) are a family of highly fluorinated organic compounds (Sunderland et al., 2019). Face masks are designed to not only prevent inhalation of particles or pathogens (bacteria, fungi) but also to repel fluids (e.g., bodily) and in many water-repellant fabrics the repellency factor indicates the potential presence of PFAS, which are known components also of speciality gear (Muensterman et al., 2022; Sunderland et al., 2019). Additionally, their abundance in facemasks could originate from sources such as PFAS-impacted water used in manufacturing and PFAS in components to maintain or operate machinery. The carbon–fluorine bonds (extremely strong), along with other special chemical properties, are responsible for the fact that many PFAS are not appreciably degraded under environmental conditions (Sunderland et al., 2019).

4.7.2. PFASs from masks – release/intake

Of the nonvolatile PFAS in masks, perfluoroalkyl carboxylates (PFCAs) showed the highest abundance, followed by fluorotelomer-based PFAS, and perfluoroalkyl sulfonates (PFSAs) (Muensterman et al., 2022). Nonvolatile PFAS were found in all facemasks, and volatile PFAS were found in five of nine (55.5%) evaluated facemasks (Muensterman et al., 2022). Total fluorine was quantifiable in most face masks and ranged up to 40,000 nmol F/cm^2. The summed PFAS concentrations ranged up to 2900 μg/m^2 (Muensterman et al., 2022). In the estimates of human exposure wearing masks treated with high levels of PFAS for extended periods of time can be a notable source of exposure: High physical activity increased inhalation exposure estimates to over 70% (children), 700% (women), and 400% (men) more than the summed ingestion and dermal exposure routes (Muensterman et al., 2022).

4.7.3. Limits for PFAS

A regulatory standard for PFAS in face masks is not established. Our calculations show disturbing values of PFAS concentrations in masks. In contrast, the US Environmental Protection Agency (EPA) wants the limits for individual PFAS in drinking water to be as close as possible to zero with concentrations in parts-per-trillion (10^{-12}), e.g. 0.004 ppt for PFOA and 0.02 ppt for PFOS (US EPA, 2020). Similarly, the European Commission in the long term aims to ban all PFAS, but its Drinking Water Directive, which took effect in January 2021, includes a limit of 0.5 μg/l for all PFAS (Directive (EU) 2020/2184 on the quality of water intended for human consumption (recast)) (Directive(EU) 2020/2184, 2020; Per- and polyfluoroalkyl substances PFASs - ECHA, 2023). Alarmingly, Muensterman et al. estimated exposure via inhalation to children wearing a PFAS-rich mask at moderate physical activity level being 7.04 μg/kg bodyweight/day, exceeding the reference dose for 6:2 fluorotelomer alcohol (FTOH) of 5 μg/kg bodyweight per day based on data from the Danish Ministry of Environment (Kjølholt et al., 2015; Muensterman et al., 2022). Moreover, calculating with an average weight of 2.5 g for cloth masks and 3 g for surgical masks (Fernández-Arribas et al., 2021; Xie et al., 2022) and an average mask surface of 0.023 m^2 (Rengasamy et al., 2009) according to data from Muensterman et al. the mask PFAS content would exceed the Oeko-Tex norm concentration of 250 μg/kg (Oeko-Tex® Standard 100, 2023): for surgical masks by a factor of 1.4 (352.7 μg/kg) and for cloth masks by a factor of 33.5 (8372 μg/kg) (Muensterman et al., 2022).

4.7.4. PFAS – risks

For PFAS an evidence for increased cancer risk exists (Sunderland et al., 2019). There is also solid data indicating immunosuppression and increased infection susceptibility related to PFAS exposure, as well as metabolic diseases such as diabetes, overweight, obesity, and heart diseases (Sunderland et al., 2019). And regarding pregnant women, there are neurodevelopmental effects of PFAS to the offspring including attention-deficit/hyperactivity disorder (ADHD) and disturbed behaviours in childhood, and neuropsychological functions such as IQ decline (Sunderland et al., 2019). These risks explain why the EPA wants the limits for PFAS to be as close as possible to zero (US EPA, 2020).

4.8. Trace elements and (heavy) metals including TiO_2

4.8.1. Trace elements and heavy metals from masks – origin

In particular, both surgical and KN95 masks, are composed of synthetic thermoplastic carbon polymers which are synthesized by a variety of chemical processes, which require a range of heavy metal catalysts (Sb, Ti, Zr and Sn) (Bussan et al., 2022).

In addition, to the catalytic function, metals and heavy metals are involved in several other stages of polymer manufacturing such as: additives for flame retardants (Sb and Al), pigments (Pb, Cd, Cr, Cu) and stabilizers (Pb and Cd) (Bussan et al., 2022). Some masks have intentionally titanium dioxide nanoparticles bound within the fibers, as this compound exhibits antimicrobial properties (Delgado-Gallardo et al., 2022). In addition, TiO_2 particles are applied as a white colourant or as a matting agent, or to assure durability reducing polymer breakdown by ultraviolet light (Verleysen et al., 2022). Moreover, Cu nanoparticles incorporated into polymer matrices are used to develop polymer nanocomposites with antibacterial properties (Bussan et al., 2022). Additionally, since face masks are manufactured of several filter layers and a nose wire metal frame, some of the detected trace elements and heavy metals might have their origin from the nose wire made of stainless steel. Stainless steel is produced by galvanization and, e.g. zinc used in galvanized steel, as well as trace amounts of lead can contaminate it (Hui Li et al., 2022). However, also metals accumulated from the environment, metals from additives such as the dye applied to the masks, as well as metals from other sources in a particulate or non-particulate form are assumed to be detected in mask samples (Meier et al., 2022).

4.8.2. Trace elements and heavy metals from masks – release/intake

Trace elements and heavy metals in a mask can reach the mask wearer via the moist breath and saliva. The exposure could occur in people who extensively use contaminated masks or to children who may chew/play with the mask material. It is also important to point out, that human saliva contains a multitude of enzymes that could enhance metal leaching (Bussan et al., 2022).

In their saliva experiments Bussan et al. could demonstrate there is a high possibility for trace elements to leach out of a mask that contains them. Specifically, Pb leached out close to 60% after a 6-h exposure to a saline solution (Bussan et al., 2022).

Fittingly, besides release of other toxins, Li et al. could prove that surgical masks contain several types of potentially toxic metals such as Cd, Cr, and Pb and leached them in the following order of concentration: Pb > Cr > Cd (Hui Li et al., 2022).

In their experimental study, Verleysen et al. described the total TiO_2 mass up to 152,345 μg per reusable textile mask (Verleysen et al., 2022). The estimated TiO_2 mass at the inhalable fiber surface ranged from 17 to 4394 μg, and systematically exceeded 1220-fold the acceptable exposure level to TiO_2 by inhalation (3.6 μg, calculated by Verelysen et al.) in a scenario where face masks are worn intensively (Verleysen et al., 2022).

4.8.3. Limits for trace elements and heavy metals

Standards for face mask do not exist regarding trace elements and heavy metals to our knowledge. Textile standards like the Standard 100 by Oeko-Tex defines contents of toxins in textiles which are not harmful to the health for consumers and include also limits for trace elements and metals (Oeko-Tex® Standard 100, 2023). According to our calculations based on the data of Sullivan et al. (Table 1), these threshold values set by Oeko-Tex standard would be exceeded in a worse case scenario for Pb, Cd and Sb by a factor of 3.4, 1.92 and 1.31 respectively (Oeko-Tex® Standard 100, 2023; Sullivan et al., 2021).

Similarly, a calculation with data from Bussan et al. showed also an exceeding of the limit values for Pb (surgical), Cu (surgical) and Sb (KN95) by a factor of 66.5, 8.2 and 3, respectively (Bussan et al., 2022; Oeko-Tex® Standard 100, 2023). Also, regarding the maximum results reported by Z. Liu et al. for Cd, Pb and Co the Oeko-Tex Standard 100 levels would be exceeded 2.2-, 1.1- and 1.3-fold, respectively (Liu et al., 2022b; Oeko-Tex® Standard 100, 2023).

4.8.4. Trace elements and heavy metals – risks

Heavy metals can have several different effects, depending on the specific metal and its concentration, including neurological disorders and muscular diseases (Delgado-Gallardo et al., 2022). TiO_2-nanoparticles can cause oxidative stress and have a genotoxic effect (Delgado-Gallardo et al., 2022). Moreover, when inhaled, TiO_2 is a suspected human carcinogen (Verleysen et al., 2022). Similarly, ingesting Cd, Co, Cr and Pb was reported to have potential carcinogenic risk to both children and adults (Liu et al., 2022b). Even low exposures to Pb can lead to neurological damage and be detrimental to foetal development (Sullivan et al., 2021). Inhaled and ingested Pb can cause severe brain damage, reproductive system damage and in higher concentrations death (Bussan et al., 2022). Sb is a possible carcinogen and it can cause pneumoconiosis, also chronic bronchitis, chronic emphysema, pleural adhesions, and respiratory irritation (Bussan et al., 2022). As such, contact allergy to Cr, Ni and Co are the most common metal allergies and approximately 1–3% of the adult general population are affected (Liu et al., 2022b). Additionally, multiple metal–metal interactions, e.g. Cd, Cu, Ni, and Zn, may contribute to a higher toxicity in a mixture (Liu et al., 2022b).

4.9. Consequences for science and supervisory authorities

Long before the pandemic face masks had been introduced both in medicine and healthcare (notably surgery, surgical masks), and in some of the manufacturing industries (predominantly FFP2 and FFP3, N95) to protect humans (Belkin, 1997; Hodous and Coffey, 1994; Kisielinski et al., 2021; Lee et al., 2008; Matuschek et al., 2020), aiming to prevent or minimise infection or contamination (Gralton and McLaws, 2010; Kisielinski et al., 2021; Kisielinski et al., 2023a; Lee et al., 2008; Liu et al., 2023; Loeb et al., 2009; Ntlailane and Wichmann, 2019; Qian et al., 1998; Rengasamy et al., 2009; Samaranayake et al., 2020; Smith et al., 2016; Willeke et al., 1996). This is due to primary prevention, but sometimes masks can be used as secondary or tertiary prevention. Those indications comprise e.g. the following desired protective effects: 1) workers from inhalation (self protection), 2) wounds from surgeons breath/aerosols loaded with bacteria (source control), 3) environment from contagious patients, e.g. tuberculosis (source control) and 4) individuals and medical staff from aerosols from contagious patients (self protection). Nevertheless, the real-world effectiveness of face masks in healthcare settings was debatable long before 2020 (Vincent and Edwards, 2016) and even their role in the operating theatre remains controversial (Burdick and Maibach, 2021). The risks and benefits of requiring mask use by populations must be weighed from ethical and medical standpoints according to evidence based medicine (Kisielinski et al., 2021, 2023a; Sandlund et al., 2023; WHO, 2001; World Medical Association, 2013). For masks to be demanded, the real-world side effects and risks must be lower than the risk of not wearing a mask. A gold-standard Cochrane evaluation, based on clinical trials found no substantive evidence of efficacy in preventing viral respiratory infections (Jefferson et al., 2023). Correspondingly, a recent systematic review of studies failed to find an evidence of benefit from masking children, to either protect themselves or those around them, from COVID-19 (Sandlund et al., 2023). And, one recent cross-sectional study with 3209 participants, albeit with several possible confounders, even found mask-wearing to be associated with an increased risk of COVID-19 infection (+33% to +40%) (Elgersma et al., 2023).

Currently, the quality control of face masks is only focused on their physical and biological properties, that is, the filtration efficiency, e.g., ASTM F2101 and EN 14683 (Forouzandeh et al., 2021; Rengasamy et al., 2009), BS EN 14683:2019 (Jin et al., 2021) and microbial populations, e.g., ISO 11737–1 (Jin et al., 2021) but does not address the levels of hazardous chemicals contained in them. This fact needs to be reconsidered, as our scoping review revealed the repeated detection of several hazardous ingredients in face masks and also their calculated emissions and contents of concern with exceeding institutional limit thresholds of WHO, EPA, European Union (EU) and German Federal Environmental Agency (see Table 3A, Table 3B and Table 3C). In addition, the masks have higher content of certain substances than the health maintaining Oeko-Tex Standard 100 label allows. Thus, health concerns for some masks and individual mask wearing conditions cannot be excluded (skin contact, inhalation at nearly zero distance, oral intake). In this regard, mask wearing may exert a higher risk of exposure than many environmental sources. Thus, a special, customized risk assessment for individual toxins in masks appears necessary. The evidence we have found for toxins in masks is more than troubling, especially given the worldwide use by diverse even susceptible portions of the population (e.g. children, pregnant women, adolescents).

In this context it is necessary to take into consideration that children are not just small adults with a higher susceptibility to negative environmental factors due to less developed protective/conjugative pathways but they also form, together with pregnant women a special subgroup with more susceptibility to toxins (Faustman et al., 2000). Exposure criteria should be based on information relevant to predicting risks for children and should account for such toxicokinetic differences occurring with development. Some authors from the reviewed studies report unacceptable toxin levels for VOC, Phthalates and PFAS in children while wearing a mask (Chang et al., 2022; Muensterman et al., 2022; Xie et al., 2021, 2022). These toxic substances have teratogenic, mutagenic and cancerogenic potential. We believe there is an urgent need for action to protect children from toxins in face masks. Despite having the lowest risk of severe or lethal disease from a SARS-CoV-2 infection (Bagus et al., 2021; Pezzullo et al., 2023; Sorg et al., 2022), children have endured the highest disproportionate disruption to their lives in their decisive formative years during the pandemic (Ladhani, 2022). Interestingly, a systematic review of studies failed to find any evidence of benefit from masking children, to either protect themselves or those around them, from COVID-19 (Sandlund et al., 2023). The toxicological risks are exacerbated by the physiological, psychological and sociological effects of the masks. In reality, there is strong evidence that masks pose various risks, especially for pregnant women, children and adolescents, as well as older adults and the unwell (Ahmad et al., 2001; Kisielinski et al., 2021, 2023a; Ryu and Kim, 2023; Sukul et al., 2022; Walach et al., 2022), They have several demonstrably adverse effects, affecting physiology (Al-Allaff et al., 2021; Kisielinski et al., 2021, 2023a; Law et al., 2021; Patel et al., 2023; Sukul et al., 2022; Vakharia et al., 2021), psychology and, most obviously, social interactions (Carbon et al., 2022; GOV.UK, 2022; Grundmann et al., 2021; Kisielinski et al., 2021; Mathis, 2023; McKenna et al., 2022; Pavlova et al., 2023; Proverbio and Cerri, 2022; Schönweitz et al., 2022; Sönnichsen et al., 2022; Truong et al., 2021; Villani et al., 2022).

Effects on childhood development are a particular concern. They impede learning, especially for children (Carbon, 2020; Carbon et al., 2022; Kisielinski et al., 2023a; Ladhani, 2022; Schwarz et al., 2021;

Table 3B
Exemplary limit threshold exceedance of organic compounds in a worst case scenario while wearing a mask.

Publication	Mask type	Outcome	Result*	Threshold value, Institution/Organisation**	Factor of exceedance
Kerkeling et al. (2021)	N95	**TVOC** release	**403 mg/m^{3}** (17 min)	0.3 mg/m^{3} target guideline European Community (Public Services and Procurement Canada, Government of Canada, 2002; Tsai, 2019; Tuomi and Vainiotalo, 2016; Umweltbundesamt, 2007) German Federal Environment Agency (Fromme et al., 2019; Mølhave et al., 1997; Seifert, 1999; Umweltbundesamt, 2007, 2013)	**1343**
Kerkeling et al. (2021)	N95	**TVOC** release	**403 mg/m^{3}** (17 min)	0.5 mg/m^{3} Oeko-Tex Oeko-Tex® Standard 100 (2023)	**806**
Xie et al. (2022)	textile	**DEHP** content	**36.7 μg/g**	0.01% of weight Oeko-Tex Oeko-Tex® Standard 100 (2023)	**367**
Xie et al. (2021)	textile	**SVOC** carcinogenic risk (CR)	**2.27×10^{-4}**	$\leq 1 \times 10^{-6}$ US EPA Calculating Hazard Quotients and Cancer Risk Estimates (2022); US EPA (2005)	**227**
Xie et al. (2022)	textile	**Phthalates** content	**37.7 μg/g**	0.025% of weight Oeko-Tex Oeko-Tex® Standard 100 (2023)	**150.8**
Muensterman et al. (2022)	textile (coated)	**PFAS** content	**2900 μg/m^{2}**	250 μg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**107**
Kerkeling et al. (2021)	N95	**Xylene** release	**12 mg/m^{3}** (17 min)	10 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**70.8**
Xie et al. (2022)	N95	**DEHP** content	**6.3 μg /g**	0.01% of weight Oeko-Tex Oeko-Tex® Standard 100 (2023)	**63**
Muensterman et al. (2022)	textile (coated)	**FTOH** content	**1200 μg/m^{2}**	250 μg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**44.2**
Xie et al. (2022)	textile (for children)	**Phthalate** carcinogenic risk (CR	**4.26×10^{-5}**	$\leq 1 \times 10^{-6}$ US EPA Calculating Hazard Quotients and Cancer Risk Estimates (2022); US EPA (2005)	**42.6**
Kerkeling et al. (2021)	N95	**TVOC** release	**403 mg/m^{3}** (17 min)	10 mg/m^{3} AgBB, German Federal Environment Agency (Umweltbundesamt, 2007, 2013)	**40**
Muensterman et al. (2022)	textile	**PFAS** content	**910 μg/m^{2}**	250 μg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**33.5**
Zuri et al. (2022)	N95	**phthalates** content/release	**8.16 μg/g**	0.025% of weight Oeko-Tex Oeko-Tex® Standard 100 (2023)	**32**
Zuri et al. (2022)	surgical	**phthalates** content/release	**7.56 μg/g**	0.025% of weight Oeko-Tex Oeko-Tex® Standard 100 (2023)	**30**
Jin et al. (2021)	surgical	**Acrolein** release	**0.5 μg/m^{3}** (30 min)	0.02 μg/m3 US EPA US EPA (2003); US EPA National Center for Environmental Assessment (2003)	**25**
Xie et al. (2021)	N95 (for children)	**SVOC** carcinogenic risk (CR)	**2.5×10^{-5}**	$\leq 1 \times 10^{-6}$ US EPA Calculating Hazard Quotients and Cancer Risk Estimates (2022); US EPA (2005)	**25**
Kerkeling et al. (2021)	N95	**Xylene** release	**12 mg/m^{3}** (17 min)	500 μg/m^{3} AgBB, German Federal Environment Agency (Fromme et al., 2019; Mølhave et al., 1997; Seifert, 1999; Umweltbundesamt, 2007, 2013	**24**
Xie et al. (2021)	N95	**SVOC** carcinogenic risk (CR)	**1.59×10^{-5}**	$\leq 1 \times 10^{-6}$ US EPA (Calculating Hazard Quotients and Cancer Risk Estimates, 2022; US EPA, 2005)	**15.9**
Xie et al. (2022)	textile	**Phthalate** carcinogenic risk (CR)	**1.45×10^{-5}**	$\leq 1 \times 10^{-6}$ US EPA Calculating Hazard Quotients and Cancer Risk Estimates (2022); US EPA (2005)	**14.5**

(*continued on next page*)

Table 3B (*continued*)

Publication	Mask type	Outcome	Result*	Threshold value, Institution/Organisation**	Factor of exceedance
Chang et al. (2022)	surgical	**TVOC** release	**> 1 mg/m^3** (1 h)	0.3 mg/m^3 target guideline European Community, Public Services and Procurement Canada, Government of Canada (2002); Tsai (2019); Tuomi and Vainiotalo (2016); Umweltbundesamt (2007) German Federal Environment Agency Fromme et al. (2019); Mølhave et al. (1997); Seifert (1999); Umweltbundesamt (2007, 2013)	**> 3**
Chang et al. (2022)	surgical	**TVOC** release	**> 1 mg/m^3** (1 h)	0.5 mg/m^3 Oeko-Tex Oeko-Tex® Standard 100 (2023)	**> 2**
Muensterman et al. (2022)	surgical	**PFAS** content	**46 µg/m^2**	250 µg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**1.4**
Muensterman et al. (2022)	textile	**FTOH** intake estimation 10 h mask use	**7.04 µg/kg-bw/day**	5 µg/kg-bw/day Danish Ministry of Environment Kjølholt et al. (2015)	**1.4**
Xie et al. (2021)	N95	**Naphthalene** content	**2.43 µg/g**	2 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**1.2**

Legend: AgBB= Ausschuss zur gesundheitlichen Bewertung von Bauprodukten (Committee for the Health Evaluation of Building Products, Federal Environment Agency Germany), DEHP= di(2-ethylhexyl) phthalate, FTOH= 6:2 fluorotelomer alcohol, kg-bw= kilogram per bodyweight, PFAS= Poly- and perfluoroalkyl substances, SVOC= semi volatile organic compounds, TVOC= Total Volatile Organic Compounds, US EPA= United States Environmental Protection Agency, VOC= Volatile Organic Compounds.

Footnotes:

**If necessary, the units had to be converted, with the surface area of the N95 respirator being 175 cm^2 (0.0175 m^2)* (Roberge et al., 2010) *and the surface area of the surgical/textile mask being 230 cm^2 (0.023 m^2)* (Rengasamy et al., 2009)*. If not given in the studies the average weight was set at 2.5 g for cloth masks* (Xie et al., 2021, 2022)*, 3 g for surgical masks and 4 g for N95 mask* (Fernández-Arribas et al., 2021)*. Breathing air was estimated to be 10 m^3 in 12 h according to USEPA* (US EPA, 1989)*. Please note: VOCs release in the first hours is known to decrease exponentially* (Chang et al., 2022)*.*

**for further details see discussion section, limits for VOCs, PFAS, phthalates.

Sezer et al., 2023; Shobako, 2022; Thomson, 2022; Walach et al., 2022). These adverse effects have been recently summarised as the so-called mask-induced exhaustion syndrome MIES (Kisielinski et al., 2021, 2023a; Sukul et al., 2022). Interestingly, some authors (Elgersma et al., 2023; Fögen, 2022; Spira, 2022) found significantly higher SARS-CoV-2 infection and mortality rates in the mask-wearing cohorts (Fögen, 2022; Spira, 2022). However, according to the data we found, there could be an additional toxin dependent developmental risk to healthy children and early life from prolonged mask wearing.

Researchers have shown with their calculations that the special mask situation also requires a different evaluation without simple recourse to room air or product standards (Jin et al., 2021; Verleysen et al., 2022; Xie et al., 2021).

Fifteen of the 24 face mask studies included (63%) indicated high or excessive concentrations of inanimate toxins (institutional and organizational limits) (Table 3A, Table 3B and Table 3C). Thereof, five studies on MP an NP showed highly elevated levels (Li et al., 2021a; Liang et al., 2022; Ma et al., 2021; Meier et al., 2022; Zuri et al., 2022) with possible exceedances for both surgical and N95 masks (Table 3A). Six papers indicated levels that are above institutional and organisational limits for organic compounds (Table 3B) including TVOC, VOCs, phthalates, acrolein, DEHP and PFAs in all types of masks (textile, surgical and N95 masks) (Chang et al., 2022; Jin et al., 2021; Kerkeling et al., 2021; Liu et al., 2022b; Muensterman et al., 2022; Xie et al., 2021, 2022).

As can be seen from Table 3C four studies revealed exceedances for trace elements and heavy metals including Pb, Cd, Co, Cu, Sb and TiO_2 in textile, surgical and N95 masks (Bussan et al., 2022; Liu et al., 2022b; Sullivan et al., 2021; Verleysen et al., 2022).

The charts in Fig. 4 show the differences in exceedances of limit thresholds in various mask types and studies broken down by toxin classes (microplastics, organic and inorganic toxins). With regard to organic toxins, the N95 and textile masks with high limit value exceedances are striking, while for microplastics the N95 seems to be responsible for higher exceedances than the surgical mask. For inorganic toxins, the textile and surgical masks appear to be the main sources. However, more studies are necessary to clarify these trends.

Fig. 5 summarises the toxic substances and classes that may be responsible for limit value exceedances with resulting potential life-shortening effects.

Moreover, there are possible chemical reactions of all the reported chemicals with each other and with the exhaled compounds resulting from human metabolism (Zannoni et al., 2022) in the mask breathing zone (mask dead space), e.g. oxidation. For this reason, the mask breathing zone could act as a “chemical reactor” at the entrance of the airways. This phenomenon could lead to further toxic compounds with a new kind of threat to human health. One has to consider that the mask dead space does not only have a higher temperature, but is more humid (Kisielinski et al., 2021), which facilitates many chemical reactions. It should not go unmentioned, that there is an additional possibility of amplifying toxic effects, resulting from the mixture of toxins.

Mask use may additionally – even if not exceeding threshold values – increase the burden of the airways and lungs and organs with chemical compounds, heavy metals, micro- and nanoplastics. And there could be a cumulative effect concerning indoor use of masks (which was recommended by the WHO during the pandemic) (World Health Organization (WHO), 2020), because indoor air exposition to several toxic compounds (e.g. VOCs, MPs and NPs) is per se higher than outdoors (Kerkeling et al., 2021). Some of the substances are ultrafine (e.g. TiO_2, NPs) and require another risk and toxicological evaluation (Bonner, 2010; Brohi et al., 2017; Ma et al., 2021; Verleysen et al., 2022). Interestingly, face masks have no toxicological regulations so far.

Despite a broad narrative during the SARS-CoV-2 pandemic supporting the efficacy of face masks against virus transmission (Kisielinski et al., 2023a) there is only weak evidence for the effectiveness against respiratory viral infections even from the highest evidence-based institutions (Jefferson et al., 2023). Regarding our results of multiple toxic

Table 3C

Exemplary limit threshold exceedance of anorganic toxins and compounds in a worst case scenario while wearing a mask.

Publication	Mask type	Outcome	Result*	Threshold value, Institution/Organisation**	Factor of exceedance
Verleysen et al. (2022)	textile, reusable	**TiO_2** exposure Adverse effect level (AEL_{mask}) two masks per day, 8 h	**4394 μg**	3.6 μg ANSES, France ANSES (2021, 2020); Bermudez et al. (2004)	**1220**
Bussan et al. (2022)	surgical	**Pb** content	**13.3 μg/g**	0.2 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**66.5**
Bussan et al. (2022)	surgical	**Cu** content	**410 μg/g**	50 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**8.2**
Sullivan et al. (2021)	textile	**Pb** content	**0.68 μg/g**	0.2 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**3.4**
Bussan et al. (2022)	N95	**Sb** content	**90.18 μg/g**	30 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**3**
Liu et al. (2022b)	surgical	**Cd** content	**0.22 μg/g**	0.1 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**2.2**
Sullivan et al. (2021)	textile	**Cd** content	**0.19 μg/g**	0.1 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**1.9**
Liu et al. (2022b)	surgical	**Co** content	**1.33 μg/g**	1 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**1.33**
Sullivan et al. (2021)	textile	**Sb** content	**39.3 μg/g**	30 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**1.3**
Liu et al. (2022b)	surgical	**Pb** content	**0.22 μg/g**	0.2 mg/kg Oeko-Tex Oeko-Tex® Standard 100 (2023)	**1.1**

Legend: Cd= Cadmiun, Co= Cobalt, Cu= Copper, Pb= Plumbum (Lead), Sb= Stibium (Antimon), TiO_2 = Titandioxide.

*Footnote: *If not given in the studies the average weight was set at 2.5 g for cloth masks (*Xie et al., 2021, 2022*), 3 g for surgical masks and 4 g for N95 mask (*Fernández-Arribas et al., 2021*).*

**for further details see discussion section, limits for trace elements and heavy metals.

substances released by face masks that can be ingested and inhaled (Table 2, Table 3A, Table 3B and Table 3C; Figs. 4 and 5), the introduction of mask mandates by law for the general population in many countries during the SARS-CoV-2-pandemic 2020–2023 appears questionable from an empirical and scientific perspective.

Considering the weak antiviral effectiveness (Elgersma et al., 2023; Jefferson et al., 2023; Kisielinski et al., 2023a; Sandlund et al., 2023) and the lack of medium or strong empirical evidence for face mask effectiveness in preventing respiratory virus infections (Jefferson et al., 2023; Kisielinski et al., 2021, 2023a), wearing face mask frequently during the SARS-CoV-2 pandemic – according to our results – may have led to negative health and possible life shortening effects (Figs. 4 and 5). From environmental science a lot of chronic subthreshold toxic effects have been evaluated and described and have been named “silent killer effects” (Alasfar and Isaifan, 2021; Houston, 1991; Huckelba and Van Lange, 2020; Nawrot and Staessen, 2006; Shaldon and Vienken, 2009; Zaynab et al., 2021). As the mask wearing may be linked to toxin exposure and an unprecedented use worldwide occurred, a toxic influence related to the general population could contribute to a similar effect (Alasfar and Isaifan, 2021; Houston, 1991; Huckelba and Van Lange, 2020; Kisielinski et al., 2021; Nawrot and Staessen, 2006; Redlich et al., 1997; Shaldon and Vienken, 2009; Zaynab et al., 2021). Thus, without a thorough risk-benefit analysis enforced mask obligations by law as happened in the SARS-CoV2-pandemic, acting against the evidence of science (regarding mask effectiveness and mask hazardous substance content standardization), should not be repeated in the future.

5. Limitations

This review does not claim to be exhaustive, especially with regard to the evaluation of the results. This is because inhalation toxicology is a very complex field, and combined exposure in particular must be considered separately, since the toxic effects can reinforce each other.

In our tables, we quote maximum values; if these are not available, we quote mean values. In this way, we ensure a worst-case consideration (Directorate-General for Health and Consumers, 2013), which is quite common in toxicology. Since we do not perform any toxicological evaluation to ensure human safety, this worst case consideration is not only legitimate, but necessary. Most of the studies included in our review are in vitro studies and give only estimation data for an in vivo human exposure to diverse toxins which may be different under real world conditions. Our estimated and discussed exposition might be different than in real life, due to the fact that masks may be crumpled up in pockets etc. or changed frequently during a day as it has been recommended (Chen et al., 2021; World Health Organization, 2020). Moreover, we have taken average physiological variables for our tentative preliminary calculations, e.g. respiratory rate, tidal volume, however, the diversity and individuality of the breathing pattern (Benchetrit, 2000) is worth being taken into account as there could be more harm for one subject and less for the other. Correspondingly, some authors could show higher toxin exposure in physical activity (Muensterman et al., 2022) respectively under rapid breathing (Ma et al., 2021).

The release of microplastics was assessed in a worst-case scenario

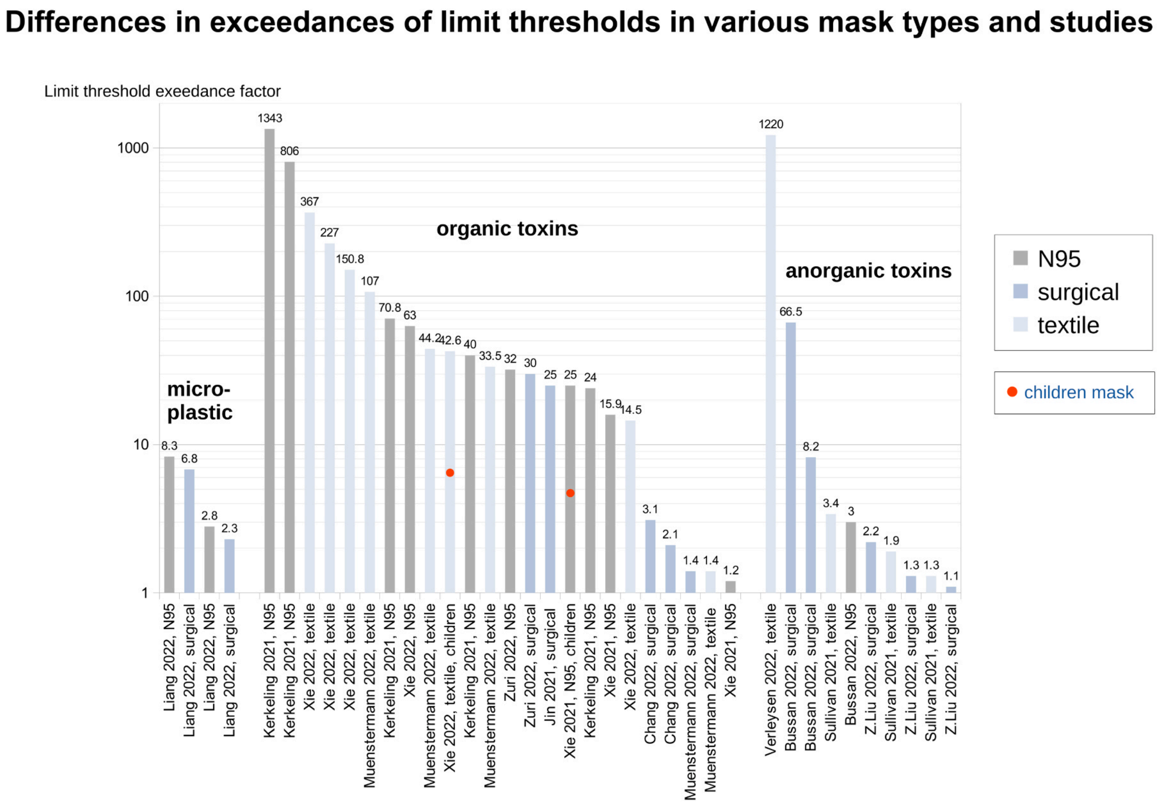

Fig. 4. Comparison of the calculated exceedance factors for different mask types and studies, broken down by toxin class. Logarithmic scale of the y-axis due to the large differences in limit value exceedances. The limit value references and values can be found in Table 3A, B and C, as well as further details on the studies, the calculations and the substances evaluated.

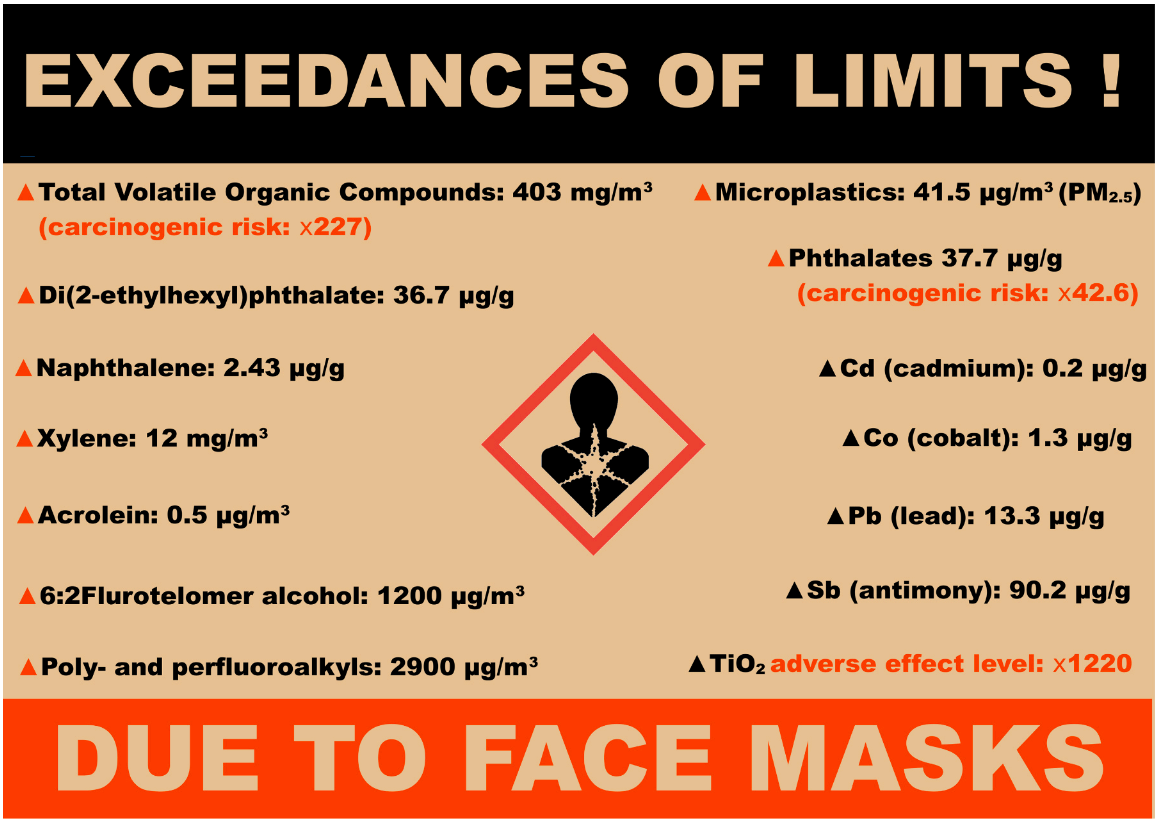

Fig. 5. Summary of those toxic substances and classes with possible limit value exceedances as shown in Tables 3A, 3B and 3 C that may be responsible for potential toxicity in the mask wearer and – in the worst case – contribute to life shortening.

(liquid extractions etc.) (Chen et al., 2021; Delgado-Gallardo et al., 2022; Dissanayake et al., 2021; Liang et al., 2022; Ma et al., 2021; Meier et al., 2022). However, a more realistic air-based scenario using breathing models (e.g. Sheffield heads) could show different outcomes (Meier et al., 2022). Unfortunately, too few such studies having been carried out so far, further evaluations regarding more realistic microplastic inhalation risk assessment could not be performed. Nevertheless, studies with breathing simulations show a significant inhalation risk, e.g. for microplastics (Li et al., 2021a). In the above estimations we applied WHO limits in our calculations (WHO, 2005). However, slightly different regulations exist in many countries, e.g. Germany (Mitteilungen der Ad-hoc-Arbeitsgruppe, 2008) and are also regulated in the European Union (Directive, 2008/50/EC, 2008). Moreover, the limit thresholds, e.g. like the WHO Air Quality Guidelines (AQG) for particulate matter in ambient air cannot be transferred one-to-one to the mask wearing situation. Thus, our comparisons and calculations should only act as a preliminary exploratory analysis, since the particle inhalation at nearly zero distance predominantly with oral breathing (less nasal filtration) while using a mask may represent a different condition than inhaling ambient air with predominantly nose breathing.

We did not address the risks of the inhalable living organisms in our review, although there is also a large body of scientific evidence on this issue, describing the health risk for humans from animate toxins (Delanghe et al., 2021; Kisielinski and Wojtasik, 2022; Kisielinski et al., 2023b; Luksamijarulkul et al., 2014; Park et al., 2022; Sachdev et al., 2020; Zhiqing et al., 2018).

As we concentrated on the direct human health risks resulting from direct absorption of possible toxins from the mask while wearing it, the environmental effects including pollution and damage of the animate ecosystem could not be taken entirely into account. However, these consequences also may have indirect health threatening repercussions on humans (Masud et al., 2023) (e.g. via the nutrition circle).

We regarded the toxins separately, however their mixture and interaction can contribute to a higher toxicity than each substance on its own. Additionally, we could not evaluate further risks of chemical reactions (Zannoni et al., 2022) in the mask breathing zone which we assume to be a “chemical reactor“ at the entrance of the airways.

We also did not address the toxicological risks of inhaled CO_2 from the mask dead space, as it is not a manufactured content of the face mask, and moreover has been extensively evaluated in a recent review (Kisielinski et al., 2023a).

6. Conclusions

Of course, masks filter larger dirt and plastic particles and fibers from the air we breathe, but according to our data, they also carry the risk of inhalation of microplastic and nanoplastic particles and potentially toxic substances originating from the mask material itself. Therefore, the benefits (depending on the application situation and application-related efficacy) and the risks of use must be carefully weighed.

Undoubtedly, our results show, that the mask mandates around the world during the SARS-CoV-2 pandemic have generated an additional source of potentially harmful exposition to toxins with health threatening and carcinogenic properties at the population level from nearly zero distance to the airways (predominantly oral inhalation route) and to the gastrointestinal tract. Among the 24 included studies, 63% showed strikingly high values and possible exceedances for substances such as micro- and nanoplastics (MPs and NPs), volatile organic compounds (VOCs), xylene, acrolein, per- and polyfluoroalkyl substances (PFAS), phthalates including DEHP, as well as heavy metals like Pb, Cd, Co, Cu, Sb and TiO_2 (Tables 3 A, 3B and 3 C). For the N95 mask, MP release was 831 μg in 24 h and up to 4400 particles within 4 h (with predominant size <1 μm) and up to 6×10^9 NP in 4 h. Surgical masks released up to 3152 microfibers in <1 h. Our worst-case estimations show breathing, that may exceed the WHO Air Quality Guideline (AQG) limits. Also, we found exceedances of total VOCs (TVOCc) with 403 mg/m^3 within 17 min for the N95 mask, and >1000 μg within the first hour for the surgical mask, being over the threshold limits of EU target guideline, German Federal Environmental Agency and the Oeko-Tex Standard 100. The textile norms were also exceeded for PFAS (N95, surgical, textile mask), DEHP, phthalates, flurotelomer-alcohol, FTOH (textile masks each), naphthalene (N95), Pb (surgical, textile), Cu (surgical), Sb (N95, textile), Cd and Co (each surgical). Additionally, acrolein (surgical) and xylene (N95) were above the USA and German environmental protection agency levels, respectively. Regarding the potential negative short- and long-term effects of the aforementioned toxins, some of the immediate discomforts while wearing a mask (headaches, dry cough, rhinitis, and skin irritation) could be related to this. In this way, the toxic substances of face masks could also contribute to the symptoms already described, known as mask-induced exhaustion syndrome (MIES). Moreover, from a toxicological point of view, concerning their potential risks of use, face mask obligations enforced by law 2020–2023 have been introduced without preceding comprehensive risk analyses and without regulatory provisions (as is common for various products). On top of that, there was (Jefferson et al., 2020) and still is no empirical evidence for the effectiveness of the masks in limiting the spread of viruses in the general populace (Jefferson et al., 2023). Regarding the numerous toxic face mask contents, further reappraisal, research and normative acts are imperative.

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Kisielinski Kai: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hockertz Stefan:** Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Validation. **Hirsch Oliver:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Korupp Stephan:** Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. **Klosterhalfen Bernd:** Methodology, Writing – original draft, Writing – review & editing. **Schnepf Andreas:** Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Dyker Gerald:** Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used in the review are publicly available (referenced publications).

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