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Review article

Cleaning products: Their chemistry, effects on indoor air quality, and implications for human health

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ABSTRACT

The use of cleaning and disinfecting products both at work and at home increased during the COVID-19 pandemic. Those products often include surfactants, acids/bases, carcinogens such as chloroform, and endocrine-disrupting chemicals, such as cyclosiloxanes, phthalates, and synthetic fragrances, which may cause harmful health effects among professional cleaners as well as among people exposed at home or in their workplaces. The aim of this study was to synthesize the effects of the commonly used chemical, surface cleaning and disinfecting products on indoor air quality, focusing on chemical and particulate matter pollutants, exposure, and human health in residential and public buildings. We also provide a summary of recommendations to avoid harmful exposure and suggest future research directions. PubMed, Google Scholar, Scopus, and Web of Science (WoS) were used to search the literature. Analysis of the literature revealed that the use of cleaning products and disinfectants increase occupants' exposure to a variety of harmful chemical air contaminants and to particulate matter. Occupational exposure to cleaning and disinfectant products has been linked to an increased risk of asthma and rhinitis. Residential exposure to cleaning products has been shown to have an adverse effect on respiratory health, particularly on asthma onset, and on the occurrence of asthma(-like) symptoms among children and adults. Efforts to reduce occupants' exposure to cleaning chemicals will require lowering the content of hazardous substances in cleaning products and improving ventilation during and after cleaning. Experimentally examined, best cleaning practices as well as careful selection of cleaning products can minimize the burden of harmful air pollutant exposure indoors. In addition, indirect ways to reduce exposure include increasing people's awareness of the harmfulness of cleaning chemicals and of safe cleaning practices, as well as clear labelling of cleaning and disinfecting products.

1. Introduction

Cleaning products contain a complex mixture of chemicals such as carbonyls, glycol ethers, and hydrocarbons, and these cleaning products include substances serving as detergents, fragrances, pH stabilizers, and solvents which are classified as hazardous by the European Union (Wei et al., 2016).

The use of cleaning products including disinfectants increased during the outbreak of COVID-19 caused by the spread of SARS coronavirus 2 (SARS-CoV-2) starting in December 2019 (Casas et al., 2023; Dewey et al., 2022; Hora et al., 2020; Lou et al., 2021; Vayisoglu and Oncu, 2021). For example, in France, Le Roux et al. (2021) observed a significant increase in exposure to home cleaning products such as biocides and alcohol-based hand sanitizers. In America, Gharpure et al. (2020) found increased and unsafe use of home chemicals and disinfectants among 33 % of adults when trying to protect themselves against COVID-19. In Turkey, Vayisogly and Oncu (2021) reported that during the pandemic period, compared with the pre-pandemic period, both the

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frequency of cleaning and the amount of cleaning product usage increased significantly, by 69 % and 74 %, respectively.

Active ingredients in commonly marketed disinfectants recommended for use against SARS-CoV-2 include chemicals such as quaternary ammonium compounds (QACs), hydrogen peroxide, bleach (sodium hypochlorite), and alcohols (Dewey et al., 2022; Samara et al., 2020).

Although cleaning activities and cleaning products promote hygiene and are important in combating the spread of disease, the use of cleaning products may lead to harmful exposure to primary and secondary indoor air pollutants due to the emission of products and their reactions with other compounds in indoor air (Nicole, 2021; Salonen et al., 2018; Wei et al., 2016; Wolkoff et al., 1998). Humans can be exposed to disinfecting chemicals through inhalation, dermal absorption, and ingestion, and exposure to disinfectants during the pandemic has raised questions of exposure-related long-term health risks and occupational safety (Dewey et al., 2022). QACs have been linked to occupational illnesses such as asthma and an increased risk of chronic obstructive pulmonary disease (COPD) (Dewey et al., 2022). In an observational human study, the presence of QACs in human blood was associated with changes in health biomarkers such as an increase in inflammatory cytokines, decreased mitochondrial function, and disruption of cholesterol homeostasis in a dose-dependent manner (Hrubec et al., 2021). Excess use of alcohol-based disinfectants, bleach, or hydrogen peroxide can cause respiratory damage and has been linked to an increased risk of developing and exacerbation of asthma (Dewey et al., 2022).

Cleaning agents including disinfectants can be more harmful to children than to adults for the following reasons: children have higher breathing rate and breathe more air per unit of body mass than adults; they breathe closer to the ground where air pollutants can concentrate; they have more skin covering their bodies relative to their weight than adults; they typically have more skin contact with the floor; and their hand-to-mouth behavior results in that they ingest more dust and residue (which may contain many toxic chemicals, for example from cleaning products, pesticides, and furnishings) than adults (Li et al., 2021; Özkaynak et al., 2022; US EPA, 2011). As children spend a large part of their day time in school buildings (~30 % of their time at school, around 70 % of which inside a classroom) (Csobod et al., 2014), cleaning agents used in the school setting can contribute considerably to daily exposure.

With a growing body of evidence on the impacts of cleaning products on human health, there is a need to synthesize the researched information on this important topic. In this review, we aim to synthesize the effects of the commonly used chemical, surface cleaning and disinfecting products on indoor air quality, focusing on chemical and particulate pollutants, exposure in residential and public buildings, and human health in an occupational and non-occupational context. We also interpret the reviewed studies by providing a summary of the means to avoid harmful exposure and present our future perspectives.

2. Methods

This study reports a comprehensive literature search using 26 search terms (Table 1) and different combinations of those terms (Table S1). All combinations included one of the following primary search terms: 'cleaning agent', 'cleaning chemical', 'cleaning product' or 'household product'. All four primary search terms were used with different combinations of the other search terms (3–5 other search terms at a time). The consulted databases were PubMed, Google Scholar, SCOPUS, and Web of Science (WoS). The search resulted in 310 publications. After the duplicates were discarded, 230 publications were included in the selection process. Two researchers screened the abstracts of the included publications. Data published between 1 January 2013 and 15 February 2024 were included, but older key literature was considered where deemed necessary. Publication addressing the following topics were included: cleaning chemistry; the effect of surface cleaning and disinfecting products on indoor air quality; exposure to cleaning and disinfecting products in residential and public buildings; and the occupational and non-occupational health effects of cleaning and disinfecting products. The abstract screening determined that 72 publications did not meet the inclusion criteria. The search was then extended to the reference lists of selected full-text articles (158), and after the abstracts were screened (and duplicates discarded), an additional 40 full-text articles were assessed for review analysis. Four further articles were recommended by experts. After the full selection process, 202 studies were included in the review analysis. The article selection process is visualized in Fig. 1. The literature search process was conducted by the authors H. Salonen and T. Salthammer.

The sections on the history and chemistry of cleaning agents essentially describe fundamental processes that serve to support the discussion. Textbooks were preferred for this purpose. The further literature search was limited to the updating of the chemical substances in cleaning agents. The cited references were selected to summarise the current state of the art.

Table 1
Terms used for the search in the chosen databases.

Acids	Bases	Bleaching
Cleaning agent	Cleaning chemical	Cleaning product
Concentrations	Daycare centres	Disinfectant
Enzymes	Exposure	Healthcare facilities
Health effects	Household products	Indoor air quality
Indoor environment	Kindergartens	Occupants' exposure
Office	Particles	Public buildings
Reactive chemicals	Residential buildings	School buildings
Surface cleaning	Surfactants	

3. Results and discussion

3.1. Historical background of cleaning and cleaning chemicals

Cleaning with chemical agents has been known since ancient times. As early as 3000 BCE, soda was described as a detergent in Egypt. In ancient Rome, the urine scrubber became a common profession after it had been empirically found, without knowing the active ingredient urea, that urine could be used to clean textiles. Jumping into the 20th century, it becomes clear that until the 1970s there was hardly any literature on the effects of cleaning agents on people. This is particularly because the ingredients of the products were declared either insufficiently or not at all for a long time. In Europe, this changed in 2008 when the CLP (classification, labelling, packaging) regulation came into force. Only in 1975, with the first edition of Selinger's book *Chemistry in the Marketplace* (Selinger and Barrow, 1975/2017), did the general public become aware of the advantages and disadvantages of chemical products in the indoor environment.

Systematic investigations began in the 1980s with the publication by Pickrell et al. (1994) on formaldehyde in consumer products. Flyvholm (1991) presented a list of contact allergens in registered chemical products in 1991. Further key findings from this period are listed in the 1998 publication by Wolkoff et al. (1998), which extensively addresses the risks in cleaning and identifies disinfectants as the most hazardous group of cleaning agents. The ingredients of consumer products have changed significantly over the years (Weschler, 2009). The reasons for this are manifold and relate to new legislation, voluntary self-regulation, and technically improved active ingredients and additives. However, these substitutions did not necessarily lead to an improvement in the impacts on indoor air quality. In 2004, Nazaroff and Weschler (2004) stated that terpenes in particular react with oxidants such as ozone to form secondary organic pollutants and aerosols. Due to the frequent variation of many products, we consider the last 10 years to be a plausible timeframe for this study, although the basic chemistry has changed little over time.

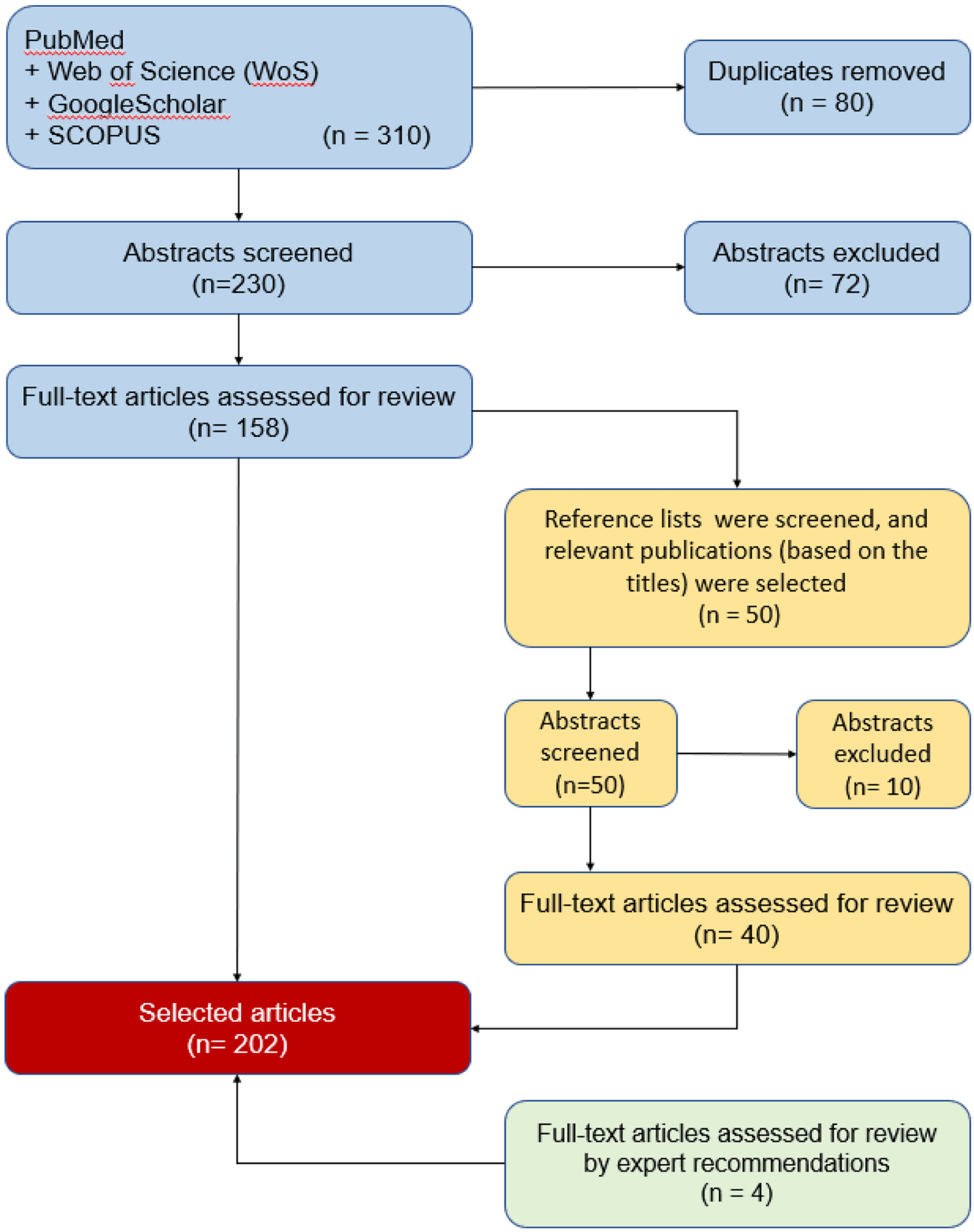

Fig. 1. Flow chart describing the literature search and selection process. Blue: search for articles in databases; yellow: search in reference lists of articles; green: other recommendations; red: number of finally selected articles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. The chemistry of cleaning agents and their effect on indoor air quality

We found 77 scientific publications that reported the effects of cleaning products and disinfectants on indoor air quality. The summary of the relevant papers with this topic is presented in Table S2. In total 33 %, 34 %, and 3 % of the studies reported the effects of cleaning products/disinfectants on indoor air quality in public buildings, residential buildings, or in both type of buildings, respectively. Altogether, 12 % of the studies reported the results from test house, laboratory or chamber studies. In total, 18 % of the relevant studies were 'other type of studies' including, for example, modelling and questionnaire studies.

3.2.1. Stains and soils

Understanding the diverse ingredients in cleaning products requires an overview of the most stubborn and difficult-to-remove stains. In addition to fats, oils, proteins, water-insoluble salts, and oxides, these are often coloured organic compounds and polymers. Anthocyanins, a subgroup of flavonoids, are dyes found in the cells of land plants. They give fruits as well as vegetables their characteristic red colour (Belitz et al., 2009). The colour of red wine is mainly due to the plant dye malvidin (Waterhouse et al., 2016). Curcumin, a yellow polyphenol, is a component of curry mixtures and is used to colour mustard. Lycopene and β-carotene, the pigments in tomatoes and carrots, belong to the group of carotenes. Other common contaminants include Maillard products and chlorogenic acids (from coffee), polyphenols (from tea), malt (from beer) (Barth, 2022), haemoglobin (from blood), and chlorophyll (from plants).

3.2.2. Acid and base chemistry

Acidic cleaners cover the entire pK_a spectrum from strong to weak (see Fig. 2). Acids are offered as toilet and sanitary cleaners, lime and rust removers, and as all-purpose cleaners. Lactic acid also serves as a limescale remover and has an antibacterial effect. Chemically, it is the classic reaction between a salt and an acid, as shown in Eq. (1) using calcium carbonate and acetic acid as an example.

$$CaCO_3 + 2CH_3COOH \longrightarrow Ca(CH_3COO)_2 + H_2CO_3 \quad (1)$$

Moreover, citric acid can complex alkaline earth metal ions, which then no longer form insoluble carbonates. Ethylenediaminetetraacetic acid (EDTA), which complexes metal ions through chelation, has a similar effect. Aged rust that contains a high proportion of Fe_2O_3 is hardly attacked by diluted acids. Rust converters therefore contain phosphoric acid, which first dissolves the rust and then applies an iron phosphate layer for passivation. It is also advisable to avoid combining certain acidic cleaners. If, for example, hypochlorite is used together with hydrochloric acid, chlorine gas is produced according to Eq. (2).

$$HOCl + HCl \longrightarrow Cl_2 + H_2O \quad (2)$$

Alkaline cleaners (see Table 2 and Fig. 2) can attack organic material. This usually occurs through the nucleophilic addition of OH^- ions to the carbon atom of a carbonyl group, followed by bond cleavage. A well-known example is the alkaline hydrolysis of esters shown in Fig. 3. According to this mechanism, fats can be split into the salts of fatty acids and glycerol. Proteins are also broken down into peptides and amino acids in this way.

A drastic reaction is used to clean drains. In aqueous solution aluminum and sodium hydroxide react strongly exothermic under the formation of hydrogen gas (see Eq. (3)). The cleaning effect is a combination of chemical attack on the organic material and mechanical gas pressure (Selinger and Barrow, 1975/2017). The hydrogen is converted by nitrate into ammonia (see Eq. (4)). This can escape into indoor air if not flushed sufficiently.

Table 2
Common ingredients in cleaning products.

Surfactants	Alkyl polyglycosides, polyalkylene glycol ether, alkyl benzene sulphonates, sodium lauroyl sarcosinate, sodium cocoyl glutamate, quaternary ammonium compounds
Acids	Formic acid, acetic acid, citric acid, hydrochloric acid, hypochlorous acid, phosphoric acid, amidosulphonic acid, lactic acid, EDTA
Bases	Sodium hydroxide, ammonia, sodium carbonate, potassium carbonate, sodium silicate
Enzymes	Proteases, amylases, lipases, pektinases, cellulases
Solvents	Glycols and glycol ethers (2-(2-butoxyethoxy)ethanol, propylene glycol), 1-butylpyrrolidin-2-one, aliphatic and isoaliphatic hydrocarbons (C9–C12), aromatic hydrocarbons
Alcohols	Ethanol, 2-propanol, C10–C16 alcohols (ethoxylated)
Fragrances	Coumarin, citral, geraniol, eugenol, isoeugenol, linalool, limonene, farnesol, cinnamal, amyl cinnamal, hexyl cinnamal, citronellol, α-isomethylionone, benzyl alcohol, benzyl benzoate
Bleaching agents	Hydrogen peroxide, sodium percarbonate, sodium perborate, TAED
Preservatives	Formaldehyde releasers (DMDMH, bronopol), isothiazolinones (MIT, BIT), 2-phenoxyethanol, sodium pyrithione
Propellants	Propane, butane, 2-methylpropane
Other	Urea, organic (fluorescent) dyes, aluminum, sodium nitrate, phosphonates, per and polyfluorinated organic compounds (PFAS)

$$2Al + 2NaOH + 6H_2O \longrightarrow 2Na^+ + 2\left[Al(OH)_4\right]^- + 3H_2 \quad (3)$$

$$4H_2 + NO_3^- \longrightarrow NH_3 + 2H_2O + OH^- \quad (4)$$

The combination of alkaline and acidic cleaners should also be avoided. As an example, the use of hypochlorite together with ammonia finally leads to trichloramine (NCl_3) according to Eq. (5).

$$NH_3 \xrightarrow{+HOCl,-H_2O} NH_2Cl \xrightarrow{+HOCl,-H_2O} NHCl_2 \xrightarrow{+HOCl,-H_2O} NCl_3 \quad (5)$$

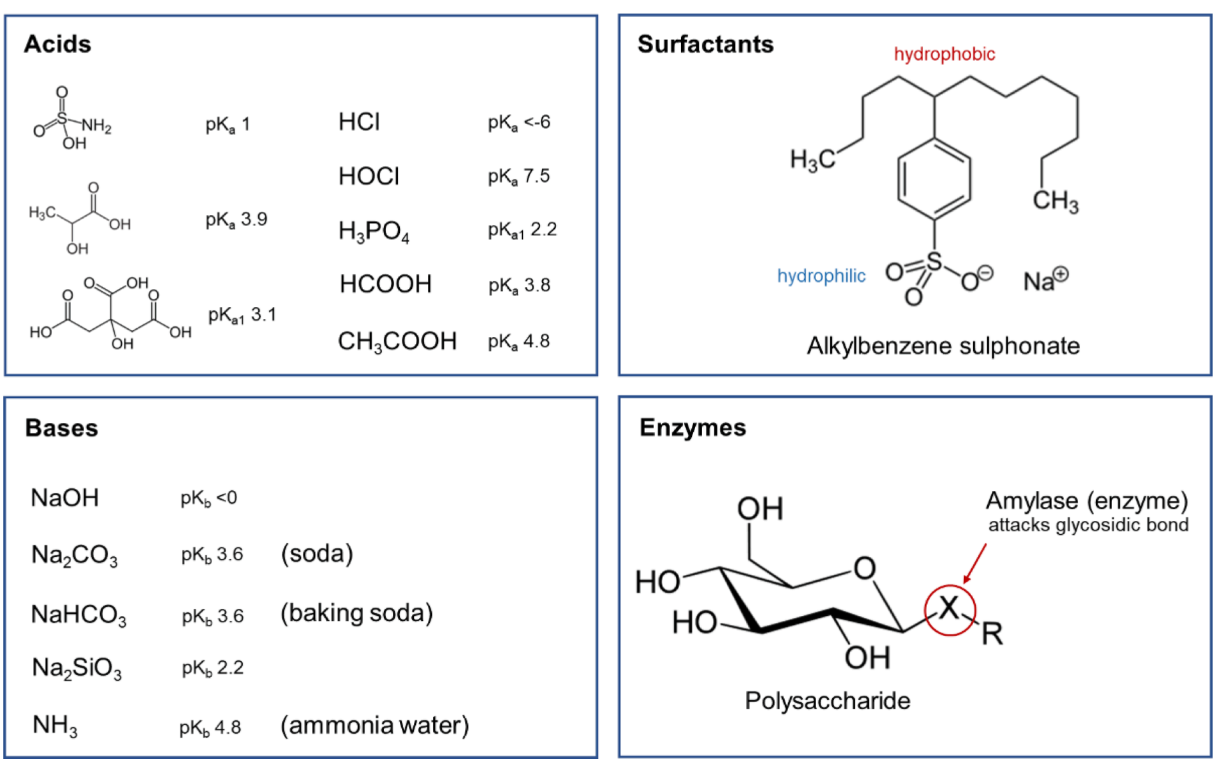

Fig. 2. Examples of active ingredients in cleaning products and their properties.

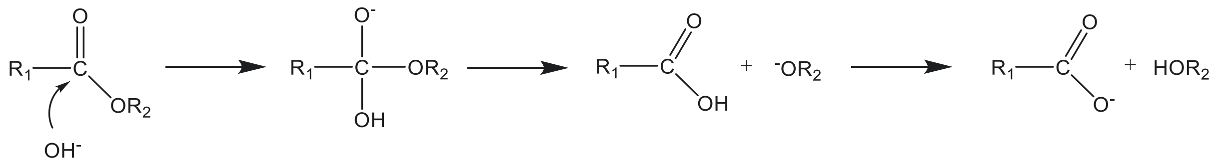

Fig. 3. Schematic process of alkaline ester hydrolysis.

The reaction of urea with HOCl also leads to the formation of trichloramine (Schmalz et al., 2011).

3.2.3. Surfactants

The surfactant molecule often has a fairly long alkyl chain, which is hydrophobic, and a small, often electrically charged head, which is hydrophilic. There are four known types (Farn, 2006): (1) Anionic agent: the surfactant is an anion and the charge is in the hydrophilic head; (2) Cationic agent: the head carries a positive charge; (3) Non-ionic agent: no specific charge, but the hydrophilic portion of the molecule is usually achieved by incorporating a chemical group into the molecule that polarizes this section of the molecule to be slightly negative; (4) Amphoteric agent: the molecule carries both a positive and a negative charge.

The surfactants form a thin layer on the water surface, which lowers the surface tension. Freely moving micelles are formed in the water, which enclose hydrophobic molecules and solids. In domestic detergents, anionic and non-ionic surfactants are predominant (see Table 2) (Selinger and Barrow, 1975/2017). Fig. 3 shows the structure of the common anionic surfactant alkylbenzene sulphonate. The classic soft soaps are sodium and potassium salts of higher fatty acids and therefore belong to the anionic surfactants.

3.2.4. Enzymes

The enzymes used for cleaning purposes (see Table 2) are proteins which, depending on their molecular structure, can catalyse specific chemical reactions. Essentially, they serve to remove cellular contaminants, sugars, and starches. Proteases (peptidases) cleave proteins and peptides by hydrolysis, amylases break down polysaccharides at the glycosidic bonds, lipases cleave free fatty acids from lipids, pectinases break down the polysaccharides of pectins, and cellulases cleave the glycosidic bonds of celluloses. The principle of cleaving a glycoside bond by amylases is shown in Fig. 3. Sometimes enzymes are now replaced by urea. This agent has a denaturing effect on proteins, disintegrates polymer layers and generally increases the solubility of biofilms (Sanawar et al., 2021). However, the actual material to be removed may also contain enzymes. Typical are peroxidases, which catalyse the reduction of peroxides. In this case, cleaning processes at higher temperatures are necessary to inactivate the peroxidases.

3.2.5. Bleach chemistry

Bleaching agents are used to discolour surfaces. They are often components of cleaning products but can also be used in their pure form. Sodium percarbonate and sodium perborate are frequently used in detergents, often in combination with tetraacetylethylenediamine (TAED). Hydrogen peroxide (H_2O_2) and hypochlorous acid, which are also disinfectants, can be sold freely within the European Union as a 3 % solution. Under certain conditions, hydrogen peroxide can also be obtained as a 12 % solution from pharmacies. Hypochlorous acid usually exists as the sodium salt and is used in large quantities to disinfect water (Zwiener et al., 2007). Bleaching agents usually have an oxidizing effect that is, they are reduced themselves in the process. A high positive electrochemical standard potential is advantageous for their effectiveness. Standard potentials of active cleaning agents are $E_0(Cl_2/Cl^-) = +1.38$ V, $E_0(HOCl/Cl_2) = +1.63$ V, $E_0(HOCl/Cl^-) = +1.48$ V and $E_0(H_2O_2/H_2O) = +1.78$ V (Rumble et al., 2020). Nebulization of H_2O_2 and HOCl solutions is common in the hospital sector for the purposes of disinfection, but the method is questionable for private and public indoor environments where people live or work permanently (Uhde et al., 2022). Jahn et al. (2024) report the formation of chlorophenolic disinfection byproducts during the injection of NaOCl microdroplets from a nebulizer into an environmental chamber. Surface cleaners containing H_2O_2 have become very popular for use in private households, and high emissions of H_2O_2 have been measured both in chambers (Zhou et al., 2020) and in residences (Souza et al., 2023) when using such cleaners.

As early as 2008, Obadasi (2008) reported the formation of halogenated organic compounds when using cleaning agents containing hypochlorite. In a later work, Odabasi et al. (2014) examined the content of halogenated and oxygenated volatile organic compounds in chlorine-bleach containing household products. The authors concluded that the risk may reach considerably high levels for those regularly using bleach products. Collins and Farmer (2021) also pointed out that using chemistry for cleaning purposes leads to the introduction of new chemically reactive materials to the building and may initiate an unintended cascade of reactions.

The indoor chemistry of hypochlorous acid was studied by Wong et al. (2017) and later by Mattila et al. (2020a,2020b). In addition to the already described substances chlorine and trichloramine, dichlorine monoxide (Cl_2O) and nitryl chloride ($ClNO_2$) in particular were evident, the formation of which is assigned to reaction Eqs. (6) and (7).

$$2\,HOCl \longrightarrow Cl_2O + H_2O \tag{6}$$

$$HOCl + NO_2^- \longrightarrow ClNO_2 + OH^- \tag{7}$$

Regarding possible sources of NO_2^-, Mattila et al., (2020b) speculated on the basis of findings by Wang et al. (2020) that indoor surfaces represent a reservoir for NO_2^- and that the formation of $ClNO_2$ is associated with the additional uptake of gaseous nitrous acid (HONO).

To a small extent, the active species Cl_2, HOCl, and $ClNO_2$ are also photolyzed in the indoor environment, which leads to the formation of radicals. This then results in hydrochloric acid through hydrogen abstraction from VOCs (Dawe et al., 2019).

When using cleaning products, terpenes can also react with bleaching agents, which was investigated by Wang et al. (2019) for the combination limonene/HOCl/Cl_2. The authors assumed addition mechanisms at the double bonds of limonene, which should finally lead to dichlorohydrin and limonene chloride. Deeleepojananan and Grassian (2023) studied the gas-phase and surface chemistry of limonene/HOCl/Cl_2 and showed that the reaction products adsorb on surfaces for days, providing potential sources of human exposure and sinks for additional reactions.

3.2.6. Ozone and OH chemistry

Various products for indoor use contain terpenoids and the indoor chemistry of this group of substances has been particularly well researched. Singer et al. (2006a,2006b) and Destaillats et al. (2006) conducted extensive studies on the formation of secondary products from terpene-based cleaning products in the presence of ozone. This is a classic reaction based on the Criegee mechanism (Criegee, 1975). The reaction process is rather complex, and therefore only the essential products are listed in Fig. 4 using limonene as an example. In the first step, the primary ozonide is formed. This breaks down into a carbonyl compound and a carbonyl oxide (Criegee intermediate). Further

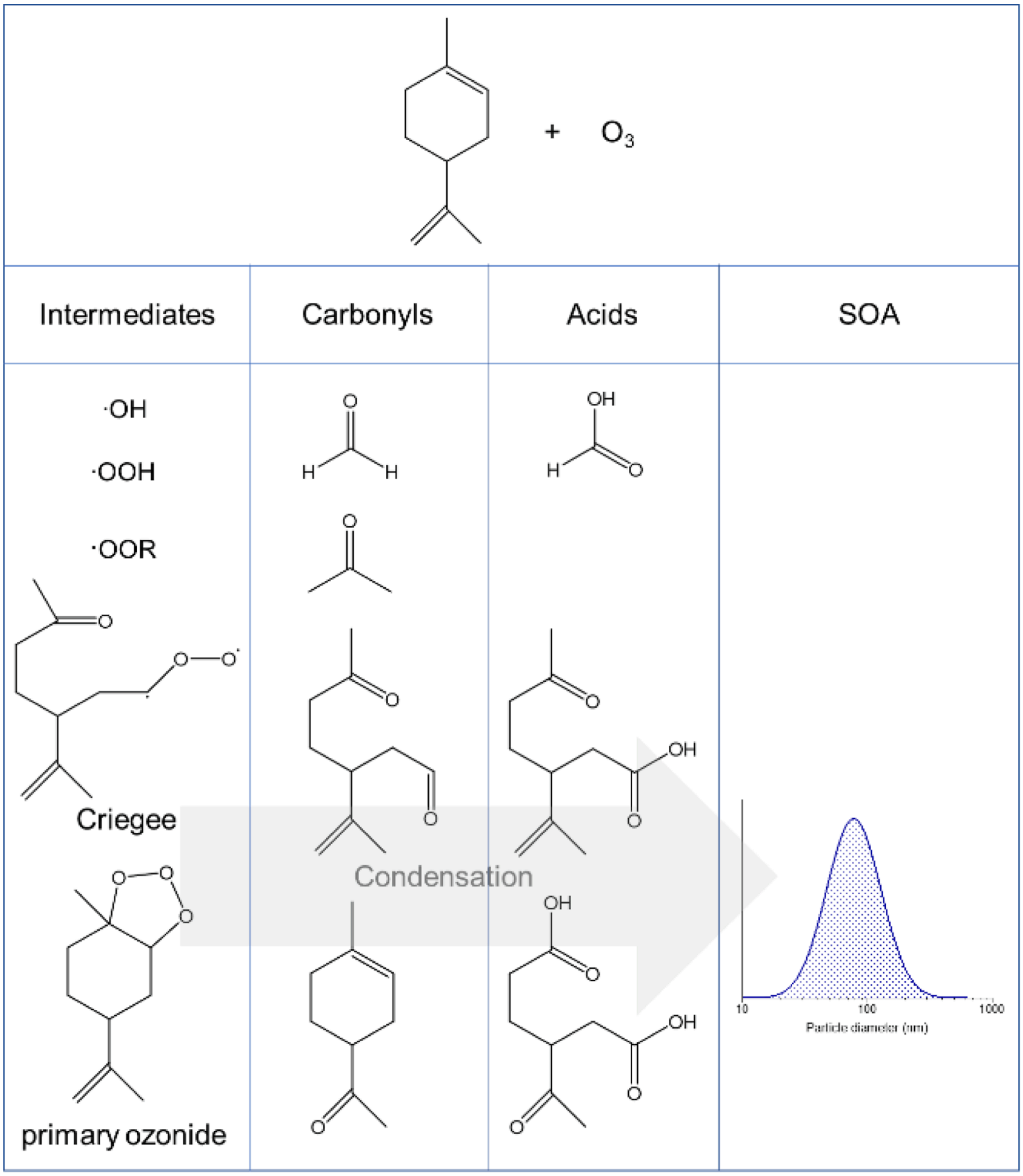

Fig. 4. Selected products and intermediates of the reaction of limonene with ozone (adapted from Morrison (2010))
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oxidation and rearrangement reactions produce additional carbonyl compounds and acids. These form larger molecules and finally secondary organic particles (SOA). The oxidation products of terpene/ozone reactions are well studied (Nørgaard et al., 2013; Wolkoff et al., 2000), as are their irritant effects on humans (Nørgaard et al., 2005). Wolkoff et al. (1997) have suspected that the oxidation of unsaturated VOCs contributes significantly to the formation of indoor irritants.

Carslaw et al. (2017) found a significant increase in OH and HO_2 concentrations when using limonene-based cleaning products in a classroom, as well as various oxidation products of limonene. Xu et al. (2023) studied the release of VOCs from detergent application and identified secondary VOCs as products of typical ozone chemistry. Carslaw and Shaw (2022) carried out investigations with cleaning agents of different terpene compositions and came to the conclusion that substances such as β-pinene, which reacts significantly more slowly with ozone and OH radicals than limonene, lead to fewer oxidation products. The formation of particles from reactions related to cleaning product components is discussed in Section 3.3.

3.2.7. Other reactions and emissions

The spectrum of chemical substances from cleaning agents is hardly manageable in terms of quality and quantity. In this respect, Table 2 can only provide a rough overview of the most important chemicals. It is also not advisable to consult older publications because many substances have disappeared from today's products. However, it is worth mentioning that many of the fragrances still used in cleaning products are found on the EU Directive list of 26 fragrance allergens (Sarkic and Stappen, 2018). Other critical substances are the preservatives. Formaldehyde releasers (including dimethyloldimethylhydantoin (DMDMH) and 2-bromo-2-nitro-1,3-propanediol (bronopol)), isothiazolinones (methylisothiazolinone (MIT), benzisothiazolinone (BIT) octylisothiazolinone (OIT)) and 2-phenoxyethanol are often used. The European Detergents Regulation prescribes a declaration obligation for allergenic fragrances from a concentration of 0.01 %. In addition, preservatives such as isothiazolinones and benzalkonium chloride are considered contact allergens when they come into contact with the skin. Kireche et al. (2011) stated that bronopol is an atypical formaldehyde releaser that produces other degradation products, which can cause allergic reactions.

During application, people are exposed to higher concentrations of released ingredients or reaction products of the cleaning agents than people who are not in the immediate vicinity. Room air measurements are therefore not very helpful, but personal measurements must be carried out when assessing professional or non-professional exposure during cleaning activities. Toxicologically based guide values are available for many volatile components of cleaning products, especially solvents (Fromme et al., 2019). An alternative is biomonitoring to determine internal exposure. There are already methods and comparative values available for a number of substances, such as N-methyl-2-pyrrolidone (Schmied-Tobies et al., 2021), methylisothiazolinone (Murawski et al., 2020) and 2-phenoxyethanol (Jäger et al., 2022).

3.3. Effect of cleaning chemicals on particle concentrations indoors

Particles in the air originate either directly from source emissions into the air (primary particles) or are formed in the air from gaseous precursors through gas to particle conversion, under the conditions of the environment that favour particle formation (Kulkarni et al., 2011). These particles are called secondary organic particles or secondary organic aerosols (SOAs). A commonly observed cause of SOA formation is ozonolysis of alkenes according to the Criegee mechanism (Criegee, 1975) as shown in Fig. 4. In general, secondary particles when formed are initially very small and then grow in the air to larger sizes by coagulation with other particles and by nucleation of volatile material in the air on their surfaces. Usually, the process of secondary particle formation is very fast. Once formed in the air, secondary particles are removed from the air by surface deposition and ventilation.

The application of cleaning products on indoor surfaces results in the emission of gaseous volatile organic and semi-volatile organic compounds (VOCs and SVOCs) and hence in the creation of conditions under which they become precursors to particle formation. Direct emissions when spraying chemicals are also possible, but it is expected that such particles are relatively large and deposit by gravitation soon after emission and then contribute to surface emissions of VOCs and SVOCs. It is out of scope of this paper to discuss the complex physical chemistry involved in particle formation from the gaseous precursors emitted from cleaning products; some general aspects of this are discussed by Gligorowski and Abbatt (2018).

Numerous studies have investigated particles resulting from the application of cleaning products under laboratory conditions or in test houses, as well as in various types of real indoor environments including schools, offices, and residential homes. The results were reported in terms of particle number concentration (PNC) and/or particle mass (PM) concentration, measured as PM_1 or $PM_{2.5}$ (the concentration of particles smaller than 1 or 2.5 μm, respectively).

All studies conducted under laboratory conditions or in test houses demonstrated the impact of cleaning products on SOA formation. Rossignol et al. (2013) found in their experimental 'real condition' house study an initial increase of PM concentration (reaching 25.6 $\mu g/m^3$ and corresponding to primary, mainly larger, particle emissions) when the housecleaning product (a foam surface detergent) was applied. After 15 min, SOAs were also formed, showing a mode at 25 nm. Mattila et al., (2020a) studied the emission of organic PM_1 and ion fragments generated by mopping with a bleach solution inside a test house. They observed a 25 % increase in oxygenated organic aerosol fragments when carrying out post-cooking bleach cleaning. However, this only represented <3 % of the total organic PM_1 mass. The authors assumed that SOAs were generated when organics released during mopping reacted to form particles. Light-induced particle formation resulting from the prior formation of gas-phase products through dark reaction between terpenes and constituents of chlorine bleach solution was observed by Wang et al. (2019) inside an environmental test chamber. Stabile et al. (2021) conducted tests in a chamber and also in a real indoor environment, demonstrating a significant increase in very small particles (SOA size range) from half of the products under investigation. The emission factors measured by the authors were up to 1.1×10^{11} particles/m^2 (8.8×10^{10} particles/mL product) and comparable to emissions from other major indoor sources.

Several studies have investigated the impact of cleaning products in schools. SOA formation was shown in experiments conducted in a school classroom in Australia, in which using a detergent containing limonene led to an almost immediate increase in the UFP number concentration, with the concentration in the classroom increasing by about 3×10^4 particles/cm^3 above the background level (Morawska et al., 2009). Another study conducted in Australian classrooms demonstrated that cleaning during non-school hours elevated indoor PNC by more than five times, with an average emission rate of $(2.09 \pm 6.30) \times 10^{11}$ particles/min (Laiman et al., 2014). Monitoring of daily patterns of particulate matter in school classrooms in Portugal revealed the importance of cleaning activities, occupancy, and resuspension of dust for the increase in particle concentrations (Faria et al., 2020). The authors found an increase in $PM_{2.5}$ concentrations before the beginning of the classes (9 a.m.) due to the cleaning of the classroom, without, however, identifying the fraction of particle resulting from the application of cleaning products. It is important to note that classroom floors were cleaned not only by using cleaning products but also by sweeping, which promotes the resuspension of deposited particles (Faria et al., 2020).

A handful of studies have been conducted to investigate the impact of cleaning on particle concentrations in residential houses. In a study carried out in Portugal, Faria et al. (2020) identified elevated levels of $PM_{2.5}$ mass concentrations caused by the presence of the housekeeper performing the cleaning activities during the morning period in residential buildings. In a study conducted in an apartment in the Czech Republic, Vu et al. (2017) found that particles generated from cleaning activities showed unimodal number size distributions, with the majority of particles (>98.2 %) in the ultrafine (UFP) size range (<100 nm). The authors observed the generation of UFPs with a maximum concentration of 1.25×10^5 particles/cm^3 and a peak number mode of 30.6 nm while cleaning the kitchen counter with the application of a foam containing organic compounds. UFP concentration levels decreased rapidly due to coagulation and deposition processes after termination of the cleaning activity. A study conducted in Edmonton, Canada investigated the elemental composition of PM_1 in 74 homes and apportioned their sources based on receptor modelling (Bari et al., 2015). Among 12 factors identified, only a small signature in factors 11 and 12 was linked to cleaning activities and products.

In office buildings, common cleaning practices, such as mopping the floor and spraying windows with a glass cleaner, were reported to generate air fragrances and aerosols (Zarogianni et al., 2018). The authors also found that cleaning affected the number concentrations of all particle sizes, but $PM_{>0.4}$ (particles with a diameter above 0.4 μm) were the most affected. The highest concentrations were observed during mopping the office floor with a solution of general-purpose cleaner in combination with cleaning the windows with a glass-cleaning spray. Audignon-Durand et al. (2023) calculated average and range of UFP peak concentrations through a meta-analysis of studies reporting concentrations linked to indoor, non-occupational activities. They calculated an average UFP peak concentration from using spray air freshener of 17×10^3 particles/cm^3 with a range of 4–30 $\times 10^3$ particles/cm^3 and a peak of 107×10^3 particles/cm^3, and a range of 2–330 $\times 10^3$ particles/cm^3 when handling cleaning products. These values were in the lower spectrum of the calculated UFP peak concentrations when compared to activities such as cooking.

The studies reviewed above were conducted according to different designs with different aims (not necessarily focused on secondary particles), and their results were presented in different formats. Therefore, direct comparison of particle characteristics is not possible. It is important to note, however, that all experimental studies where it was possible to separate SOAs generated as a result of application of cleaning products from other particle generation sources during cleaning (in particular dust resuspending), demonstrated formation of SOAs and high or very high PN concentrations compared to 1 h concentrations considered as typical in outdoor urban air by the World Health Organization (WHO, 2021). This means that exposure to particles formed or emitted during cleaning activities is a health risk that must be mitigated. The studies also showed that $PM_{2.5}$ concentrations were elevated during and shortly after cleaning activities; however, there are no WHO $PM_{2.5}$ short-term exposure guidelines (only 24 h and annual), and therefore it is more difficult to conclude on the impacts on health of short-term exposure to $PM_{2.5}$ during cleaning activities.

The summary of the 77 relevant scientific publications reporting the effects of cleaning products and disinfectants on indoor air quality is presented in Table S2 in the Supplementary Material.

3.4. The effect of cleaning products on occupants' health

We found 65 studies that reported the effects of cleaning products/disinfectants on human health. The scheme of the effect of surface cleaning on human exposure and health is described in Fig. 5, and the list of the studies with an outline of the topics covered is presented in Table S3 in the Supplementary Material.

In total, 54 % of the selected health studies reported **occupational exposure (work-related exposure)** to cleaning chemicals. Occupational exposure studies mainly considered the detrimental health effects of cleaning chemicals among professional cleaners and those responsible for cleaning or disinfection tasks in hospitals and other healthcare facilities. There is a broad consensus among such studies that cleaning chemicals are among the most frequently implicated causative exposure agents for occupational asthma, asthma symptoms, otherwise impaired respiratory health, and rhinitis (Clausen et al., 2020; Folletti et al., 2014; Svanes, 2023; Vizcaya et al., 2015).

Asthma symptoms are associated with frequent, low-level exposure to irritants including chlorine, ammonia, hydrochloric acid, chloramine, and sodium hydroxide, and occupational exposure to quaternary ammonium compounds increases the risk of rhinitis and asthma (Clausen et al., 2020). Dose–response relationships between asthma or new-onset asthma and exposure to specific products, including ammonia, bleach, chloramines (from mixing bleach with cleaning products), and cleaning sprays have been established (Folletti et al., 2014). Cleaning and disinfecting activities (CDAS), as a sub-category of 'cleaning', are well-established and important risk factors for asthma-related outcomes among healthcare workers (Folletti et al., 2017; Mazurek and Weissman, 2016; Su et al., 2019; Virji et al., 2019; Wiszniewska and Walusiak-Skorupa, 2014). Although the complexity of CDAs and the exposures they generate in healthcare settings are rarely studied, it has been reported that various combinations of product applications, such as using alcohols, bleach, high-level disinfectants, and enzymes to clean surfaces and disinfect instruments, have been identified as risk factors for different asthma symptoms (Su et al., 2019). A recent study raised concerns over the implications of exposure to cleaning agents for offspring asthma as well. Svanes (2023) reported that mother's occupational exposure preconception to cleaning agents and disinfectants is associated with increased offspring asthma, raising the issue of potential germ cell impacts of cleaning chemicals. Somewhat, but not truly in contrast to the reported risk associations for cleaning-related exposures and asthma, some work has raised speculations that asthmatic cleaners may be more protected from the negative effects of certain irritants than non-asthmatic subjects, possibly because of the elevated production of the mucus that acts as a trap for water–soluble compounds, such as formaldehyde (Clausen et al., 2020; Fadeyi et al., 2015).

In addition to asthma and asthma symptoms, a higher risk of chronic obstructive pulmonary disease (COPD) or chronic bronchitis (De Matteis et al., 2016), increased rates of death due to COPD (Van den Borre and Deboosere, 2018), and an accelerated decline in lung function (Svanes, 2023) have been reported among cleaning workers. Inhalation exposure is not the only pathway whereby cleaning agents have adverse health impacts: research has also found that cleaning agents increase the risk of skin symptoms (Garrido et al., 2022). Lee et al. (2014) found that chemical-related symptoms were more common among workers who performed patient-area cleaning (44 %) without protective clothes except for gloves.

Non-occupational exposure (household exposure) to cleaning chemicals was reported in 51 % of the included health studies. Summarising, the publications conclude that frequent use of cleaning products in indoor environments may increase occupants' exposure to a variety of harmful environmental toxicants including volatile organic

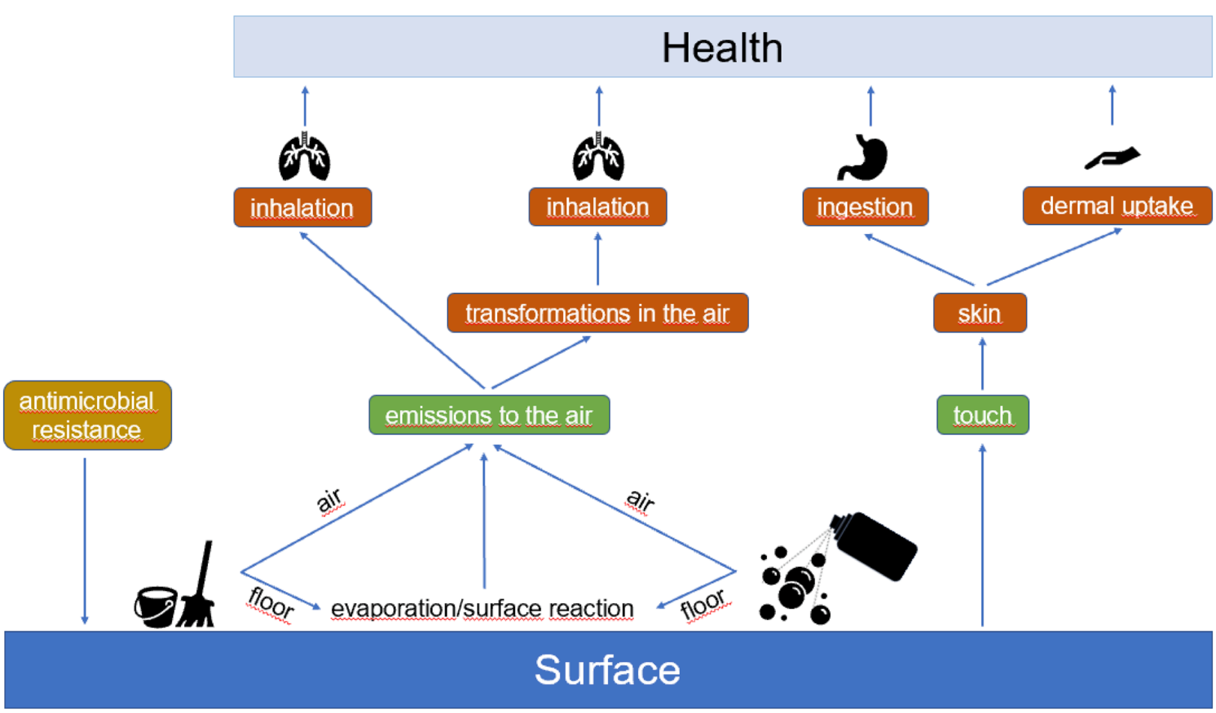

Fig. 5. Possible pathways of human exposure to chemicals from surface cleaning activities.

compounds (VOCs), particulate matter (PM), and nitrogen dioxide. The results of the studies consistently show clear evidence that the use of household cleaning products has negative effects on the respiratory health of adults and children.

In adults, the use of cleaning products increases the risk of asthma, its symptoms, and poor asthma control (Casas et al., 2023). Accelerated lung function decline has also been found among women cleaning regularly in their own homes (Svanes, 2023). In contrast, adolescents are an understudied population group in which no associations with asthma, rhinitis, or eczema were observed in one Dutch study (Bukalasa et al., 2019).

Most research on residential cleaning agent use and health effects has been conducted in children: exposure to cleaning products has been associated with airway obstruction, decreased lung function, inflammation, increased allergen sensitization, and the exacerbation of asthma symptoms (Goldizen et al., 2016; Hollenbach and Cloutier, 2015). Consistent evidence is observed for symptoms (wheezing) but not for asthma, which is, however, difficult to diagnose at a young age.

Casas et al. (2013) and Mikeš et al. (2019) found an association between exposure to cleaning products during either pregnancy or the first years of life and persistent wheezing in early childhood. In a Canadian birth cohort study (Parks et al., (2020), exposure to frequent use of household cleaning products in early life was associated with an increased risk of childhood wheezing and asthma but not atopy at 3 years of age. Liu et al. (2016) found an increase in the odds of rhinitis in Chinese primary school children. Recently, Maung et al. (2022) published a review study about the effects of PM and VOCs on children and people with pre-existing lung disease and concluded that high levels of VOCs—with cleaning agents among the relevant VOC sources—were associated with upper airway and asthma symptoms and with cancer.

Cleaning products applied in spray form are suggested to have more harmful effects on the respiratory system than other application types of cleaning agents, and thus this application deserves particular attention. Regular use of cleaning sprays increases asthma incidence, current asthma, and poorly-controlled asthma in adults, and wheezing in children (Casas et al., 2023). The frequent use (4–7 days per week) of sprayed disinfectants has been associated with an increased risk of asthma in young adults, with some evidence of a dose–response relationship (Weinmann et al., 2017).

A persistent or increased weekly use of sprayed cleaning products over time may have an adverse effect on the evolution of asthma symptoms among women, and the use of cleaning sprays at home has also been associated with poorer lung function among individuals both with and without asthma (Da Silva et al., 2023; Le Moual et al., 2014).

Vayisogly and Oncu (2021) studied the use of cleaning products and the relationship with the increasing health risks during the COVID-19 pandemic. They found that the frequency of reporting health issues related to the use of cleaning products was high (47 %). The most commonly reported problems were skin disturbances (68 %) and shortness of breath (23 %).

Although rather strong evidence of the health effects of some cleaning products exists, inconsistencies are observed across studies, which may be strongly related to study design. The investigation of the health effects caused by household cleaning is challenged, for example, by difficulties relating to the accurate quantitative assessment of exposure to cleaning chemicals in epidemiological studies and by the issue of possible misclassification errors (uncertainty about the used products) in studies that use questionnaires for exposure assessment, which is the case for most epidemiological studies (Dumas and Moual, 2020). In the case of studies on children's health, cross-sectional studies are inconclusive, and even longitudinal studies often do not have sufficiently long follow-ups to detect the onset of new asthma (Casas et al., 2023). The available research results suggest that both timing and level of exposure are important factors in a potential causal association of household cleaning products on respiratory health (Dumas and Moual, 2020). Connected to this, Rook and Bloomfield (2021) recommend that targeting hygiene practices at key risk moments and sites can maximize protection against infection while minimizing any impact on essential microbial exposures. This recommendation was made in the context of the known importance of microbial exposure for the development of a health-promoting immune system during early childhood (Kirjavainen et al., 2019). According to Rook and Bloomfield (2021), reducing the direct exposure of children to cleaning agents must be one aim, because these agents probably exert T_H2-adjuvant effects that trigger allergic responses to normally innocuous antigens.

3.5. Means to reduce exposure to cleaning chemicals and disinfectants

Based on the reviewed literature, we identify ten main means to reduce exposure to cleaning chemicals and disinfectants.

(1) Optimal cleaning practices and product selections, including avoiding the overuse of chemicals and air fresheners in cleaning as these may be contributing additional hazardous substances to the air (Nwanaji-Enwerem et al., 2020); avoiding essential-oil-based cleaners as they could be significant and versatile sources of formaldehyde and fragrance molecules (Milhem et al., 2021); minimizing the use of disinfectants (Blackley et al., 2023); and purchasing ready-to-use products (ready-to-use peroxide products are preferred over bleach for cleaning because they do not need to be diluted daily). We also strongly encourage further investigation into alternative, non-chemical disinfection technologies as a means to simultaneously reduce healthcare workers' exposure to disinfectants while also minimizing costly healthcare-acquired infections (Blackley et al., 2023).
(2) Cleaning schedules should take into account the activity inside the facilities: if possible (e.g. in office and school settings) cleaning should be conducted when the space is unoccupied and cleaning should be finished at least five hours before people enter the room (Zarogianni et al., 2018). In school buildings, cleaning should be done after school hours to avoid exposure to harmful chemicals and ultrafine particles (Rivas et al., 2018). In hospitals, cleaning schedules should be adapted to reflect clinical risks, hand-touch frequency of surfaces, location, and type of site, and should be evaluated for benefit versus cost for both outbreak and routine situations (Dancer, 2014). Cleaning should be conducted from cleaner to dirtier areas to avoid spreading dirt and microorganisms (CDC and ICAN, 2019).
(3) Correct storage and maintenance of cleaning tools, such as removing of cleaning supplies from occupied spaces promptly after cleaning (CDC and ICAN, 2019).
(4) Adequate and well-functioning ventilation: ventilation should be increased during and after cleaning (Wei et al., 2016) and the air velocity should be increased when spreading disinfectants (Lu et al., 2018).
(5) The use of gloves (Nelson and Phalen, 2022). The selection of the 'best' glove for a specific task requires balancing the science such as performance, properties, and limitations of gloves with the art of glove selection including comfort, ease of use, comfort, protection, and cost (Nelson and Phalen, 2022).
(6) The use of protective clothing: chemical related symptoms can be decreased with the use of protective clothing (Elbadry, 2019; Lee et al., 2014).
(7) The use of appropriate respiratory protection (e.g. for disinfection tasks) should be considered where other control measures are not feasible (Cummings and Virji, 2018; Gomes et al., 2016; Memarzadeh, 2021; Siracusa et al., 2013), and the combination of engineering, administrative, and personal protective equipment controls to reduce exposure (Blackley et al., 2023).
(8) Education and awareness-raising about safe use and the health risks of cleaning products and chemicals among cleaners and health workers, as well as consumers (Cummings and Virji, 2018;

Gola et al., 2019; Pirincci and Altun, 2016; Samara et al., 2020; Siracusa et al., 2013; Vayisoglu and Oncu, 2021; Wiszniewska and Walusiak-Skorupa, 2014).

(9) Co-operation between scientific communities and health and safety agencies (Siracusa et al., 2013).

(10) Safety data sheets and labelling of cleaning and disinfecting products must be accurate in order to support the safe use of cleaning and disinfecting products (Quinn and Henneberger, 2015).

3.6. Future perspectives

There is currently a clear trend towards sustainable ingredients in cleaning products. However, the sustainable alternatives still lack general acceptance, as the cleaning process can be slower and might require more effort from the user. Therefore, users often accept exposure to strong acids and alkalis, biocides, etc. during the application of conventional products, which work faster and require less effort to achieve the same effect. The increased use of strong oxidizing agents such as HOCl and H_2O_2 during the COVID-19 pandemic has also shown that people prefer highly effective chemicals for perceived safety reasons. Therefore, future research should prioritize developing cleaning products with eco-friendly, biodegradable, and non-toxic ingredients, of which performance is efficient and effective. This includes creating surfactants and solvents from renewable resources like plants and algae, aiming to replace traditional chemicals, which may cause harmful environmental or health impacts. Smart cleaning products that respond to environmental conditions or specific contaminants hold great promise. These include pH-responsive agents and contaminant-specific enzymes that adjust their activity based on the surrounding environment or type of dirt, ensuring more efficient and targeted cleaning.

Another important research area is reducing VOCs from cleaning products. Innovative approaches targeted at developing low-VOC formulations, alternative fragrance delivery systems, such as microencapsulation and natural essential oil-based solutions as well as avoidance of preservatives and allergens. A complementary approach to protect against high VOC concentrations in the air when applying cleaning products would be the use of sensors. A photoionization detector (PID) for total volatile organic compounds (TVOC) cannot identify any health risk, but can indicate peak concentrations (Salthammer, 2022) EDTA and microplastics have been criticized for their water-polluting properties. Although acetic acid is an effective and sustainable cleaning agent, acceptable concentrations in the room air can easily be exceeded when using products containing acetic acid, so alternatives are being sought for this substance as well.

Many cleaning products can be made do-it-yourself, often the only thing missing is the recipe. An all-purpose cleaner can be easily mixed from water, citric acid, a natural surfactant, a natural essential oil (optional, as an odorant) and sodium chloride. The main component of a scouring cream is the abrasive made of calcium carbonate or lactic acid clay with the appropriate grain size. A combination of acetic acid and sodium hydrogen carbonate (baking soda) has proven to be suitable for cleaning drains. In principle, most cleaning tasks in the household sector can be accomplished with just a few sustainable chemicals. However, there is still a lack of information on how the active ingredients can be combined and used sensibly.

This review of the literature has largely focused on chemical, antimicrobial cleaning, while microbial-based products slowly but steadily conquer space in the cleaning product shelves. These are cleaning approaches that either contain microbial byproducts, first and foremost enzymes that can be highly effective against organic material and biofilms, or that contain live microorganisms in so-called Probiotic Cleaning and Hygiene Systems (PCHS) (Velazquez et al., 2019). The big promise of such 'pro-microbial' cleaning approaches is a reduction in the indoor chemical loads and subsequent human exposure to cleaning chemicals, at the same time avoiding the emerging issue of antimicrobial resistance induced by antimicrobials used in chemical cleaning agents. We have reviewed the literature on the impacts of cleaning on the microbiomes of surfaces (Täubel et al., 2024) and find promising results from the application of PCHS, in particular in competitive exclusion of pathogens in hospital settings (Caselli et al., 2018; Caselli et al., 2016; Soffritti et al., 2022; Stone et al., 2020; Vandini et al., 2014). However, these findings still require replication and rigorous evaluation and aspects of quality control and safe application with respect to human exposure need to be addressed. PCHS in other than health-care environments have been little explored. We nevertheless consider this to be an area that deserves more attention in future research efforts.

As concerns epidemiological health research, future work should also include efforts to improve exposure classification (rather than only relying on questionnaires) and sufficient follow-up duration in longitudinal studies to establish if there are long-term health impacts caused by the products. Integrated assessments of particle, chemical and microbial footprints of cleaning will improve our understanding of human exposure. Cleaning induced changes to surface microbiomes and subsequently to human exposure and health have so far not been sufficiently addressed in epidemiological studies (Täubel et al., 2024). Research involving sensitive populations will help to identify and mitigate potential health risks, with multi-exposure assessments providing a clearer picture of how different chemicals interact and affect health in real-world conditions.

4. Conclusions

This review presents a comprehensive picture of the impacts of chemistry-based cleaning products on indoor air quality, human exposure, and health in residential and public buildings. Based on the reviewed literature, the following conclusions can be drawn: (A) The use of cleaning products indoors may increase occupants' exposure to a variety of harmful environmental pollutants including volatile and semi volatile organic compounds (VOCs and SVOCs), particulate matter (PM), and nitrogen dioxide; (B) Common cleaning practices, such as mopping the floor and spraying windows with a glass cleaner, burden the air with fragrances and aerosol; (C) Some household cleaning agents are sensitizers or airway irritants, and have been associated with impaired respiratory health among children and adults; (D) Cleaning products applied as sprays are suggested to have the most harmful effects on the respiratory system; (E) Regular use of products in spray form at home can increase asthma incidence, current asthma, and poorly controlled asthma in adults and wheezing in children; and (F) Specific factors of the study design (e.g. exposure misclassification bias when using questionnaires or insufficient follow-up time in longitudinal studies) contribute to inconsistencies in results across studies.

The means to reduce exposure to cleaning chemicals and disinfectants include optimizing cleaning practices and product selections, the timing of the cleaning (depending on the activity inside the facilities), correct storage and maintenance of cleaning tools, adequate and well-functioning ventilation, the use of suitable clothing, gloves and protective equipment if needed, education and awareness raising about safe use and the health risks of cleaning products and chemicals, co-operation between scientific communities and health and safety agencies, and accurate safety data sheets and labelling of cleaning and disinfecting products.

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CRediT authorship contribution statement

Heidi Salonen: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Tunga Salthammer:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Emmanuelle Castagnoli:** Writing – review & editing, Writing – original draft. **Martin Täubel:** Writing – review & editing. **Lidia Morawska:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Conceptualization.

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

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.108836.

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