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Microplastics in indoor environment: Sources, mitigation and fate

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Highlights

- High abundance of microplastics in indoor air environment.
- Microplastic sources and types in indoor air are discussed.
- Mechanism of spreading and transportation of microplastics in indoor environment is included.
- Knowledge gaps and future research directions on indoor microplastics are presented.

Abstract

The problem of microplastics associated with an exponentially growing production of plastics is becoming one of the most concerning issues of the 21st century. Although, there is still little evidence about the harmful effect of micro and nanoplastics pollution, they have to be considered as a possible threat, since their concentration is continuously growing. Several studies have already demonstrated the presence of microplastics in the aquatic environment, but only limited number of studies investigated the presence of airborne microplastics in the terrestrial environment especially in indoor air environment. The objective of this study is to review the existing literature to establish the extent of this new emerging phenomenon by identifying sources, types and levels of microplastics presence in indoor air, as well as their formation methods, characteristics, accumulation, behaviour and fate. The study also involves exploration and evaluation of the existing methods of testing airborne microplastics to assess their effect and risk to human health and the environment. Possible methods of controlling, reducing and mitigating of these pollutants are also investigated. The results of the literature

overview revealed the scale and complexity of airborne microplastics pollution, technological deficiencies in testing methods, and the need to develop recommendations for potential short- and long-term measures to help reduce the impact of this pollutant on human health and the environment.

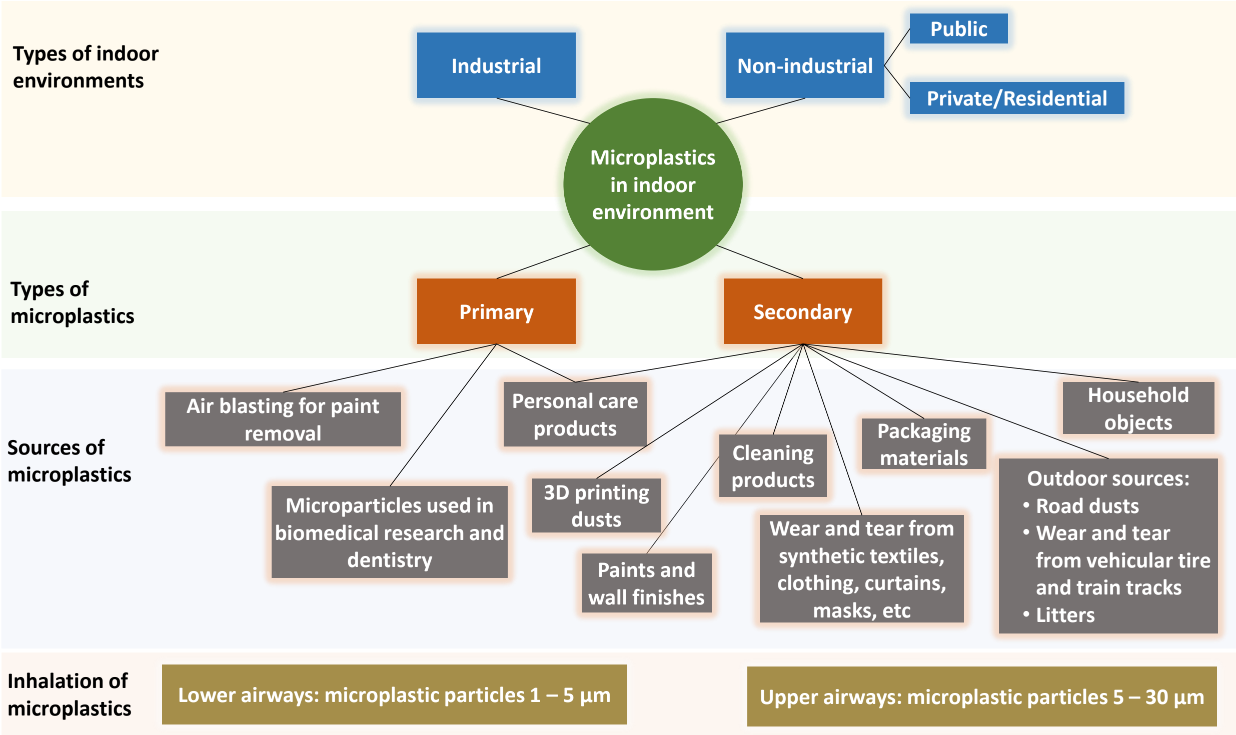
Keywords: Microplastics, indoor environment, pollution, airborne contaminants

Nomenclature

ABS	Acrylonitrile-Butadiene-Styrene
AC	Acrylic
ALK	Alkyd Resin
AR	Acrylic Resin
BPA	Bisphenol A
BYO	Bring Your Own
CE	Cellophane
CEN	Committee of European Norms (European Committee for Standardization)
CO	Carbon Monoxide
CV	Viscose (Rayon)
DEHP	Di (2- Ethylhexyl) Phthalate
EP	Epoxy Resin
EVA	Ethylene Vinyl Acetate
FPA	Focal Plane Array
FTIR	Fourier Transform Infrared Spectroscopy
FRs	Flame Retardants
GBCA	Green Building Council of Australia, known as Green Star Rating
H_2O_2	Hydrogen Peroxide
HEPA	High Efficiency Particulate Air (filter)
Hg	Mercury
HVAC	Heating, Ventilation and Air Conditioning
IARC	International Agency for Research on Cancer
ISO	International Organization for Standardization
IWBI	International WELL Building Institute
MERV	Minimum Efficiency Reporting Value
NaClO	Sodium Hypochlorite (bleaching agent)
NO_x	Nitrogen Oxide (conversion of nitrogen oxides NO and nitrogen dioxide NO_2)
O_3	Ozone
PA	Polyamide
PAA	Poly (N-Methyl Acrylamide)

PAN	Polyacrylonitrile
Pb	Lead
PBDEs	Polybrominated Diphenyl Ethers
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene Terephthalate
PES	Polyester
PM	Particulate Matter
PP	Polypropylene
PPR	Polymerized Petroleum Resin
PS	Polystyrene
PTFE	Teflon
PU/PUR	Polyurethane
PVA	Poly (Vinyl Acetate)
PVC	Polyvinyl Chloride
PVC-HS	Polyvinyl Chloride Heat Stabilizer
RY	Rayon
SI	International Unit (Système Internationale)
SO_2	Sulphur Dioxide
TBBPA	Tetrabromobisphenol A
ULPA	Ultra-Low Penetration Air (filters)
UV	Ultraviolet (radiation)
VOCs	Volatile and Semi-Volatile Organic Compounds
Zn	Zinc
$ZnCl_2$	Zinc Chloride

Graphical abstract



1. Introduction

The exposure of humans to indoor airborne microplastics has not yet been given proper attention. Many studies and research have been dedicated into the presence of microplastics in the aquatic environment, but not as much into the presence of microplastics in the indoor environment [1]. Some studies suggest that the concentration of this pollutant in indoor air is substantially higher than in outdoor air [2, 3]. Microplastics in indoor air are also different to outdoor air as they come from different sources. They are being generated by friction, heating, lighting or wear and tear of everything made from or with various types of plastics. This includes some furniture, other household items like carpet or curtains or building materials including wall paints or floor finishes. However, the majority of microplastics in the indoor air come from synthetic fabrics such as acrylic, nylon or polyester used in clothing [3]. Microplastic fibres released from these materials are usually longer and more harmful to humans. They tear from clothes during wearing, cleaning and drying [3]. Microplastic particles less than 5 µm in diameter, when inhaled, will not be filtered out through the nose, but may and will become lodged deep within the lungs causing a wide range of health problems from a simple cough to lung infections like pneumonia [4]. Particles of less than 2.5 µm can cause permanent lung damage. They can also enter the bloodstream and cause serious health consequences including cardiovascular diseases or even cancer [5]. Airborne microplastics may not only absorb, but also carry toxic chemicals/matter, e.g. bacteria or viruses [6]. Microplastic particles are bio-persistent, so when they penetrate the human body they cannot be expelled or broken down.

Considering that people in developed countries spend more than 90% of their daily life in indoor spaces [6], the presence of microplastics within the indoor environment, their impact on human health and the mitigation measures are of paramount importance. Addressing and investigating the problem shall clarify many aspects of the pollutants present in indoor air and provide valuable information to help create effective methods to control it in the air we are breathing, particularly in enclosed spaces. The objective of this study is to establish the extent of this new emerging phenomenon by identifying sources, types and levels of microplastics presence in the indoor air, in different types of dwellings and to recommend safe, reliable and effective methods of controlling these pollutants.

2. Microplastics in the indoor environment

To investigate all possible aspects of the microplastic presence in the indoor environment and assess the extent of this problem, it is necessary to analyse not only the types, but also the nature of the spaces in which they occur in, methods of their formation and spreading as well as their physical and chemical characteristics. Microplastics are very complex pollutants and require the use of a multifaceted approach to their research. The following review of the existing research and findings confirms the complexity and challenging nature of microplastics.

2.1 Types and uses of indoor spaces

There are many different types, characteristics and uses for indoor confined spaces. The indoor environment is generally divided into two types of spaces: industrial and non-industrial. Industrial spaces are guarded by specific regulations associated with the type of industrial activities occurring inside and they are classified as manufacturing buildings, laboratories, storage facilities and various agricultural plants. The non-industrial indoor spaces could be divided into public and private buildings. The private or residential spaces include individual houses or apartment blocks. The public or non-residential spaces include office buildings, carparks, community structures such as schools, hospitals, hotels and other public services areas. The public spaces also include social or recreational activities areas usually associated with large public access such as shopping centres, theatres, cinemas, restaurants, gyms or other sporting facilities. The public spaces also include all forms of public transport, usually small, but heavily crowded spaces such as busses, trains or airplanes [7, 8]. All of the above-mentioned indoor spaces contribute to an increased human exposure to various air pollutants associated with enclosed areas. The density and type of the pollutants depends on the location of the space (urban, suburban or rural), climate (humidity and temperature, rain/snowfall), occupancy (high, low or fluctuating), furnishing etc. [8]. The issue is more significant in developed, particularly industrialised countries, where people spend a great majority of their time indoor [6].

There are many different air-born pollutants associated with the indoor environment in the form of organic, inorganic, biological and even radioactive pollutants such as volatile compounds, NO_x, CO, O_3, SO_2, particulate matters, radon and microorganisms [9]. Although, research is still in its early stages, microplastics are also a part of air pollutants, and their concentration in the indoor environment appears to be higher than in the outdoor environment [2, 3]. The concentration of microplastics in the indoor air depends mainly on the type and use of indoor space.

2.2 Characteristics of microplastic particles

The term *microplastics* was invented in 2004 to describe smaller particles of plastic, and in 2018, Friah and Nash attempted to define microplastics as: *'any synthetic solid particle or polymeric matrix, with regular or irregular shape and with size ranging from 1 μm to 5 mm, of either primary or secondary manufacturing origin, which are insoluble in water'* [10]. This definition is still debated among scientists and the consensus has not yet been reached.

Considering that humans spend almost 90% of their time indoors, the quality of indoor air is of great importance to human health. Microplastic particles suspended in the air or deposited in the dust are being inhaled or ingested by humans in increased amounts in the indoor environment. Although, there is no research confirming a toxic effect of microplastics on human health, there are some reports suggesting that microplastic particles, particularly smaller than 50 μm can induce inflammation of lungs and other organs [11]. The most common synthetic or semisynthetic polymers occurring in the indoor environment are '*polyester, rayon, acrylic, cellophane, polypropylene, polystyrene, and polyamide'* fibres [11].

These microplastics can have a physical or chemical effect on human health. The physical effect is associated with the microplastic particles sizes, shapes, lengths or concentration. The chemical effect is associated with chemicals added to plastics during manufacturing to improve their quality, strength and performance. '*Fillers, plasticizers, antioxidants, UV stabilizers, lubricants, dyes and flame-retardants'* [12] are some of the additives. Most of them do not bond chemically to the plastics and many of them are toxic, so during use and degradation they can penetrate into the air. Microplastic particles are also susceptible to microbial biofilm growth. All these aspects are not yet fully understood and require more research to find sources and reasons for pollutants presence on microplastics [12].

2.3 Classification of microplastics

According to standard international unit (SI units) nomenclature, microplastics are classified as 1 μm to 5 mm in size. Microplastic particles less than 1 μm in size are usually classified as nanoplastics [8]. There is, however no unified classification agreed by various researchers [13]. The building blocks of microplastics are carbon and hydrogen atoms that are bound together in polymeric chains [14]. They also contain chemical substances called phthalates which are salts or esters of phthalic acid added to plastics to improve their flexibility and strength. Other chemicals also often added to plastics are polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol A (TBBPA) to reduce plastics flammability [14]. Over 5000 different types of plastics using even more chemicals being currently used on the market [15]. Microplastics are usually classified into two categories, primary and secondary. Each of the categories also comprise of many subcategories.

Primary microplastics are purposely produced for commercial use and considered as such due to their direct function. They consist of very small particles used in some industries, particularly cosmetic. The particles known as microbeads are made from polyethylene, polypropylene, polyethylene terephthalate or nylon [13, 16], and are usually 10 μm to 800 μm diameter spheres used in personal care products such as facial cleaners, scrubbers or creams and toothpastes. Primary microplastics are also used in biomedical research, dentistry products and in high pressure air-blasting technologies to remove paint and rust [17], and in cleaning products, varnishes and paints. Due to the recently discovered negative consequences of the microbeads presence, particularly in the aquatic environment, they have been banned in many countries [16]. Secondary microplastics are micro-size pieces of plastics formed from the breakdown of larger pieces of plastic and as a result of their use, ageing and decaying through weathering and/or exposure to sun rays. These microplastics generally differ in sizes, shapes, colours and chemical composition. Many of them could produce a toxic effect due to their sorption characteristics or physical degradation. Interaction of microplastics with other contaminants could produce hazardous chemical mixtures [17]. Deterioration of plastic bags and other plastic packaging breaking over time into small pieces and then into micro pieces are a good example of secondary microplastics. **Figure 1** shows the types of microplastics and their sources in indoor environment.

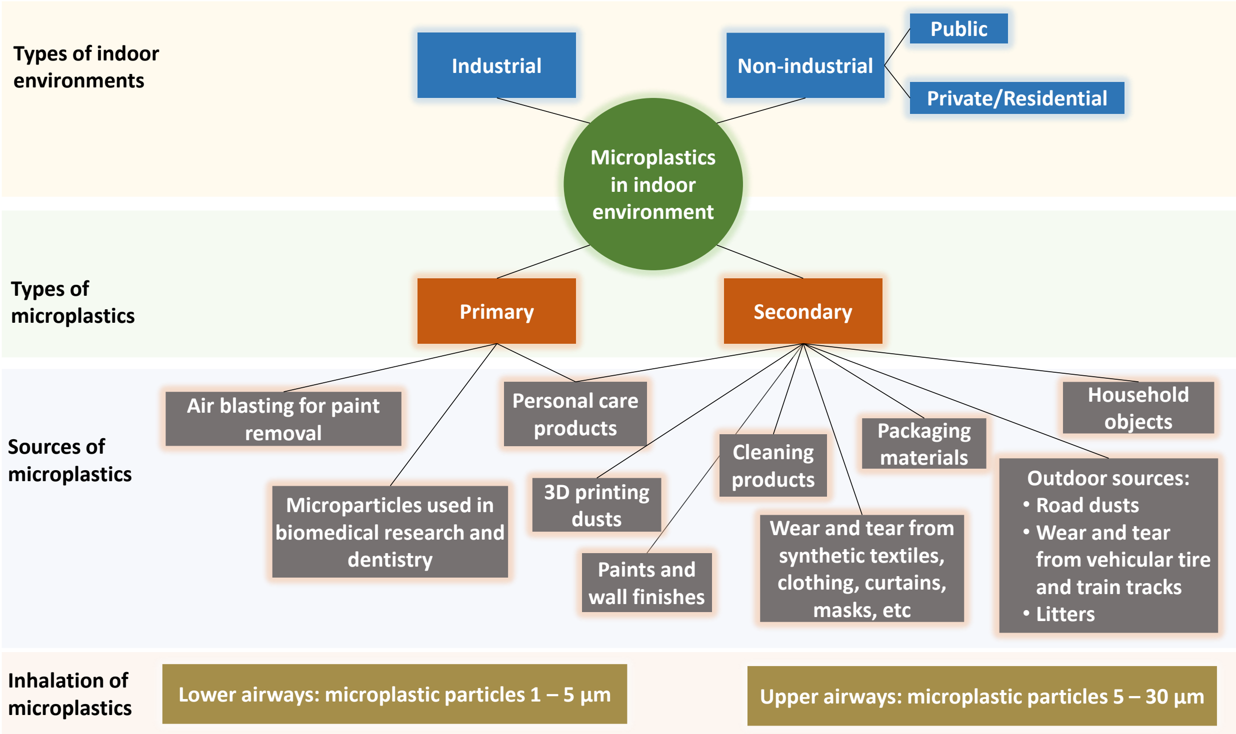


Figure 1. Types and sources of microplastics in the indoor environment.

Some scientists argue that synthetic fibro which comes from synthetic fabrics should also be considered as primary microplastics [11]. Although these fibros were not made intentionally as microbeads were, but they are small particles made for human use which shed microfibres in their original form. The same concept applies to synthetic rubber which rubbed/falls off from tires or shoes through their use and wearing [16]. All these microplastics effecting mostly the aquatic environment, but they are also significant pollutants of air. **Figure 2** shows magnified images of primary and secondary microplastic particle samples. The primary particles are of regular spherical shapes between 10 and 100 µm and the secondary particles are larger irregular shapes pieces varying in sizes and colours [17].

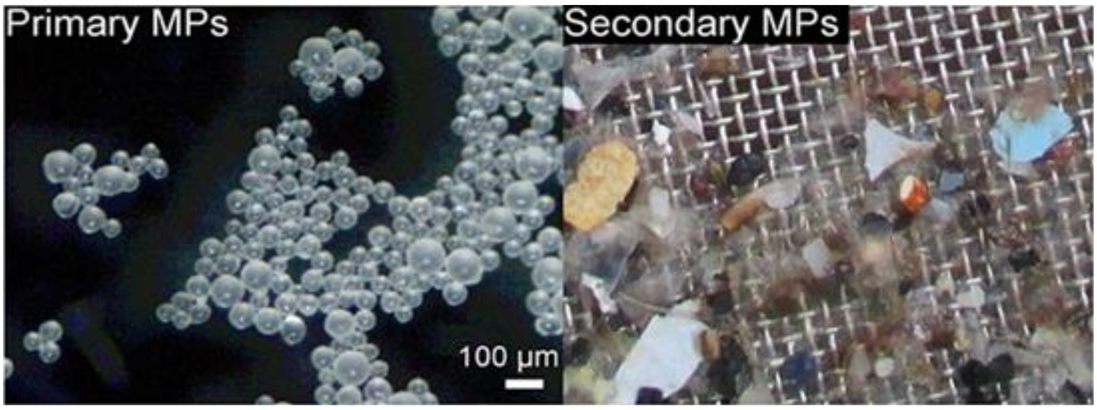


Figure 2. Example images of primary and secondary microplastics [17].

2.4 Sources and mechanisms of the formation of microplastics

One of the more important aspects of analysing the microplastics in the indoor environment are their sources, and mechanisms of their formation. There are limited details in the literature, but some basic information is sufficient to analyse the issue. The major source of microplastics in the indoor environment derives from synthetic textiles, household item finishing's and cleaning products [3]. Clothing, bedding, curtains, carpets and other items made from synthetic or semi-synthetic fibres such as nylon, acrylic, polyamide, polyester, polyolefin, elastane or rayon are some of the most common contributors to microfibres release into the indoor air typically through shedding during everyday movement and use [11]. Release from the synthetic textile occurs in all residential or commercial indoor spaces. Its density depends on the population and intensity of people and air movement [14].

Another internal source of microplastics is generated by wear and tear of all surface finishes such as walls/ceilings paints, polyvinyl chloride (PVC) flooring and polyurethane (PU) floor finishes, wall papers and other plastic items, kitchen plastic utensils including scouring pads, brushes and cloths and general multipurpose cleaning products. The release of microplastics from these surfaces usually occurs as a result of using, cleaning, rubbing, cutting, scratching or maintaining the surfaces [7]. Again, the density of microplastics released into the indoor air depends on the frequency of use, maintenance and cleaning activities. Residential kitchens will produce more microplastics than similar office facilities. Offices will produce more microplastic pollution associated with the use of electronic equipment, printing, shredding etc. The indoor environment is also susceptible to outdoor microplastics sources such as industrial or agricultural fumes containing microplastics respective to their processes. The other common external pollutant affecting many indoor environments are traffic microplastic particles coming from car tires [18]. Indoor spaces, located close to busy roads are more vulnerable to the exposure to traffic microplastics. These sources, although, born externally could easily penetrate internal spaces through windows, infiltration or mechanical ventilation.

2.5 Mechanism of spreading and transportation of microplastics

Another important aspect of analysing the microplastics in the indoor environment is their methods of transportation, spreading and deposition. Transport is a result of ambient, wind, speed and direction. Spreading depends on local air movement caused by turbulence or disturbance and deposition depends on the size and shape of microplastics particles [6].

Many microplastics pollutants are being transported from the outside to inside environment by the wind, through open windows and by infiltration. Air conditioning and supply ventilation without effective filtration systems also contribute into transferring outside air pollutants into the buildings through outside air components. This is particularly applicable to the commercial buildings using exclusively air conditioning systems incorporating outside air as part of their operation. These commercial air conditioning systems are also using economy cycle (circulating only outside air) for more than half the year, so if the filtration systems are inadequate, the intake of outside pollutants is high. This includes microplastic particles. Internally, the external and indoor air born pollutants settle or deposit on the floor and other surfaces together with general dust and are being dispersed back into the air by foot traffic and associated air turbulence. [19] In areas with higher foot traffic there is usually an increased microfiber shedding from synthetic clothing indicated by a higher fibre density measured in these areas. It occurs due to increased human activities and intensified air movement [11]. Similarly, air conditioners, when operating, increase indoor air turbulence causing movement and resuspension of dust and microplastics into the air. [19] Some buildings, particularly industrial, have only exhaust systems to remove fumes and other process pollutants, and the makeup air is usually drawn through walls openings and doors. In this scenario the intake of outside air pollutants is high (no filtration) and due to constant air flow inside the building, the microplastics and other pollutants never settle on the floor, but are constantly present in the air.

The same principle applies to the natural cross ventilation. Outside air systematically replaces indoor air by natural air movement and the indoor air becomes a mixture of unfiltered outside and indoor air. The breeze from the natural cross ventilation lifts the pollutant particles from the floor and other surfaces into the air. Ceiling fans have a similar effect.

Figure 3 illustrates the significant increase in microplastic particles presence in the indoor air with the air conditioning system operating as reported in a previous study [11]. After 6 hours the amount of microplastics particles collected 1.2 m above the floor level increased five times with the air conditioning on, when compared with the sample collected without air conditioning. The air movement during air conditioning operation lifts microplastics particles from the floor into the air [11].

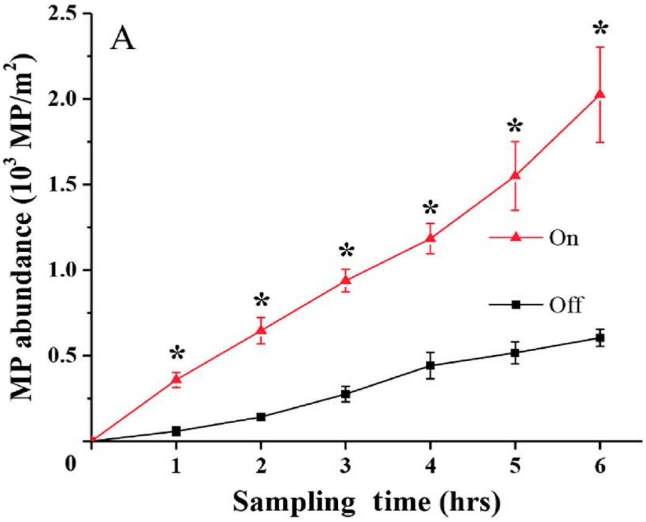


Figure 3. Effect of air conditioning systems on the amount of microplastics in air samples [11].

2.6 Identification, testing and analysis of microplastics content

A large portion of globally produced plastic accumulates in the natural environment. Through weathering, wearing and other forms of degradation, plastic loses its mechanical integrity and disintegrates into microplastic particles. These particles permeate not only the aquatic environment [20], but also the terrestrial environment, therefore it has become necessary to measure the microplastics in the atmospheric fallout to examine their contamination level in different indoor and outdoor locations in view of human health.

Many studies have been dedicated to the plastics and microplastics pollution in the aquatic environment, but very little to airborne microplastics, and the available testing methods are limited. First such studies were published in 2016 and less than 20 studies are up to date [6].

Some measurements have already been conducted and described including methods of sampling and testing the pollutants in different locations [6, 21]. Some of them also describe methods of separating microplastics from other organic and inorganic matter [6, 22].

Testing methods of microplastic content in the indoor environment are complex and usually require a combination of physical and chemical characterisation methods including physical microscopy and chemical spectroscopy and/or thermal analysis are often used together to identify and analyse the microplastics more accurately and achieve a reliable result [23]. All of the methods are needed to identify polymer types, sizes, shapes and colours. The difference between them is the range of particle sizes they are able to detect.

The testing procedure involves passive and active samples collecting methods. Passive method allows to collect airborne microplastic fallout during a specified period and evaluate a mass balance. It is a time-consuming procedure and it requires the evaluation of the deposition of resuspended particles due to air movement [25]. This method was used for testing procedures in 39 major cities of China [23] or in Hamburg, Germany [32]. Active method is using pumping devices to suction air through sequential filters and allows to calculate the concentration of microplastic particles in a volume of air [25]. This method was used for testing in Paris, France to measure indoor and outdoor deposition of microplastic particles [21].
Following the collection, the appropriate filtration method is used to reduce the volume of the sample. Zinc chloride ($ZnCl_2$) solution in which the microplastic particles will either float or sink allows density separation [6]. Since the microplastics cannot be removed from the samples other particulate matter [40], such as the organic and inorganic substances are being removed [25] using hydrogen peroxide (H_2O_2) or sodium hypochlorite (NaClO) known as bleach.

To identify the contents of microplastics, many different methods are used. Some large microplastic particles, 2-5 mm can be identified visually by the naked eye, but it could only be used as an indicative assessment of the sample content [39] as the presence of microplastic particles increases significantly with the decreasing of their sizes.

Traditional microscopy is suitable to measure physical characteristics of microplastics particles. Microscope observation allows for manual counting of microplastic particles 100-500µm and their classification by shape (fibres, fragments etc.) or colour. Samples from 39 cities in China [23] and California State University Channel Islands [24] were observed by microscope Olympus, CX21, at 100× magnification stereoscope Olympus, SZ61, integrated with a digital camera at 40× magnification respectively. Although California State University Channel Islands claimed consistent results in identifying microplastic particles size 20µm [24]; this method is not effective for particles less than 100 µm.

Staining the samples with the Nile Red lipid soluble fluorescent dye sticking exclusively to the surfaces of microplastic particles and making them glow under a fluorescent light made the counting of microplastics particles easier and more accurate. This technique allows to identify microplastic particles size up to 20µm [41] and with the use of a dark background, sizes up to 10 µm [24].

For detection of chemical characteristics and smaller particles, use of µFT-IR or µRaman spectroscopy is recommended. µRaman spectroscopy is suitable for particles of sizes 10µm down to 1 µm [43]. It uses vibrational spectroscopy [42] to identify molecules in complex mixtures based on the vibrational spectrum [24]. It allows to characterise fibres and fragments of individual microplastics and separate them from non-plastic substances. It identified not only many polymer types, but also traces of polymeric and synthetic dyes and additives, very important for health risk assessments [24].

µFT-IR spectroscopy is effective for particles larger than 20 µm [25]. Micro Fourier Transform Infrared (FTIR)) is a technique allowing to identify polymeric and other synthetic and organic materials using an infrared light spectrum to scan the samples and compare them with a references data library of individual and unique molecules' fingerprints [44], to positively identify the substance and its chemical composition. A study in Denmark used a Focal Plane Array-Fourier Transform-Imaging-Micro-Spectroscopy to be able to assess microplastic particles as small as 11 µm [33].

All these methods are being routinely used, but they are expensive and time consuming. They also do not cover microplastics of less than 1 µm which are presenting a higher risk to human health and the environment than larger particles.

2.7 Microplastic particles presence in the indoor environment

The content of microplastic pollutants in the indoor environment depends on the location, use, function and furnishing of the indoor space. Although, there is no comprehensive research or data dedicated to the assessment of microplastic presence and quantity in the indoor environment, some of the air and dust samples collected in different indoor environments shows significantly high level of microplastic content than in the outdoor environment. For example, in one study, three sites in Paris, two apartments and one office were tested for indoor air microplastics contamination. Also, an outdoor space, on the roof of the office was tested for reference [21]. Both, indoor and outdoor air monitoring was conducted during different days and season times. The results reveal that the microfibre concentration in the indoor air was 1.0 to 60.0 fibres/m^3 and was substantially higher than in the outdoor air which was between 0.3 to 1.5 fibres/m^3. The fibres sizes for indoor and outdoor air varied between 50 to 3250 µm and 50 to 1650 µm, respectively and were twice as large in the indoor environment. [21]. The dominant polymer was polypropylene [26]. The concentration of the pollutants in one of the apartments was higher than in the other, and similar to the office. The analyses revealed that living habits (line drying versus tumble dryer) and different finishes (timber versus carpet floor) contributed to the differences [21]. Overall, this study revealed that humans are exposed into the synthetic fibros in the indoor environment, but they are too large to be inhaled. This method, however, is not reliable and could only be considered as indicative as it is unable to detect smaller inhalable fibres which have the potential to effect human health [21].

In another study, thirty-nine apartments in thirty-nine major cities in China were tested for indoor and outdoor microplastics presence for three consecutive months. Among others, six different types were detected. They included polyester, polyurethane, nylon, polyethylene, polypropylene and polyacrylonitrile [27]. High levels of polyethylene terephthalate were detected in all indoor and outdoor dust samples (i.e., 1550 to 120,000 mg/kg and 212 to 9020 mg/kg, respectively). Polycarbonate was detected in three quarters of the samples and the results were up to 107 mg/kg for indoor samples and up to 61.6 mg/kg for outdoor samples. Both microplastics were significantly higher in the indoor environment compared to outdoor. Further analyses of the samples also revealed that textile fibres are the major contributor into the indoor dust. The μ- Fourier Transform Infrared Spectroscopy (FTIR) analysis confirmed that nearly 40% of tested fibres were of synthetic origin [27].

In a study by Gaston et al. [28], ten indoor and eleven outdoor locations at California State University Channel Islands were chosen to be tested for the occurrence of airborne indoor and outdoor microplastic for three consecutive months. The samples were analysed using '*gross traditional microscopy, Nile red stain with fluorescence microscopy, and/or microspectroscopy (μFT-IR or μRaman')'* [28]. The results of the traditional microscopy revealed that the indoor concentration of microfibre was 2.5 to 20.8 fibres/m^3 and was higher than the outdoor concentration which was 0.4 to 2.6 fibres/m^3. Concentration of microplastics fragments in the indoor environment was 0 to 14.6 fragments/m^3 and was lower than the outdoor range of 7.6 to 23.1 fragments/m^3. Three other techniques were used to assess sampled indoor and outdoor air for their microplastic content. These techniques were able to provide different information about the sources and compositions of the microplastics in the investigated samples. These three techniques included Nile Red Staining technique which was able to pick up the presence of microplastic fragments less than 50 μm, not visible in traditional microscopy. The two other technics, μFT-IR and μRaman spectroscopy were both able to confirm presence and chemical composition of microplastics in the indoor and outdoor air. The μFT-IR spectroscopy confirmed that 15% of the indoor and 5% of the outdoor air samples were plastic polymers. Polystyrene (PS) and polyethylene terephthalate (PET) were most common in the indoor and outdoor air, polyethylene (PE) was detected only in the indoor air and acrylic only in the outdoor air. The µRaman spectroscopy revealed that polyvinyl chloride heat stabilizer (PVC-HS) was the major plastic identified in the indoor and outdoor air samples [28].

Characteristics of microplastic detected in samples collected in indoor and outdoor air in various locations are combined together and presented in **Table 1**. The testing results include concentration or deposition of microplastic particles, their sizes, shapes and polymer types [15], [6], [29]. The inconsistency in methods and testing procedures makes the comparison of results difficult. There are no standards or protocols for analysis of microplastics and this requires urgent attention.

Table 1. Characteristics of microplastic samples collected from air in various locations.

		Indoor Air Sample			**Outdoor Air Sample**		
Ref	**Location**	**Concen-tration or Deposi-tion in Particles No/**	**Size Shape**	**Polymer types**	**Concen-tration or Deposi-tion in Particles No/**	**Size Shape**	**Polymer types**
[26]	Paris, France				2.1–355.4/ m^2 /day	200–1400 µm (fibres)	RY, PET, PA
[21]	Paris, France	1- 60 /m^3 or 190–670 /mg	50 - 3250 µm (fibres)	RY, PE, PA, PP	0.3 - 1.5 /m^3	50 – 1650 µm (fibres)	RY, PE, PA, PP
[30]	Dongguan, China				175–313/ m^2 /day	200–4200 µm (fibres, foams, films, fragments)	RY, PE, PP, PS
[31]	Yantai, China				115–602/ m^2 /day	50–1000 µm (fibres, foams, films, fragments)	PET, PE, PVC, PS
[32]	Edinburgh, UK	1.7 – 14 2 /m^3	< 500 µm (fibres)	PET, PUR			
[33]	Sakarya Province, Turkey				259–12895/ Litre	< 500 µm (fibres, fragments)	RY, PA, PE, AR

[34]	Pyrenees mountains, France				366/ m^2 /day	50–300 µm (fibres, films, fragments)	PS, PE, PP, PVC, PET
[35]	Shanghai, China				0 - 2.84 /m^3	23–500 µm (fibres, fragments, granules)	PET, PES, PE, PAN, PAA, EVA, EP, ALK
[36]	Hamburg, Germany				137-512/ m^2 /day	63 - 300 µm (fibres, fragments)	PTFE, PVA
[37]	Aarhus, Denmark	3.5 – 15.1 /m^3	4–398 µm (fibres, fragments)	PAN, PE, PES, PP, AR			
[38]	Nottingham UK				0–31/ m^2 /day	38–5000 µm (fibres)	Acrylic, PA, PES, PP
[39]	West Pacific Ocean				0–1.37/ m^3	17.4 - 891 µm (fibres, fragments, granules, microbeads)	PET, EP, PE-PP, PS, PE, PVC, AR, ALK, RY, PAA: PA, PVA, PAN, PP
[27]	39 major cities in China	1550 - 120,000 mg/kg dust	50-2000 µm (fibres/granules)	PET,	212–9020 mg/kg dust	50-2000 µm (fibres/ granules)	PET,
		0 -107 mg/kg dust		PC	0-61.6 mg/kg dust		PC
		17 - 620 fibres/mg 6–184 particles (granules)/ mg		Micro-plastics	7–431 fibres/mg 0–100 particles (granules)/mg		Microplastics
[40]	East China University Shanghai, China				0 – 2/ m^3	12.4–2191 µm (fibres, fragments, granules, microbeads)	PET, EP, PE, ALK, RY, PP, PA, PS
[11]	East China University Shanghai, China	500-29000/ m^2 /day	50–2000 µm	PS, PA, PP, CE, AC, CV, PES			
[19]	California, USA	2.5 - 20.8 / m^3	22-8961 µm (fibres)		0.4 - 2.6 / m^3	25 - 2061 µm (fibres)	PS, AC, PET, PVC-HS,

		0 - 14.6 / m^3	20 - 850 µm (fragments)	PS, PE, PET, PVC-HS, PVC, PC, PA,	7.6 - 23.1 / m^3	51 – 408 µm (fragments)	
[41]	Central London				510 - 925 / m^2/day	(fibres, fragments, films, granules, foams)	PAN, PES, PA, PP, PVC, PE, PET, PS, PUR, PPR

3. Health consequences of microplastics presence in the indoor air

Research on microplastics that accumulate in the indoor environment is very limited, but many observations have reported their high concentration in the indoor air, causing great concern about human health due to the exposure by inhalation, skin contact and ingestion. Although, ingestion is usually occurring through eating externally contaminated food, the microplastics in the indoor air depositing on plates during meals can also be ingested. Exposure to microplastics particles in the contaminated food, particularly seafood, and its effects on the human digestive system appears to be the most researched, while exposure by inhalation the least explored route [42, 43].

The exposure to indoor microplastics, results in inhaling on average 26 to 130 airborne microplastic particles per day [44], as estimated by some researchers, but it could also be as high as 272 particles per day as reported by other researchers [37]. The major reasons for the variability could be associated with the use of different sampling methods and different environments, but the space usage and occupancy, type of ventilation, location of sampling apparatus, level of outside air penetration of the indoor space and accumulation of primary and secondary microplastics also contributed to the different results.

Microplastics particles less than 10 µm including ultrafine particles less than 0.1 µm are the most dangerous to human health even in relatively low polluted spaces, as they easily penetrate respiratory systems, causing the development of serious diseases in susceptible individuals. Chronic inflammation like bronchitis, allergic reactions like asthma or even pneumonia, are some of the human responses to inhaled microplastic particles.

Deposition of microplastic particles in the lungs through interception, impaction, sedimentation or diffusion should trigger an immediate body clearance reaction including:

- mechanical method in the form of sneezing,
- muco-ciliary escalator which moves secretion containing foreign particles, produced by the upper respiratory tract to be swallowed or coughed up,
- phagocytosis of microplastic particles by macrophages which initiate the immune response to get rid of unneeded or unrecognised cells
- lymphatic transport which helps to remove impurities from the body through perspiration, urine or breathing.

All these clearing systems help individuals with strong and healthy immune systems to remove the inhaled microplastic particles from their bodies, but the individuals with compromised immune system are at high risk of developing chronic inflammation as a result of microplastics built-up in their bodies [44].

Despite the existence of clearing systems within the human body, the removal of microplastics, particularly fibres, is not easy as these particles have a very high surface area. The increased surface areas make them carriers of other pollutants. They adsorb the contaminants including pathogenic microorganisms and subsequently release them which makes them more toxic [44].

The microplastics themselves are toxic as they often contain chemical additives to improve their quality, such as bisphenol A (BPA) or phthalates, esters of phthalic acid (DEHP), some heavy metals like Zinc (Zn), Mercury (Hg) or Lead (Pb) or chemical compounds such as flame retardants (FRs) [12]. The microplastics are even more dangerous when exposed to UV radiation, weathering or aging, as these processes could alter their chemical composition.

Despite limited knowledge on the effects of human exposure to airborne microplastics it is apparent that the increased incident of many diseases including immune disorders, neurodegenerative diseases, cardiovascular diseases, congenital disorders or cancers could be associated with the exposure to microplastics and due to their bioresistance and biopersistence characteristics they could be very difficult to remove from the bodies. [15]. Exposure to a higher concentration of microplastics in an occupational environment such as the textile or PVC industry increases the workers risk of inhaling more microplastics and subsequently suffering from higher incidents of respiratory diseases. A previous study have shown that some of the smallest particles, less than 0.1 μm are able to break the alveolar capillary barrier to reach the bloodstream and can cause damage to many parts or systems in the body including cardiovascular or the central nervous system [45].

The airborne microplastic particles are considered toxic due to their high surface area, with or without oxidative organisms or other poisonous substances adsorbed to their surface. Microplastics toxicity occurs by dust overload, oxidative stress, cytotoxicity, metabolism disruption and translocation usually when the body clearance system is weakened and the persistent nature of the microplastic particles is making their removal difficult causing inflammatory responses. Chronic inflammatory lesions could lead to the development of cancer. All routes of exposure, dermal, inhalation or ingestion could lead directly or indirectly to inflammation and subsequently to translocation or cancer [42].

All the above information is explaining possible adverse effects resulting from human exposure to microplastics and it sounds very alarming, but most of the pathways of exposure and the extent of toxicity of microplastics are mainly hypotheses and the true potential of airborne microplastics contaminants is still very unclear, inconsistent and needs more research.

4. Overview of mitigation measures for airborne microplastics pollution

Despite the fact that airborne microplastics is a new subject and only a limited number of studies in relation to this subject have been completed, almost all of them reported that exposure to airborne microplastic particles could be harmful to human health [44] and their indoor concentration is much higher than in the outdoor environment [2]. Before the subject could be better explored and understood some immediate mitigation measures could be employed to reduce the human risk of exposure to this pollutant.[44]

Currently, there are two methods available to reduce microplastic presence in the indoor environment: indirect and direct. The indirect method involves installation of appropriate filters in new or existing ventilation or air conditioning systems, serving public spaces such as offices, or use air purifiers in private dwellings which don't have or don't use too often air conditioning systems. The direct method is to reduce the sources of microplastics. Both methods are complicated and often difficult to incorporate.

In the indirect method, the existing ventilation and air conditioning systems may not have enough space to install the suitable filters. The existing fans may not be able to produce enough static pressure to overcome resistance of the new filters. The higher maintenance and running cost of the systems with new filters might be excessive.

The direct method is even more difficult to follow. It is a long-term solution which requires public education and awareness of the microplastics issue and willingness to cooperate in rejecting their sources. It also requires the industrial sector to investigate new sources of materials to reduce and preferably eliminate the use of all forms of plastics.

Both methods have their pros and cons and would not be needed if we could replace bio-resistant plastics with biodegradable materials, or invent a method to safely decompose plastics.

4.1 Air filtration systems

Filters are usually rated by the size of particles they can remove from air stream. The value is described as filter efficiency [46]. Increased efficiency is directly related to a filters' air flow resistance. **Table 2** presents the US and International rating standards for filter efficiency classification. The data was, however, obtained in slightly different conditions, so the ISO results shows lower filter efficiency.

Table 2. Filter efficiency ratings based on ASHRAE Standard and ISO Standard [46, 47].

ASHRAE Minimum Efficiency Reporting Value (MERV) (Standard 52.2)	**Able to captures particles greater than**	**International Organization for Standardization (ISO) 16890 Rating & efficiency**	**ISO *e*PM$_{1}$ (particulate matter efficiency) 0,3 - 1 µm**	**ISO *e*PM$_{2.5}$ (particulate matter efficiency) 0,3 – 2.5 µm**	**ISO *e*PM$_{10}$ (particulate matter efficiency) 0,3 - 10 µm**
MERV 1-5	>10 µm	ISO Course - 80%	-	-	-
MERV 6-7	> 3 µm	ISO Course - 90%	-	-	-
MERV 8	> 3 µm	ISO Course - 95%	-	-	50%
MERV 9	> 1 µm	*e*PM$_{10}$	-	-	50%
MERV 10	> 1 µm	*e*PM$_{10}$	-	50% - 65%	60%
MERV 11	> 1 µm	*e*PM$_{2.5}$	-	50% - 65%	60%
MERV 12	> 1 µm	*e*PM$_{2.5}$	-	50% - 65%	60%
MERV 13	> 0.3 µm	*e*PM$_{1}$	50% - 65%	65% - 80%	85%
MERV 14	> 0.3 µm	*e*PM$_{1}$	65% - 80%	90%	90%
MERV 15 - 16	> 0.3 µm	*e*PM$_{1}$	80%	95%	95%

Considering that filtration systems are able to remove particles as small as 0.3 µm, the airborne microplastics particles could also be removed from indoor spaces. Filters are a very important part of any mechanical ventilation system. They not only remove harmful substances from the air, but also protect heating, ventilation and air conditioning (HVAC) appliances. There are many different types of filters on the market and they will remove a percentage of any dust particles according to their ratings. There are, however, factors such as quality of the installation or concentration of the pollutants which may affect performance of the filters.

Current market trends are associated with the removal of particles as small as $PM_{1,}$ less than 1 µm, as many such particles are rated by the International Agency for Research on Cancer (IARC) as Group 1: *carcinogenic to humans,* which include, for example, diesel engine exhaust particles, or vinyl chloride used in production of polyvinyl chloride (PVC), one of the many, very popular microplastics [48]. Commercial buildings fitted with filtration systems able to remove such small particles are desirable by the consumers, particularly in areas exposed to high levels of PM_1 or $PM_{2.5}$ pollutants from, for example, heavy road traffic or industrial activities [47]. It should also include buildings with heavy internal human traffic, high density occupation and intense usage, all of which increase the production and movement of microplastic particles in the indoor air [14].

Filters of higher efficiency than MERV13, or ISO $ePM_{1,}$ 50% - 65% are suitable to protect the indoor environment against the ultra-fine particles. Typically, such filtration systems comprise of less efficient pre-filters such as MERV 6-7, or ISO Course - 90% to remove larger particles and protect the higher efficiency filters against too frequent clogging [47].

Use of higher efficiency filters usually increases the running cost of the heating, ventilation and air conditioning (HVAC) systems as these filters have a higher initial pressure drop which increases considerably during use. This problem could be overcome by the use of high-quality filters which have a larger surface area, therefore reduced pressure drops across the filters. Frequent maintenance including replacement of the filters medias also reduces the running cost, but the replacement is expensive. The balance between the running and maintenance cost is often difficult to achieve, as Green Building Council of Australia (GBCA) known as Green Star rating, requires low energy usage, therefore increases significantly the maintenance cost [47]. As a result, building managements often reduce the filtration quality to reduce the running and maintenance cost.

The new International WELL Building Institute (IWBI) known as the WELL Building Standard takes into consideration the optimisation between running cost and indoor air quality awarding extra points for implementing higher filtration levels and achieving superior comfort standards [49].

All filters are rated in accordance with their performance, although methods of testing and standards vary between each other. Generally, filters could be divided into four major categories representing their average removal efficiencies and are grouped using Minimum Efficiency Reporting Value (MERV) [50]

- Coarse Dust Filters (MERV 1 – 4)
- Fine Dust Filters (MERV 5 – 8)
- Highly Efficient Particulate Air Filters (HEPA) filter (MERV 9 – 12)
- Ultra-Low Penetration Air Filters (ULPA) (MERV 13 – 16)

Coarse dust filters include fiberglass air filters which are cheap, disposable and simple filters best used for protecting HVAC systems from debris. They are not effective in improving air quality. Washable air filters have a similar efficiency to fiberglass air filters, but despite being more expensive to buy, they can be washed and reused, so they are environmentally friendly and cheaper in the long run [51]. They are able to hold microplastics particles larger than 10 µm, but are ineffective in holding smaller particles.

Fine dust filters include many different types of pleated filters made from cotton or polyester. They include simple pleated filters, pocket or bag filters, or v-type filters. They are more effective as they have an extended surface area, so they could trap more pollutants. They are more expensive to buy and have a higher resistance than fibreglass filters, but they could provide some improvement to indoor air quality. They are often used as pre-filters for more efficient filters like HEPA or ULPA [51]. They could trap particles larger than 3 µm.

Highly efficient particulate air filter are capable of capturing 99.97% of airborne pollutants and particles as small as 0.3 µm [52]. They are widely used in many different industries to control contamination, but they are most popular in the health, pharmaceutical and aviation industry. Due to the growing demand for higher indoor quality standards they are being used more frequently in many HVAC installations. They however, require more energy consuming fans to compensate for their higher resistance. They require pre-filters and need to be professionally replaced [46]. In view of the developing knowledge about microplastics and their negative health effects the HEPA filters may become necessary for most HVAC systems to reduce or remove the small, less than 5µm diameter microplastic particles, considered harmful to humans [4].

Ultra-low penetration air filters remove even smaller particles, 0.12-0.4 µm range. Although they eliminate such a small particle, they have a very high resistance, up to four times higher than HEPA filters. They are more expensive to buy, they require pre-filters and are significantly more expensive to run due to their flow resistance, and have to be replaced almost twice as often so, they are used only in specific industries such as microelectronics manufacturing or for cleanrooms [53].

Air purifiers also known as air cleaners are appliances designed to remove all possible pollutants from indoor air. They circulate internal air through a sequence of filters and capture any impurities including microplastics, contained in the air. Producers of some of such devices claims that their products are able to remove particles as small as 0.003 µm, much smaller than the smallest microplastic particles already detected, so they should remove successfully all possible microplastics. This technology is based on *HyperHEPA* filtration system [54]. Other producers claim that their HEPA filters-based Air Purifiers remove particles up to 0.3 µm and *HEPASilent* technology which combines electrostatic filters and HEPA filters removes particles up to 0.1 µm [55].

Reducing airborne microplastics in the indoor environment helps to clean indoor air, but filters need to be replaced or cleaned, so the microplastics caught by filters are actually only relocated from the indoor to the outdoor environment. Air filtration could help to protect human health, particularly that we spend 90% of our time indoor [6], but this method is just shifting the pollutant from one environment to another. Filtration helps, but it is not a solution to the airborne microplastics problem. Most of the filter's medias are made from plastic, although they should be removing it from the air stream. Studies evaluating plastic filters media contribution to the increase of microplastics in the indoor air should also be considered.

4.2 Source reduction approaches

Some recent research show that we are breathing microplastics in the rate of 26 to 130 particles per day which could pose a serious risk to human health. Cardiovascular, lung or autoimmune diseases could be some of the consequences of exposure to microplastics particles, particularly in susceptible individuals [44]. More research is needed to explore the effects of inhaling airborne microplastics.

There are many practical steps we could take now to reduce their formation in the indoor environment, although, the issue of eradicating microplastics from the environment is far more complicated, particularly that plastic already accumulated is deteriorating and breaking into smaller pieces. The simple steps to reduce airborne microplastics in the indoor environment should start from frequent cross ventilation of the interior, as indoor microplastics contamination is usually much higher than outdoor [11]. This should be followed by frequent floor vacuuming, preferably using a central vacuum system as it exhausts the contaminants outside the vacuumed spaces. If this is not possible, vacuum cleaners with HEPA filters should be used to prevent the contaminants re-entering the space. All carpets and PVC or other plastic type floors, trap or release microplastics respectively, so they should be replaced with natural timber or ceramic floors. The timber floors, furniture and walls varnish, and paints should also be free from synthetic additives. Cutting boards, utensils, cleaning sponges and scrubbers, plastic plates and cutleries, plastic pots handles and plastic containers wear and tear during use. They should be avoided or replaced with products made from natural materials such as timber, rubber, metal or glass [7].

The other group of products responsible for producing a majority of microplastics in enclosed spaces are clothing, bedding, curtains and other items made of synthetic fabrics, which are shedding synthetic fibres during everyday movement and use. This major contributor of microplastics released in indoor spaces could be easily avoided by using natural fabrics and textiles such as 100% cotton, linen, wool or silk [11]. It would, however, require the cooperation of fabric manufacturers, fashion designers and producers, which could be very difficult to achieve. This whole industry is predominantly based on synthetic fabrics and will strongly oppose a conversion to natural fabrics, which are more expensive, more difficult to work with and not as durable as synthetic fabrics. It may require regulations on the Government level to control this industry in respect of synthetics use.

Another group of products which should be avoided are personal hygiene products such as soaps or toothpastes and cosmetics, and general cleaning products containing microbeads [17]. They are banned in many countries and almost phased out voluntarily from cosmetic and personal care products in Australia, although the relevant legislation is still pending [56].

Plastic bags and packaging should also be avoided. Reusable bags made of natural fabrics should be used. Plastic bags should not be brought home, to the office or other occupied private or public spaces and should not be stored as they disintegrate with time and fall apart into microplastics. The same applies to plastic water bottles or disposable cups. Reusable bottles and cups made of glass or metal should be used instead. Plastic packaging should also be avoided. Many products could be packed in paper, paper bags or cardboard boxes. Reusable glass jars could be used for liquid products. Reusable BYO, preferably glass or metal containers should be used for takeaway food. Standardised sizes of such containers should be available for sale.

Opening plastic packaging by cutting with scissors, knives or by tearing with hands should be done carefully as this task generates microplastics [57].

All the above recommendations are applicable to private and public spaces. Public spaces may have additional sources of microplastics such as a considerable amount of electronic equipment or printing facilities, or heavy human traffic but the same steps will help to reduce the formation of microplastics.

4.3 Preventive strategies to reduce microplastic pollution

Microplastic pollution is rapidly gaining recognition as a serious global environmental problem. The continuously increasing use of plastic products resulted in the accumulation of unprecedented amounts of plastic fragments or microplastics [58]. Their presence in the outdoor and indoor environment is causing a significant threat to the natural environment and human health and the currently available methods of detecting, testing and identifying microplastic particles are inaccurate and limited. Considering that microplastics exist in the environment only as a transitional product between macroplastics and nanoplastics, it is necessary to understand the complexity and nature of all plastics in their primary state. A large part of the more than 8 billion tons of plastic already produced [59] are microplastics or plastics degraded into microplastics. Considering the extent of the problem it is essential to start controlling microplastic pollution. The plan to achieve the reduction and possible elimination of microplastics from the environment should involve three different strategies: short, medium and long term.

Short term strategy should involve significant reduction leading to elimination of single-use products made from plastic, such as shopping bags, water bottles, cutleries, cups, plates containers, straws and many other similar products. Ban on these products will prevent tons of plastic waste being produced and help to protect the natural environment. This step will, however require, for example, the takeaway industry to rethink and redesign their operation. Phasing out plastic shopping bags is very inconvenient for customers, so again will require a substitute product [60]. The Australian government is planning to phase out single-use plastic products by 2025 [61] and Australian Packaging Covenant Organisation is trying to achieve also by 2025 a target of 100% for all the plastic packaging to be reusable, recyclable or compostable [62]. Such decisions should be supported via an introduction of alternative products, including their potential environmental impact and additional cost to the consumers, to ensure the effectiveness of the decisions and their public approval.

Middle term strategy should involve imposing strict government regulations to improve waste collection by introducing more effective methods of plastics segregation from other waste materials including clear labelling of the disposable plastic products [62]. It would reduce landfill loads and their impact on the environment through leakage, and increase plastics recycling rates. This will require expansion of the collecting system and then significant improvement and extension of the recycling industry. Globally, less than 10% of plastic is recycled [63], but the use of additives like chemicals or colours makes many of the plastics unrecyclable. Regulations on the government level preventing many producers from adding any improving agents during plastics production should increase the recycling rate, but many of the plastics are difficult to recycle even without additives. Therefore, the concept of recycling current product needs further investigation [60].

Long term strategy should involve scientific research to come up with methods of processing plastic waste to make all of it acceptable for recycling irrespective of its chemical composition. This concept would involve new methods of breaking plastic material into its primary polymers suitable for reuse as components for a new material. Certain enzymes, bacteria and earthworms are being tested to break down some plastics and are showing promising results. This method, if successful, could help to eradicate some plastics of various sizes from the natural environment. Alternatively, and preferably, scientist should try to create biodegradable plastic suitable to replace the current bioresistant plastic. Such new material should function in the environment similarly to glass or paper [60]. All of the above strategies are applicable to both, indoor and outdoor environment, but before any of them become a reality, the existing methods, particularly for the indoor environment should be considered.

4.4 Public awareness of microplastics phenomenon

The phenomenon of micro and nanoplastics is a serious symptom of environmental change exclusively created by human activities. The consequences of this phenomenon could pose a global risk to human health and ecology. Although, there is still little evidence about the harmful effect of micro and nanoplastics pollution they have to be considered as a possible threat, since their concentration is continuously increasing. To reduce the risk and manage the accumulation of plastics we need to change many of our daily routines and habits associated with the production, use and disposal of plastic products. Such change will not be an easy task and will challenge our practices. To convince the public that they have to accept the need to change their attitude towards the use of plastics, a global campaign explaining that visible plastics are breaking down into very complex and potentially far more harmful invisible micro and subsequently nanoplastics is necessary.

Public awareness, knowledge and understanding of microplastics is very little or non-existent. A brief, informal survey of a small group of twenty Australians, mainly professionals (medical doctors, engineers, architects, scientists and technicians) revealed that their knowledge about plastics is limited to '*beaches polluted with plastic waste, dolphins and turtles eating plastic bags* and *microbeads being used in toothpaste and cosmetics.'* [64]. They haven't heard about microplastics and their potential adverse effects on human health and environment. All of them expressed a strong disappointment with the lack of any clear media information about the microplastic phenomenon. They all showed a great interest in the subject and thought that it is unfair that the media didn't report any information on the issue in a way that would attract their attention. The discussions were very encouraging, despite bringing many concerns and feelings of insecurity. All participants were alerted to the problem and shown a willingness to comply with any reasonable recommendations to reduce plastic use, particularly single-use plastic.

The whole experience demonstrated that if the public is fully and properly informed, many would be willing to cooperate and do the right thing.

A formal survey of 42 people conducted in UK, in the Oxford and London areas in six different focus groups such as professional women, art students, water sports club members or community centre helpers also questioned the participants knowledge about microplastics. The protocol of this survey included consent forms, initial questionnaire, watching videos about plastic pollution and participating in a brainstorming session on the subject and then completing a final questionnaire [64]. The results of this survey were almost identical to the results of Australian discussion. The only difference was that the UK participants appeared to have slightly more knowledge about plastic pollution from the media, but their reaction to the television programs and news about the formation and danger of microplastics was the same. The UK participants had more problems with understanding the concept of microplastics which suggested their poor comprehension of everyday activities and a weak connection with the environment. One of the participants said *'I thought it* [microplastics] *was just bad for the environment. I didn't think it harmed us.'* [64]. Many of the UK participants blamed the Government or relevant industries for the plastic and microplastic pollution, but were not that keen on giving up on plastic products while the Australians were more open to this option.

5. Summary, challenges and future prospects

Microplastics are one of the greatest environmental challenges we are facing in the nearest future. This new emerging pollutant presents a potential high environmental and human health risk. Plastics are everywhere and their more prevalent by-product, microplastics, are being inhaled, ingested or absorbed by dermal contact especially in the indoor environment. However, the effect of microplastics intake by human bodies is still unclear and controversial.

This review has discussed the various sources, mitigation and fate of microplastics in the indoor environment. The results of the study revealed the complexity of physical and chemical composition of airborne microplastics and lack of suitable technologies to achieve comprehensive and accurate data. Most of the research concentrates on particles greater than 20 µm, leaving the smaller, more harmful, particles undetected or unidentified. Knowledge about microplastics, particularly airborne microplastics is scarce and lacking depth and clear directions. There is a potential risk to human health and the natural environment associated with the growing plastic production and accumulation.

One of the challenges is a lack of a common and clear definition for plastic pollutants. Considering the complexity, diversity and heterogeneous characteristics of microplastics, their status as just a pollutant should be revised. Microplastics are a new class of contaminant and their diversity and complexity should be recognised and reflected in any study or research strategies and mitigation methods. To achieve consensus among researchers, International Organization for Standardization (ISO) or its co-operator European Committee for Standardization (CEN) should get involved into defining and classifying microplastics. New convention, similar to Stockholm Convention on Persistent Organic Pollutants (2001) should be organised by the United Nations to provide recommendations in regards of micro/nano plastics definition, their impact on human health and environment and possible mitigation measures [43].

There is no established standard yet for microplastics testing methods, procedures and evaluations**.** Sampling methods and techniques should include specified timing, ambient conditions (temperature, humidity) collection procedure and location. Testing methods should identify both, chemical and physical characteristics such as their composition, shape or sizes. Quantification of microplastics should be standardised and results shown in the same units to allow comparison. Separate quantification of different polymer types should be included in the testing to allow for a better understanding of their sources. Protocols confirming suitability and accuracy of instruments used for measurements should be introduced to secure confidence in results [65]. New techniques, should be developed to allow for testing of smaller than 50 µm particles which are inhalable [66]. Microplastics particles less than 10 µm including ultrafine particles less than 0.1 µm are potentially able to penetrate the bloodstream and reach organs like the brain or liver. Testing and understanding the implications of these smaller particles on human health is critical [45].

Most of the studies conducted in microplastic research is related to aquatic contamination, and only a handful in atmospheric and terrestrial settings, especially for indoor environments. More importantly in the current times where many people spend most of their time indoors and the prevalence of plastic-based materials, as well as the increasing use of 3D printing, there is an urgent need to understand the sources, occurrence, pathway and fate of micro/nanoplastics and their effect on human and environmental health.

The following are some recommendations for future research directions related to microplastics in indoor environment and possible further actions:

- A comprehensive data base for all types and sizes of plastic materials found in the indoor environment, their characteristics, behaviour and concentration in different conditions, should be established and be accessible globally.
- There is a need to better understand the atmospheric transport mechanism of microplastics in the indoor environment, their accumulation and their ecotoxicological effects to the environment and human health.
- As microplastic pollution is an emerging concern, there should be an established standard specific for airborne microplastics in their quantitative and qualitative sampling, measurements and characterization.
- There is not much data on the complex interaction of airborne microplastics with other organic and inorganic materials and the surrounding environment, thus research should be carried out to understand these processes better.
- Further studies need to be carried out on the safe level of human exposure to airborne microplastics.
- New strategies to recycle and manage plastic waste together with public awareness of microplastics occurrence and their damaging effects should be increased to achieve public support and cooperation to repair the damage already inflicted, and reduce or prevent future damage to human health and the natural environment. Government organisations and various media platforms should frequently present informative and

educational programs to increase public knowledge and understanding of the seriousness of the microplastics issue.

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