

Review

Indoor Air Quality in Elderly Centers: Pollutants Emission and Health Effects

Teresa M. Mata ^{1,*}, Fátima Felgueiras ^{1,2}, António A. Martins ^{3,4}, Helena Monteiro ⁵, Maria Pia Ferraz ^{6,7,8}, Gisela M. Oliveira ⁹, Marta Fonseca Gabriel ^{1,*} and Gabriela Ventura Silva ^{1,*}

- ¹ LAETA-INEGI, Associated Laboratory for Energy and Aeronautics, Institute of Science and Innovation in Mechanical and Industrial Engineering, R. Dr. Roberto Frias 400, 4200-465 Porto, Portugal; ffgueiras@inegi.up.pt
 - ² EPIUnit, Institute of Public Health, Portugal & Laboratory for Integrative and Translational Research in Population Health (ITR), University of Porto, R. das Taipas 135, 4050-600 Porto, Portugal
 - ³ LEPABE-FEUP, Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, R. Dr. Roberto Frias S/N, 4200-465 Porto, Portugal; aamartins@fe.up.pt
 - ⁴ ALiCE—Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, R. Dr. Roberto Frias, 4200-465 Porto, Portugal
 - ⁵ Low Carbon & Resource Efficiency, R&Di, Instituto de Soldadura e Qualidade, R. do Mirante 258, 4415-491 Grijó, Portugal; himonteiro@isq.pt
 - ⁶ Departamento de Engenharia Metalúrgica e de Materiais, Faculdade de Engenharia da Universidade do Porto, Rua Roberto Frias, 4200-465 Porto, Portugal; mpferraz@fe.up.pt
 - ⁷ i3S—Instituto de Investigação e Inovação em Saúde—Associação, Universidade do Porto, R. Alfredo Allen 208, 4200-135 Porto, Portugal
 - ⁸ INEB—Instituto de Engenharia Biomédica, Universidade do Porto, R. Alfredo Allen 208, 4200-135 Porto, Portugal
 - ⁹ UFP Energy, Environment and Health Research Unit, University Fernando Pessoa, Praça Nove de Abril, 349, 4249-004 Porto, Portugal; gisela@ufp.edu.pt
- * Correspondence: tmata@inegi.up.pt (T.M.M.); mgabriel@inegi.up.pt (M.F.G.); gventura@inegi.up.pt (G.V.S.)



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Abstract: The world population is ageing, in particular in the developed world, with a significant increase in the percentage of people above 60 years old. They represent a segment of the population that is more vulnerable to adverse environmental conditions. Among them, indoor air quality is one of the most relevant, as elders spend comparatively more time indoors than younger generations. Furthermore, the recent COVID-19 pandemic contributed immensely to raising awareness of the importance of breathing air quality for human health and of the fact that indoor air is a vector for airborne infections and poisoning. Hence, this work reviews the state of the art regarding indoor air quality in elderly centers, considering the type of pollutants involved, their emission sources, and their health effects. Moreover, the influence of ventilation on air quality is also addressed. Notwithstanding the potential health problems with the corresponding costs and morbidity effects, only a few studies have considered explicitly indoor air quality and its impacts on elderly health. More studies are, therefore, necessary to objectively identify what are the impacts on the health of elderly people due to the quality of indoor air and how it can be improved, either by reducing the pollutants emission sources or by more adequate ventilation and thermal comfort strategies.

Keywords: indoor air quality; elderly care centers; pollutants emission sources; health effects

1. Introduction

Indoor air quality (IAQ) and its negative health effects have attracted worldwide interest from various stakeholders, in particular policy makers and public health professionals. Substances found in the indoor environment are among the main determinants of an individual's health, whether they are chemicals, such as volatile organic compounds (VOCs) (e.g., esters, alcohols (e.g., ethanol, isopropanol), ketones (e.g., acetone), aldehydes (e.g., hexanal) and terpenes (e.g., limonene)), formaldehyde, ozone (O₃), nitrogen dioxide (NO₂),

carbon monoxide (CO), sulfur dioxide (SO₂), particulate matter (PM) of aerodiameter <10, <2.5, and <0.1 μm (PM₁₀, PM_{2.5}, PM_{0.1}, respectively), asbestos, radon, tobacco smoke, or bio-contaminants (e.g., bacteria, fungi, viruses, molds, allergens, animal dander) [1]. IAQ and thermal comfort, which are key factors affecting comfort, health, and occupants' performance, are influenced by ambient parameters, such as indoor air temperature, surrounding surfaces temperature, air movement, rate of air exchange, relative humidity, pressure, and carbon dioxide (CO₂) [2–4].

The population ageing, due to the continued decline in fertility rates and increased life expectancy, with an increasing number of very old people (>80 years old), poses several challenges for the future. Globally, it is estimated that there are over 700 million people aged 65 years or over in the world [5]. This percentage is expected to gradually increase over the next three decades to reach 29.4% in 2050 [6]. The vulnerability of elders is a natural consequence of ageing due to the inherent deterioration of biological functions, including immune defenses, but it is often aggravated by poor health conditions such as respiratory or circulatory illness; therefore, elders have a greater predisposition to respiratory infections [7]. In addition to natural ageing health conditions, elders have an accumulated lifelong exposure to pollution and other environmental conditions [8]. Furthermore, due to their reduced mobility, they tend to spend most of their time indoors (95% in average) [9], usually in bedrooms and living–dining rooms, corresponding to about 19 to 20 h/day, above the average for the youngest people of 16 to 17 h/day [10]. This is particularly critical to residents in geriatric facilities who are potentially at higher risk of exposure to indoor air pollution [11]. Therefore, the indoors environment is more likely to influence the health of elderly people, who are one of the two most vulnerable groups to air pollutants exposure, the other being children. Indoor air accumulates several types of pollutants normally associated with specific compounds originating from the various products used, such as in cleaning, disinfection, hygiene, and healthcare activities, and also emitted from building materials and household furnishings [12]. For example, cleaning solutions and detergents, frequently used in nursing homes and healthcare institutions, reduce the risk of infection but increase the levels of total volatile organic compounds (TVOC) [9]. Therefore, keeping elderly people healthy and preventing chronic diseases is a challenge that requires better understanding of the health consequences of exposure to air pollutants [8].

So far, the respiratory health effects of indoor air pollution have been well documented in the general population but less analyzed in elderly people living in elderly centers, nursing homes, etc. [13]. The indoor air quality of these care facilities is still poorly studied [14]. Also, there are few data on exposure to indoor air pollutants and related effects on respiratory health in the elderly population. There are still few studies that relate exposure to indoor air pollutants to effects on the health of the respiratory system, such as wheezing, breathlessness, cough, asthma, or lung cancer [15]. Data on the effects of indoor allergens on respiratory health in the elderly are scarce [16].

Studies have shown that the elderly, particularly those over 80 years of age, are more likely to have health impairments, even with moderate levels of indoor air pollutants in poorly ventilated areas [7,17]. One of the most effective methods to reduce the concentration of pollutants and maintain a good quality of indoor air is simply increasing the rate of air exchange (ventilation) of the indoor spaces [18,19]. For instance, Almeida-Silva et al. [9] characterized the indoor air quality in 10 elderly care centers (ECCs) facilities in Portugal to assess the elders' daily exposure to air pollutants, showing that due to insufficient room ventilation, the concentration of some substances (CO₂, VOCs, O₃, and PM₁₀) exceeded the limit values.

Concerning the emerging compounds, Arnold et al. [20] carried out a study at ECCs in the United States and in Portugal to determine the concentrations of organophosphate esters (OPEs), brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs) in dust samples collected indoors from fourteen facilities. This study results revealed that OPEs,

PAHs, and BFRs were the most abundant and OCPs and PCBs were the least abundant semi-volatile organic compounds (SVOCs) groups in the collected dust.

Concerning biological contaminants, airborne microorganisms, such as bacteria and fungi, are often present in the indoor air. In particular, the indoor habitat harbors microorganisms that are not commonly found outdoors, which is also influenced by the air temperature, relative humidity, architectural design, and the source of air ventilation [21]. In this case, the ventilation of spaces and the density of occupants can influence the abundance of these microorganisms and also the transmission of some pathogenic microbes [22]. A study [23] of indoor air in a large hospital building revealed that the most common bacterial strains belonged to genera *Staphylococcus*, *Micrococcus*, *Kocuria*, *Aerococcus*, *Kytococcus*, *Bacillus*, *Pseudomonas*, *Corynebacterium*, and *Streptococcus*, while the most abundant fungal genera included *Cladosporium* (47%), *Aspergillus* (17.1%), *Penicillium* (7.1%), *Alternaria* (6.2%), *Geotrichium* (3.68%), and *Ulocladium* (3.2%). Frequent cleaning is an important factor for maintaining a low microbial load in the air.

The European Union (EU) has established legislation on air quality specifications for both atmospheric and indoor air. In the scope of the European Green Deal implementation and the EU Climate and Energy policies [24], alongside the economic crisis brought by the COVID-19 pandemic and the present energy crisis, it is rather obvious that energy consumption and supply security are top and urgent priorities in the EU. Presently, energy strategies are receiving public attention, and the EU legal framework for energy consumption in the buildings sector is being recast with a strong focus on energy efficiency as the main goal. The principle that “energy efficiency comes first” is a precious one that should always be implemented; however, energy savings in Heating, Ventilating and Air Conditioning (HVAC) systems cannot be achieved by reducing the ambition to continuously raise the quality of indoor air standards. In the technical and operational optimization of climatization systems and equipment, indoor air quality cannot be reduced to a secondary objective, because the quality of indoor air is a healthy determining factor, especially for elders, a growing vulnerable group due to increasing life expectancy.

2. Characteristics of Elderly Centers as Built Environments

Some characteristics of the built environment may significantly affect IAQ of elderly centers. Factors such as the building design, the construction components and materials, existing operational systems (e.g., heating/ventilation), their routine management and maintenance, the density of occupants, and occupants’ activities may determine the likelihood of exposure to different indoor air pollutants. In fact, insufficient ventilation may result in spaces with poor air quality and high concentration of different indoor air pollutants, since these are not able to be diluted or dissipated. Humidity and temperature are parameters that can intensify the presence of some pollutants. Assuring an adequate ventilation rate per person is therefore fundamental, especially in buildings where users spend most of their time indoors, such as elders and people with physical or mobility disabilities, who end up being exposed to indoor air conditions for prolonged periods of time (Figure 1).

Building design can affect the quality of life of building users. Window sizing, orientation, openings, and vents determine not only the natural sunlight but also the natural fresh-air availability that the different interior spaces may have, which are critical for interior pollutants removal by natural ventilation. A few studies have analyzed how the presence of nearby green spaces (i.e., gardens, lawns, trees, flower bushes, shrubs, green walls and roofs) may improve not only aesthetics but also air quality of elderly centers [25]. A few studies have shown that green spaces may partially filter and remove air pollutants in urban areas [26], being especially useful to reduce PM at pedestrian level in buildings close to main roads [27].

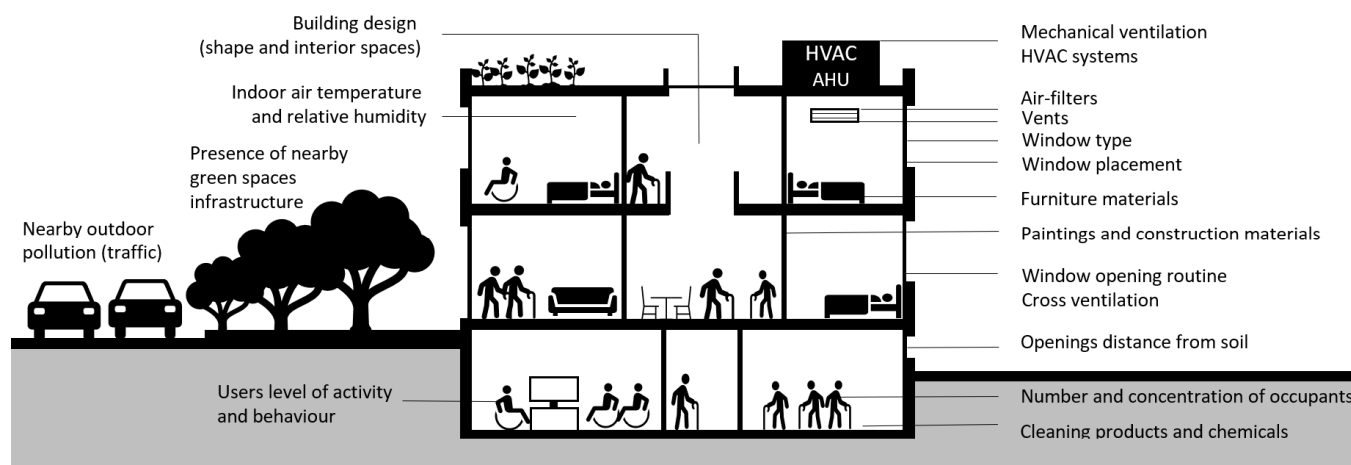


Figure 1. Factors influencing IAQ in elderly centers (authors' own creation).

Mendes et al. [2] monitored IAQ and thermal comfort parameters (CO , CO_2 , PM_{10} , $\text{PM}_{2.5}$, TVOC, formaldehyde, bacteria, fungi, room air temperature, humidity) of 22 elderly centers located in Porto (Portugal) during summer and winter to compare them to existing standards (national and international) and to understand the variability of results among spaces (i.e., bedroom, living room, medical office) within the same building and between different buildings. The authors also tried to find correlations between the building characteristics and IAQ parameters. For that purpose, an inventory of building properties was collected for each building monitored, such as type of construction components (brick or stone masonry), the presence or absence of envelope thermal insulation, the windows type (single or double glazing) and sealants, ventilation type (natural, mechanical, or both), heating system (central or local heaters), and the presence of observable building pathologies (condensations). The building characteristics that influenced the IAQ and thermal comfort most were the window frame type, heating ventilation, and thermal insulation, and the parameters most affected were the presence of microorganisms (bacteria and fungi), relative humidity, and temperature. It is important to note that many buildings were not originally projected to be elderly centers; instead, they were adapted for such function.

3. Indoor Air Quality and Emission Sources

This section presents the main outcomes from studies investigating the levels of various pollutants (chemical, physical, and microbiologic) in elderly centers.

3.1. VOCs, Formaldehyde, and Emergent Compounds

VOCs are pollutants typically found in indoor environments, with concentration levels sometimes 10 times higher than the respective outdoor air levels, regardless of the building location [28]. The major sources are building materials, furniture, cleaning products, use of incense and candles, cooking, and use of fireplaces, which associated with inadequate ventilation can cause high levels of these compounds [29]. It is very important also to highlight the occurrence of reactions with oxidants, such as indoor ozone. This is because ozone may react with some VOC as terpenes. Inhalation of terpenes themselves is generally not considered a health concern due to their low concentrations in indoor air. However, their reactions with ozone produce a multitude of products, such as formaldehyde [30], 4-oxopentanal [31], and ultrafine particles formed by condensation/nucleation processes. These reaction products can be health concerns, but more studies in this area are necessary [32]. VOCs represent cents of compounds, and there are no guideline values for all. Only carcinogenic compounds, such as benzene or trichlorobenzene, and usual compounds such as tetrachloroethylene and naphthalene are referred to in the WHO recommendations [33] that were also adopted by countries with policies on indoor air quality. In some countries, TVOC level was also adopted as an indicator of air quality, and a limit value

was established, for example, Belgium [34], Portugal [35], South Korea [36]. For this reason, a major portion of studies present results for TVOC. Formaldehyde, which mostly can be emitted by the same sources, is reported distinctly, as it is a very volatile organic compound and the sampling and analytical methods are different from VOCs. Formaldehyde is part of the WHO recommendations and is regulated in countries with policies on indoor air quality. Emergent compounds assemble different families of compounds that are SVOCs and in air aggregates to form particulate matter, and they include phthalates, polycyclic aromatic hydrocarbons (PAHs), organophosphate esters (OPEs), brominated flame retardants (BFRs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs), among others. Emergent compounds are at the moment absent from policies on indoor air quality, with the exception of PAHs, which are referenced in WHO guidelines [33].

Seven studies were identified [3,9,14,16,18,36,37] reporting VOCs determinations in elderly centers, with two types of compounds analyzed: TVOC value from sensor acquisition and individual VOCs from analytical determination (see Table 1). Formaldehyde was reported in six studies [3,9,14–16,36] (see Table 2). SVOCs, in which some emergent pollutants are included, were reported in two studies [14,20], using analytical determination (see Table 3).

One of the first studies was published in 2011, when Walgraeve et al. [37] performed six measuring campaigns, conducted between 2007 and 2009, at homes for the elderly located in the Antwerp city center and at several sub-urban cities: Broechem, Borsbeek, Hove, and Bonheiden. At each home for the elderly, four residents' rooms, a recreational room, and the garden were sampled passively for 6 and 9 days. TVOC concentrations ranged between 12 and 311 $\mu\text{g}\cdot\text{m}^{-3}$, exceeding the Flemish guideline [34] for TVOC ($\leq 200 \mu\text{g}\cdot\text{m}^{-3}$) in 13% of the samples (two buildings). The main contributor to the high TVOC concentration in the room with higher levels was limonene ($102.3 \pm 0.3 \mu\text{g}\cdot\text{m}^{-3}$), but high levels of aromatic hydrocarbons were also found ($88 \mu\text{g}\cdot\text{m}^{-3}$) when compared to other rooms in the same building ($13\text{--}29 \mu\text{g}\cdot\text{m}^{-3}$). Toluene ($60.8 \pm 0.8 \mu\text{g}\cdot\text{m}^{-3}$) accounted for the highest percentage (69%) of the aromatic hydrocarbons, representing 25% of the TVOC indoor concentration. For the other building, in the three rooms where the Flemish guideline was exceeded [34], limonene was again a major contributor, with concentrations between 60 and 139 $\mu\text{g}\cdot\text{m}^{-3}$ corresponding to 28–45% of the TVOC concentration ($207\text{--}311 \mu\text{g}\cdot\text{m}^{-3}$). Next to limonene, increased levels were also measured for ethyl acetate ($111 \pm 6 \mu\text{g}\cdot\text{m}^{-3}$), alkanes ($152 \pm 3 \mu\text{g}\cdot\text{m}^{-3}$), and hexanal ($92 \pm 3 \mu\text{g}\cdot\text{m}^{-3}$). Examples of possible important indoor sources of these substances are different kinds of cleaning products and air fresheners (limonene, ethyl acetate), solvents used for decoration or painting purposes (aromatic hydrocarbons and cycloalkanes), and furniture made of particleboard or plywood materials (hexanal). It was also observed that the Flemish guideline for benzene ($\leq 2 \mu\text{g}\cdot\text{m}^{-3}$) was exceeded in 17% of the samples. Guidelines for total aldehyde ($\leq 20 \mu\text{g}\cdot\text{m}^{-3}$) were exceeded for 33% of the samples.

Annesi-Maesano et al. [13] present the results obtained by the European project GERIE-Geriatric study on health effects of air quality in nursing homes in Europe. Eight nursing homes were randomly selected in a geographical area representative of the selected city in each of the seven countries participating in the GERIE study (Brussels, Aarhus, Athens, Reims, Arezzo, Warsaw, and Uppsala). Data were collected between February 2009 and October 2011. Among the several pollutants that were measured, formaldehyde presented a mean concentration of $7.21 \mu\text{g}\cdot\text{m}^{-3}$, and the highest values were measured in Aarhus ($13.7 \mu\text{g}\cdot\text{m}^{-3}$).

Another study published in 2013 by Mendes et al. [3] assessed IAQ and thermal comfort (TC) in two seasons in six ECCs located in Porto, Portugal, housing a total of 425 elderly people. The environmental parameters studied were formaldehyde, PM_{10} , TVOC, CO, CO_2 , total bacteria, fungi, temperature, relative humidity, and air velocity. The mean TVOC concentration was near the Portuguese reference value ($0.6 \text{mg}\cdot\text{m}^{-3}$) in both winter ($0.08 \text{mg}\cdot\text{m}^{-3}$) and summer ($0.07 \text{mg}\cdot\text{m}^{-3}$) seasons. On average, indoor TVOC levels were approximately threefold higher than outdoor levels, indicating the presence of

indoor sources, such as emissions from construction materials, furniture, cleaning products, and cosmetics. Interestingly, out of the 66 indoor formaldehyde samples collected, 60 were below the method limit of quantification (LOQ; $0.0002 \text{ mg}\cdot\text{m}^{-3}$).

Table 1. VOCs measurements conducted in Elderly Centers studies.

Referenced Study	Population Sample Investigated	Measurement Technique	Pollutants
Walgraeve et al. [37]	7 ECC located in Antwerp, Broechem, Borsbeek, Hove, and Bonheiden	Thermal desorption (TD) and GC/MS	TVOC and 25 VOCs: 9 alkanes, 10 aromatic hydrocarbons, 2 O-containing hydrocarbons, 2 Cl-containing hydrocarbons, and 2 terpenes.
Mendes et al. [3]	6 ECC located in Porto, Portugal	Thermal desorption (TD) and GC/MS	TVOC
Mendes et al. [16]	21 ECC, located in Porto, Portugal	No information	TVOC
Almeida-Silva et al. [9]	10 ECC located in Lisboa and Loures, Portugal	Photoionization detector	TVOC
Hwang et al. [36]	28 ECC in South Korea	Thermal desorption (TD) and GC/MS	TVOC
Belo et al. [38]	18 ECC located in Lisbon	Thermal desorption (TD) and GC/MS	TVOC
Pinto et al. [39]	2 ECC located in Viseu and 1 ECC in Covilhã	Photoionization detector	TVOC
Baudet et al. [14]	4 ECC in 2 French urban areas: Nancy and Rennes	Thermal desorption (TD) and GC/MS	39 VOCs: 9 aromatic hydrocarbons, 3 aliphatic hydrocarbons, 8 halogenated hydrocarbons, 5 alcohols, 2 ketones, 1 terpene, 3 ethers, and 1 peroxide
Baudet et al. [18]	2 ECC in 2 French urban areas: Nancy and Rennes	Photoionization detector	TVOC

GC/MS—Gas chromatography–mass spectrometry.

Table 2. Formaldehyde measurements conducted in Elderly Centers studies.

Referenced Study	Population Sample Investigated	Measurement Technique
Bentayeb et al. [15]	8 ECC in Brussels, Aarhus, Athens, Reims, Arezzo, Warsaw, and Uppsala	HPLC
Mendes et al. [3]	6 ECC located in Porto, Portugal	HPLC
Mendes et al. [16]	21 ECC, located in Porto, Portugal	No information
Almeida-Silva et al. [9]	10 ECC located in Lisboa and Loures, Portugal	Electrochemical sensor
Hwang et al. [36]	28 ECC in South Korea	HPLC
Belo et al. [38]	18 ECC located in Lisbon	UV-VIS spectrometry
Baudet et al. [14]	4 ECC in 2 French urban areas: Nancy and Rennes	HPLC

HPLC—High-performance liquid chromatography.

Table 3. Measurements of Emergent Compounds conducted in Elderly Centers studies.

Referenced Study	Population Sample Investigated	Measurement Technique	Pollutants
Arnold et al. [20]	11 ECC in Porto, Portugal, and 3 ECC in Indiana, USA	Solvent extraction and GC/MS	Organophosphate esters (OPEs), brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs)
Baudet et al. [14]	4 ECC in 2 French urban areas: Nancy and Rennes	Pressurized liquid extraction (PLE) and GC/MS/MS	13 SVOCs: 6 phthalates, 2 musk, and 5 pyrethroids

GC/MS—Gas chromatography–mass spectrometry.

Mendes et al. [16] extended the work to other ECCs, presenting a study with data from 21 facilities, located in Porto, Portugal. The results of TVOC show a mean concentration of $42 \mu\text{g}\cdot\text{m}^{-3}$, but with peaks of $973 \mu\text{g}\cdot\text{m}^{-3}$ above the Portuguese reference value of $600 \mu\text{g}\cdot\text{m}^{-3}$. The mean value of formaldehyde was again below the limit of quantification, but a maximum value of $320 \mu\text{g}\cdot\text{m}^{-3}$ was measured in winter, well above the Portuguese reference value of $100 \mu\text{g}\cdot\text{m}^{-3}$.

Almeida-Silva et al. [9] conducted a study in 10 EEC located in Lisboa and Loures, Portugal, housing a total of 384 elderly people. The Portuguese limit value of TVOC ($0.6 \text{ mg}\cdot\text{m}^{-3}$) was exceeded in 15 of the 20 analyzed indoor micro-environments, which was explained by the insufficient ventilation preconized in the studied sites. Regarding formaldehyde, the Portuguese limit value of $0.1 \text{ mg}\cdot\text{m}^{-3}$ was not exceeded in any of the studied ECCs.

Arnold et al. [20] present a study on SVOCs collected in eleven senior care facilities in Porto, Portugal ($n = 28$), during the spring of 2013 and in three facilities in Indiana, U.S. ($n = 14$), during the summer of 2015. Indoor settled-dust samples were collected, and the concentrations of organophosphate esters (OPEs), brominated flame retardants (BFRs), polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides (OCPs), and polychlorinated biphenyls (PCBs) were measured in these samples. Overall, OPEs, PAHs, and BFRs were the most abundant and OCPs and PCBs were the least abundant SVOC groups in dust collected from both U.S. and Portuguese facilities. SOPE, SPAH, and SBFR concentrations were significantly higher in U.S. facilities than those in Portuguese facilities ($p < 0.001$), while SOCP and SPCB concentrations were not different between the two countries ($p < 0.05$). The samples were collected from three different microenvironments, these being bedrooms, living rooms, and corridors. SOPE, SPAH, and SBFR concentrations were up to five times higher in corridors compared to bedrooms and living rooms. SOCP and SPCB concentrations were overall higher in bedrooms and in living rooms and lower in corridors.

Hwang et al. [36] measured the concentrations of indoor pollutants (PM_{10} , CO_2 , airborne bacteria, TVOC, and formaldehyde) in facilities with susceptible populations, such as hospitals, geriatric hospitals, ECCs, and postnatal care centers throughout South Korea. The mean formaldehyde ($15.9 \pm 9.6 \mu\text{g}\cdot\text{m}^{-3}$) and TVOC ($108.8 \pm 94.9 \mu\text{g}\cdot\text{m}^{-3}$) concentrations measured in the 28 ECCs were lower than the recommended limits of $100 \mu\text{g}\cdot\text{m}^{-3}$ for formaldehyde and $400 \mu\text{g}\cdot\text{m}^{-3}$ for TVOC. However, a maximum of $603.7 \mu\text{g}\cdot\text{m}^{-3}$ was attained for TVOC value.

Belo et al. [38] assessed the IAQ in 18 nursing homes located in Lisbon and the respiratory health of 269 residents. They have measured TVOC and formaldehyde among other pollutants in a total of 116 rooms, among living rooms and bedrooms. The overall results showed that the median values for TVOC and formaldehyde were below the Portuguese reference limits. For living rooms values, of TVOC were within the range $60.8\text{--}331.6 \mu\text{g}\cdot\text{m}^{-3}$, and for bedrooms, they ranged from $8.0\text{--}54.0 \mu\text{g}\cdot\text{m}^{-3}$. In the case of

formaldehyde, these values were between 8.0 and 54.0 $\mu\text{g}\cdot\text{m}^{-3}$ for living rooms and between 8.5–40.0 $\mu\text{g}\cdot\text{m}^{-3}$ for bedrooms.

Pinto et al. [39] evaluated the quality of the indoor environment in three elderly care centers in two cities in central Portugal: Viseu and Covilhã. They measured TVOC and formaldehyde, among other parameters, obtaining values below the regulated limits for all the spaces studied, with the exception of a triple room in an ECC located in Covilhã. In this triple room, a maximum value of TVOC of 0.33 ppm was obtained and, for formaldehyde, a value of 0.13 ppm. The authors speculated that this may be due to the wall coverings or other materials used.

Baudet et al. [14] carried out a study where a wide range of chemical compounds (39 VOCs and 13 SVOCs, CO_2 , fine PM) and microorganisms (fungi and bacteria) were studied. Sampling campaigns were conducted in two French cities (Nancy and Rennes) in summer 2018 and winter 2019 in six private healthcare facilities (general practitioner's offices, dental offices, pharmacies) and four care facilities (nursing homes). Considering only the four nursing homes, we have performed the calculation of the average of all the values obtained in common rooms and bedrooms, in winter and summer, that are presented next. The quantified VOCs with the highest median concentration were alcohols, with an average concentration of 399.7 $\mu\text{g}\cdot\text{m}^{-3}$ for ethanol and an average concentration of 16.1 $\mu\text{g}\cdot\text{m}^{-3}$ for isopropanol, which are two alcohols produced by hydro-alcoholic solutions and many disinfectants. From the six aldehydes quantified, formaldehyde and acetaldehyde presented the highest concentrations, 11.3 and 5.5 $\mu\text{g}\cdot\text{m}^{-3}$, respectively. Formaldehyde presented higher concentrations in summer than in winter, but for most VOCs, the concentrations were higher in winter compared with the summer, probably due to lower ventilation. The other compound with higher concentrations was acetone (16.3 $\mu\text{g}\cdot\text{m}^{-3}$). Limonene, the only terpene quantified, presented a low value (2.9 $\mu\text{g}\cdot\text{m}^{-3}$). Six SVOCs were ubiquitous and had the highest median concentrations: four phthalates (diisobutylphthalate, 362 $\text{ng}\cdot\text{m}^{-3}$ (range: 215–550); diethylphthalate, 445 $\text{ng}\cdot\text{m}^{-3}$ (range: 250–660); dibutylphthalate, 88 $\text{ng}\cdot\text{m}^{-3}$ (range: 60.5–125); and DEHP, 38 $\text{ng}\cdot\text{m}^{-3}$ (range 17.5–69)) and two musks (galaxolide, 140 $\text{ng}\cdot\text{m}^{-3}$ (range: 104.5–162.5) and tonalide, 23 $\text{ng}\cdot\text{m}^{-3}$ (range: 19–29)).

In another study by Baudet et al. [18], where TVOC (among other parameters) was measured, the mean concentration obtained in 2 ECCs was 149 ± 210 ppb (range: 0–2600). These ECCs were located in two French urban areas, Nancy and Rennes. Higher mean concentrations of TVOC were measured in winter (248 ± 174 ppb and 313 ± 277 ppb, for common rooms and bedrooms, respectively) than in summer (45 ± 155 ppb and 75 ± 130 ppb, for common rooms and bedrooms, respectively).

It can be observed that the majority of studies have performed TVOC measurements instead of individual VOC measurements, which will be more relevant. Therefore, it is difficult to have a general picture concerning individual VOCs in this kind of spaces. This reveals the need for more detailed studies in this field.

3.2. Exposure to Particulate Matter in Elderly Care Centers

Particulate matter has been considered a critical air-pollution parameter to be assessed in both ambient and indoor air [33,40,41]. Nevertheless, the investigation of exposure to airborne PM has an inherent extra difficulty, because particles existing in a given environment may be fairly variable in size and chemical composition, as well as in other characteristics. Interestingly, all of these features are likely to determine the type of the resultant health effects [42–44]. The main findings of some of the existing reports for characterizing exposure to different PM size fractions, including $\text{PM}_{2.5}$, PM_{10} , and ultrafine particles (UFP), in elderly centers are revisited in the following subsections.

3.2.1. Airborne $\text{PM}_{2.5}$

The air pollutant $\text{PM}_{2.5}$, also known as fine particles, refers to airborne particles presenting a diameter less than or equal to 2.5 μm [40]. This allows $\text{PM}_{2.5}$ to penetrate deeper into the respiratory system and to exert an adverse effect on humans' health. For instance,

PM_{2.5} is one of the pollutants included in the WHO global air quality guidelines [40]. Based on the premise of achieving clear air, these guidelines have been updated to be more stringent over time in order to effectively prevent health risks. In particular, for PM_{2.5}, WHO recently established a mean limit of 15 µg·m⁻³ for a 24 h period [40], which is considerably more restricted than the previous WHO limit of 25 µg·m⁻³ [41]. Some of the existing studies aimed at evaluating the indoor PM_{2.5} concentrations in elderly centers reported levels that exceeded the current WHO limit value (15 µg·m⁻³) in some of the audited facilities [2,9,18,45,46]. However, there are also works that found levels of PM_{2.5} in elderly centers in compliance with the current WHO guideline, showing that healthy levels can be achieved in these environments [38,47,48]. In terms of the different indoor spaces evaluated within elderly center buildings, living rooms, and drawing rooms have been described as indoor spaces with particularly higher PM_{2.5} concentrations [2,9]. In fact, Mendes et al. [2] obtained peak concentrations in drawing rooms, explained by the accelerated resuspension of particles due to the occupancy of the room and by putative emissions resultant from the drawing activities that are performed in the room. Moreover, the same authors identified ventilation, building pathologies, construction characteristics (such as insulation and flooring), and the existence of a building adaption to the use as elderly care center as putative contributors to PM_{2.5}, justifying the observation of higher levels of fine particles indoors than outdoors. Nevertheless, other studies have demonstrated that the ambient air is the main contributor to the PM_{2.5} concentrations found indoors, due to observation of indoor-to-outdoor (I/O) concentration ratios below the unit [47,48]. In agreement, the existence of statistically significant correlations between the levels measured inside elderly centers and the levels assessed in their respective surrounding outdoor environments has also been reported [47,48].

Furthermore, there is some evidence showing that PM_{2.5} levels can be influenced by seasonal effects. Mendes et al. [2], who investigated IAQ and thermal comfort in 22 elderly centers in two seasonal monitoring campaigns, found higher levels in summer than in winter. Baudet et al. [18], in a more recent study analyzing private healthcare and elderly facilities in two French areas, also achieved higher particles concentrations in the bedrooms of ECCs, which strongly varied between seasons, with the highest concentrations being found during summer. These findings suggest that the more frequent practice of opening windows during summer may allow outdoor particles to penetrate the building envelope and increase the indoor concentrations, which is of particular relevance when PM_{2.5} levels exceed WHO guidelines, as Mendes et al. [2] detected, actually, in both seasons. Indeed, Belo et al. [38] studied associations between the exposure to PM_{2.5} and an inflammatory biomarker in older adults living in nursing homes and concluded that PM_{2.5} can adversely impact the airways through acidification and inflammation. Such results demonstrate that to avoid risks to this vulnerable population, it is of utmost importance to reduce as much as possible exposure to PM_{2.5}. Recently, some air-purification strategies have been employed in order to test the effectiveness of removing particles from indoor environments. In particular, Guo et al. [45] installed air purifiers in some elderly center rooms. This intervention resulted in a reduction in PM_{2.5} levels by about 72%, showing that the reduction was particularly effective during the first 2 h after the installation of the air purifiers.

3.2.2. Airborne PM₁₀

PM₁₀ represents, by definition, the airborne particles with a diameter less than or equal to 10 µm, also known as coarse particles [40]. Similarly to PM_{2.5}, PM₁₀ is included in the WHO guidelines for air quality [40], and its limit of exposure has been recently updated from 50 µg·m⁻³ to 45 µg·m⁻³ (8 h period mean) [40]. Furthermore, in agreement with what was found for PM_{2.5}, some of the studies that have quantified PM₁₀ concentrations in elderly centers, including assessments conducted in bedrooms and living rooms of the facilities, found levels above the recommended limit value [7,36,38,49].

There is substantial evidence on temporal fluctuations in the PM₁₀ concentration to which older people may be exposed in the facilities. In particular, significantly higher concentrations have been reported for periods of high occupancy [36], in rooms where activities with associated emissions are carried out (drawing room) [3], and during the day, contrasting with the night period [50]. The existing information on the seasonal influence has been controversial. Greater levels of PM₁₀ were detected for winter than summer in at least two works conducted in elderly centers, where natural ventilation was the main employed ventilation approach [2,50]. Nevertheless, Mendes et al. [3] found for naturally ventilated areas that the highest concentrations were measured during summer, when natural ventilation through open windows is more frequent.

In accordance with the information reported above, Sousa et al. [48] found significantly higher PM₁₀ levels in outdoor air than in indoor air. The impact of polluted outdoor air in IAQ is also highlighted by a strong correlation found between the concentration measured indoors and outdoors. In fact, the characteristics of the outdoor environment, namely the existence of relevant particle emission sources as those related to heavy traffic (e.g., highways) and airports, can be related to high levels of PM₁₀ that impact both indoor and outdoor air quality [50].

In addition to the outdoor air, important sources of PM₁₀ may also exist indoors. For instance, in the work of Hwang et al. [36], levels of coarse particles inside elderly centers located in South Korea were significantly higher than those detected outdoors. Although the authors did not conduct extensive investigation to identify potential indoor sources of pollutants in the evaluated spaces, this result suggests the existence of important indoor emission contributors and/or factors that are promoting the introduction and/or the accumulation of PM₁₀ indoors. In fact, some characteristics of the building can also be related to the PM₁₀ concentrations in elderly centers. In this regard, Mendes et al. [2] found statistically significant differences in the mean PM₁₀ concentrations according to the window type, frame, and type of sealants used in the assessed spaces.

Outcomes from the European GERIE study [7] that included assessments conducted in elderly centers located in Belgium, Denmark, France, Greece, Italy, Poland, and Sweden suggest the existence of geographical variations, with the centers located in Greece being where higher PM₁₀ levels were obtained. This extensive study reported similar mean levels indoors and outdoors, demonstrating that both outdoor and indoor sources of PM₁₀ need to be tackled in order to promote actions to ensure safe levels in elderly centers. Furthermore, in the scope of the GERIE study, Bentayeb et al. [7] investigated the occurrence of health effects related to exposure to particles of this fraction size and found an increased risk of a usual/more frequent breathlessness and cough associated with high levels of PM₁₀.

3.2.3. Airborne Ultrafine Particles

Ultrafine particles (UFP) refer to particles of nanoscale size, having a diameter less than or equal to 0.1 μm [40]. Although no guideline has been established for this air pollutant, WHO [40] defined ranges for low and high levels of UFP in terms of the number of particles per volume of air, as follows:

- Low concentrations: <1000 particles/cm³ (24 h mean);
- High concentrations: >10,000 particles/cm³ (24 h mean) or 20,000 particles/cm³ (1 h mean).

Because of the growing evidence showing adverse exposure impacts on health, the inclusion of UFP in the IAQ assessment plans has been increasing over time. However, data on the levels of UFP for elderly facilities is still very scarce. In this context, according to our knowledge, only Bentayeb et al. [7] (GERIE study) reported UFP concentrations for nursing homes, monitoring for periods of 5 to 7 h in some European countries, obtaining an average of 12,907 particles/cm³. In accordance with PM₁₀ results, Greece was also the region in which greater UFP concentrations were measured (23,839 particles/cm³). GERIE project [7] also included the evaluation of the influence of the ambient air, and found similar UFP levels indoors and outdoors in the elderly facilities. Moreover, exposure to high levels of

UFP was associated with an increased risk of wheeze and a high ratio of forced expiratory volume in 1 s/forced vital capacity. In general, the obtained results suggest that, according to the current WHO recommendation, the levels of UFP in elderly centers are high, and they are likely to represent a concern to the occupants' health.

3.3. Exposure to Inorganic Air Pollutants in Elderly Care Centers

To protect people from health risks associated with exposure to inorganic air pollutants, WHO defined guidelines [33] for selected contaminants, including some inorganic species. A recent review by Villanueva et al. [51] gathered relevant information on the monitoring and sampling of inorganic pollutants, in order to properly collect representative data and ensure the quality of evaluations for several inorganic compounds, namely carbon oxides, reactive oxygen species, and N- and S-containing species. Overall, the inorganic compounds that have been most investigated in indoor air are carbon dioxide (CO₂), carbon monoxide (CO), ozone (O₃), and nitrogen oxides [52], which also correspond to the inorganic pollutants assessed in studies carried out in ECC facilities, as presented below.

3.3.1. Carbon Dioxide

Carbon dioxide (CO₂) has been used as a proxy for ventilation conditions in a wide variety of indoor environments [53–55]. In the case of elderly centers, it is of utmost importance to assess CO₂ levels, which can also be an indicator of the existence of conditions for the accumulation of hazardous air pollutants that can harm this susceptible population. ASHRAE has established a guideline concentration level of 1000 ppm for indoor spaces [56], taking into consideration that indoor CO₂ levels should be kept at a maximum of 700 ppm above outdoor concentrations (typical range of 300–500 ppm). Moreover, in the context of the COVID-19 pandemic, a recommended level of 700 ppm was defined to minimize the risk of SARS-CoV-2 transmission in indoor settings [57].

For elderly centers, CO₂ is a popular parameter that has been included in most of the IAQ evaluations conducted. Results from these assessments show that indoor CO₂ concentrations above ASHRAE recommendations have been reported in the majority of the works [9,38,39,58,59], with a limited number of studies finding CO₂ levels below 1000 ppm [7,18]. In general, the authors justified the high concentrations found in their studies with the existence of insufficient ventilation rates and/or high occupancy density [9,18]. In fact, after a ventilation system renovation in Estonian nursing homes, Mikola et al. [59] observed a remarkable reduction in indoor CO₂ levels, which complied with guidelines. Some authors reported the highest levels for bedrooms [9,38] and others for living rooms [39,58], drawing rooms [2], or dining rooms [2,58], with levels typically increasing during the afternoon period in areas where people stay for more time. Moreover, Mendes et al. [2] observed differences in the CO₂ levels detected as a function of the existence of window sealants and of the type of sealants used, which will probably influence the infiltration rate of outdoor air and consequently have an effect on CO₂ levels. Interestingly, Hwang et al. [36] found that CO₂ levels in elderly centers might be a good indicator for predicting other indoor pollutants levels (such as airborne bacteria and formaldehyde) when categorized into two levels (750 ppm and >750 ppm).

The investigation of seasonal influence on CO₂ levels was also carried out in some works [2,3,18,58]. All the referenced studies presented consistent results of higher CO₂ levels measured during winter than in summer. For example, Pereira et al. [58] reported indoors average concentrations of CO₂ ranging from 561 to about 850 ppm, while in winter varied between 792 and 1881 ppm. For instance, the behavior of opening windows and doors in a more frequent way during summer is likely to promote the introduction of fresh air in the indoor environment and, consequently, the dilution of indoor CO₂ concentrations (and of other pollutants produced indoors).

The association of the assessed CO₂ levels with the risk of effects on occupants' health was only studied by Bentayeb et al. [7], who found that an increased risk of breathless-

ness and cough in elderly people seemed to be related to the exposure to higher CO₂ concentrations in nursing homes.

3.3.2. Carbon Monoxide

Carbon monoxide (CO) is a gas that results from the incomplete combustion of fuels, such as petrol, coal, wood, and natural gas [40]. Regarding WHO guidelines [33,40], recommendations have been established for four different mean periods, as follow: 100 mg·m⁻³ (15 min), 35 mg·m⁻³ (1 h), 10 mg·m⁻³ (8 h), and 4 mg·m⁻³ (24 h). In general, the studies conducted in elderly facilities and that included CO in the panel of IAQ factors assessed showed that indoor CO levels did not exceed WHO recommendations [2,3,9,58]. Interestingly, some studies found that greater mean concentrations were found in bedrooms [3,9]. The main putative sources of CO in these environments are cooking activity, other combustion sources (e.g., tobacco smoke, incense), and outdoor air (e.g., traffic-related sources). In fact, in the scope of the GERIA Portuguese project, Mendes et al. [3] obtained the maximum CO value for a bedroom with an open window (data referring to six elderly centers located in urban areas), facing roads with heavy traffic, where outdoor levels were about 1.3-fold greater than indoors. Accordingly, outdoor concentrations reported for the total sample of elderly facilities assessed in the same project (*n* = 22) were higher than the respective levels detected indoors [2]. The authors also found that high mean CO levels were related to some building characteristics, such as insulation and roof lining, resulting from the adaptation of the facility to turn into an elderly center.

The season, also appears to have an influence on the indoor CO concentrations. Indeed, in elderly facilities, the summer period corresponds to the season when higher CO concentrations are typically found indoors, mainly due to external factors as demonstrated by the I/O concentration ratios [2,3,58]. In fact, Pereira et al. [58] reported CO levels within 0.8 to 6.4 ppm in the summer, while in the winter varied from 0.7 to 2.9. The same authors reported I/O concentration ratios for CO that were near to 1 in the summer, but more than double in the winter period. This, suggests the existence of a predominant contribution of indoor sources for CO levels, considering that during winter, the higher indoor than outdoor CO concentration is due to worse ventilation. In this context, the authors identified the proximity of the assessed areas to the kitchen and the use of incense, together with poor ventilation, as the main contributors to the indoor levels achieved in the cold season. In turn, the additional influence of traffic-related pollution loads and agricultural biomass burnings, coming from outdoors through opened windows, may justify the increased concentrations reported in the warm season.

In addition, Bentayeb et al. [7] reported that exhaled CO (used as an indicator of exposure to CO) was linked to an increased risk for chronic obstructive pulmonary disease occurrence.

3.3.3. Ozone

Ozone (O₃) is an oxidant air pollutant that results from a series of reactions between other pollutants, including NO₂ and unsaturated VOCs [40]. In addition to ambient air, O₃ can be emitted from indoor sources, namely electronic equipment and electrostatic air cleaners [60,61]. In this regard, this is a parameter of concern in several indoor environments, being among the pollutants listed by WHO in global air quality guidelines [40]: 100 µg·m⁻³ (8 h mean). Particularly for elderly centers, O₃ has been poorly explored. Among the available data, the authors of the GERIE study reported mean levels within the recommendations in all participant countries, with an overall mean of about 21 µg·m⁻³ [7]. In terms of health outcomes, no significant results were found regarding the exposure to O₃ in those spaces. Furthermore, Almeida-Silva et al. [9] measured O₃ in elderly facilities in Portugal and found levels that exceeded the guideline only very sporadically. According to the same authors, the peak concentrations were obtained in bedrooms during the morning, when the elderly are waking up and in living rooms.

3.3.4. Nitrogen Dioxide

Among nitrogen oxides, nitrogen dioxide (NO₂) has been regarded as the most relevant chemical specie with declared impacts on human health. This pollutant is present at particularly high levels in megacities/urban areas [62]. Concerning the WHO guidelines, NO₂ is regulated by having three mean periods: 200 µg·m⁻³ (1 h mean), 25 µg·m⁻³ (24 h mean), and 10 µg·m⁻³ (annual mean) [33,40]. For elderly centers, Bentayeb et al. [7] sampled NO₂ through the diffusion method and obtained mean concentrations of 20 µg·m⁻³. Greece was the country where the highest concentrations of NO₂ were measured (36 µg·m⁻³). Overall, indoor and outdoor levels were identical, suggesting the existence of a very relevant contribution from the outdoor air. Further, an increased risk of the development of cough, breathlessness, and a high ratio of forced expiratory volume in 1 s/forced vital capacity was identified and linked to exposure to high NO₂ concentrations.

3.4. Biological Contaminants

Biological contaminants are agents or substances derived from living matter and include bacteria, fungi (including yeasts), viruses, allergens (from fungi, pets, insects, and other sources, including pollen) and toxins [63].

Indoor air biological contamination may have different sources, namely outdoor air, the human body, bacteria growing indoors, and pets. Concerning indoor environments, the most important biologic contaminants are microorganisms, allergens, and toxins [17,64].

Microorganisms include bacteria, fungi, and viruses and are most commonly carried by humans or animals, causing infectious health outcomes [65]. Infectious agents are usually received from other humans (anthroponoses), from animals (zoonoses), or from environmental sources such as contaminated water and soil.

Indoor environments' most common associated bacteria are saprophytic bacteria of the normal human skin, mouth, and nose that are emitted into the indoor air and bacteria from outdoor air. Air contamination level depends on the number of persons inside and ventilation system efficiency (natural or mechanical). Bacteria genera most commonly identified in indoor air are *Staphylococcus*, *Micrococcus*, *Kocuria*, *Aerococcus*, *Kytococcus*, *Bacillus*, *Pseudomonas*, *Corynebacterium*, and *Streptococcus* [65]. Indoor environments can also be contaminated by bacteria growing in water reservoirs or moist environments. Biofilms in water pipelines and reservoirs are particularly important as sources of nontuberculous environmental mycobacteria and *Legionella* contamination. Peptidoglycans, bacterial spores, exotoxins, endotoxins, and other bacterial metabolites can also be released in air, being considered biologic contaminants [66].

In regard to fungi, the levels and type of fungi in indoor air depend on the season, construction features, building age, and the ventilation rate. *Cladosporium*, *Aspergillus*, *Penicillium*, *Alternaria*, *Geotrichium*, and *Ulocladium* are the most common fungal genera occurring in indoor environments, with the presence of yeasts also being very relevant. Fungi spores are ubiquitarians and are able to germinate in water availability ranges of 80–98% and in the presence of carbohydrates, proteins, and lipids, these nutrients being commonly available indoors [67].

Indoor air humidity can induce a longer survival time of respiratory viruses and increased risk of respiratory infection [68].

Biologic allergens are a group of agents that may cause a specific IgE-mediated reaction in humans and include fungal allergens, house dust, mites, cockroaches, pollen, animal dander, and cat saliva [69,70]. Exposure to biological allergens can result in sensitization, respiratory allergic diseases, and wheezing [64]. *Alternaria*, *Penicillium*, *Aspergillus*, and *Cladosporium* spp. fungal species can trigger type I allergic reactions and IgE-sensitization-inducing allergic respiratory diseases, especially acute asthma. *Penicillium* and *Aspergillus* allergens can trigger type-III-IgG-mediated and eventually type IV allergic reactions [71].

Endotoxins are lipopolysaccharides from the outer membrane of Gram-negative bacteria and can be released upon bacterial cell lysis. High levels of exposure to endotoxins may lead to developing respiratory symptoms or nonallergic asthma [72].

Mycotoxins are toxins produced by fungi capable of interfering with RNA synthesis and causing DNA damage. Mycotoxins produced by *Aspergillus flavus* and *Aspergillus parasiticus* (aflatoxins) may induce carcinogenic effects. Acute pulmonary hemorrhage can be associated with indoor exposure to mycotoxins produced by *Stachybotrys chartarum* [71,73].

Studies concerning the presence of biological contaminants in elderly care centers are scarce [38]. Fungi are the most common biological contamination [3]. *Cladosporium* and *Penicillium* were the most common fungi found [74], with *Aspergillus* also being present [75]. The study of Belo et al. [38] found higher levels of total bacteria and fungi in a total of 116 rooms of nursing homes.

4. IAQ-Related Health Effects in the Elderly

Indoor air contamination can induce several effects on human health. The respiratory system is usually the primary target of indoor air contamination, as inhalation is the most frequent pathway for contaminants to enter into the human body. Inflammatory and allergic reactions can be induced by the exposure to different agents (biologic and non-biologic) that are identified in indoor air. Respiratory infections are caused by microorganisms present in indoor air. There is also some evidence to suggest that exposure to contaminants in indoor air can be associated with symptoms with neurological basis such as headaches, fatigue, and forgetfulness [3,68].

The population effects of indoor air pollution have generally been well documented [70]. However, studies on the effects of indoor air pollution on the elderly are scarce [15], despite the fact that in high-income countries, elderly people spend most of their time indoors, namely in elderly centers. Furthermore, altered physiology and toxicokinetics, namely reduced renal clearance, make elderly people potentially more sensitive to air-pollution effects due to reduced capacity for elimination [15].

Chronic diseases tend to appear as people get older. Among chronic diseases that affect elderly individuals, cardiopulmonary diseases and cancer are the most prevalent [76], being COPD as well as asthma, responsible for lung function decline, leading to mortality increase [13]. The inevitable appearance of chronic diseases at advanced ages makes research imperative to understand the health consequences of exposure to environmental risk factors, namely indoor air contaminants.

Few studies have shown relationships between exposure to major indoor air pollutants and respiratory health outcomes such as wheezing, breathlessness, cough, phlegm, asthma, COPD, lung cancer, and more rarely, lung function decline [15]. Research for assessing the effects of indoor allergens on respiratory health in the elderly is also limited [16]. Inflammatory diseases, respiratory infections, and building-associated illness are the main health outcomes that have been related to exposure to indoor air contaminants; therefore, it is important to be aware of their general features.

4.1. Inflammatory Diseases

Some of the effects on the respiratory system related to indoor air contamination are due to airway inflammation and can be allergic (with the production of IgE and IgG antibodies) or nonallergic respiratory diseases. The most relevant inflammations in the respiratory system related to IAQ are shown in Table 4.

Atopic dermatitis can also be induced by exposure to the biological indoor air pollutants.

4.2. Respiratory Infections

Acute respiratory infections are classified as upper respiratory infections and lower respiratory infections. Upper respiratory infections are illnesses involving the upper part of the respiratory system (sinuses and throat), usually mild in nature and caused by biological pollutants such as fungi, fungal spores, bacteria, and viruses. Lower respiratory infections are infections on the lungs, with the most common agents being viruses or bacteria. Indoor air contaminants not only affect respiratory tract host defenses but also influence the outcome of an existing respiratory infection [77].

4.3. Building-Associated Illness

The diminished indoor air quality in buildings and houses is related with various symptoms and illnesses, being associated with inorganic, organic, physical, and biological contaminants on a sustained and regular basis, regardless of low levels of exposure. According to WHO [71], building-associated illness is caused by indoor environmental factors and is divided into two categories: sick building syndrome (SBS) and building-related illness (BRI) [63].

Table 4. Relevant indoor-air-quality-related, respiratory-system-related inflammations [63,73,78,79].

Disease	Pathophysiology	Symptoms	Observations Concerning Indoor Air Contaminants
Rhinitis	Mucosa inflammation on the upper respiratory tract.	Nasal congestion, rhinorrhea, sneezing, and conjunctivitis.	Can be of allergic or nonallergic cause.
Asthma	Long-term inflammatory disease of lung airways. Allergic asthma involves IgE-mediated sensitivity and eosinophils in presence of an atopic underlying reaction of the respiratory airways.	Wheezing, shortness of breath, chest tightness, and coughing.	People with moderate to severe asthma react adversely toward contaminants in the indoor environment due to a nonspecific bronchial hyperresponsiveness. Both allergens and viruses have been known to worsen asthma symptoms.
Chronic obstructive pulmonary disease	COPD is a progressive lung disease in which chronic, incompletely reversible poor air flow (air-flow limitation) and inability to breathe out fully exist.	Shortness of breath, cough, with or without mucus production and frequent chest infections.	Biological contamination by the presence of endotoxin can induce the pathogenesis of bronchitis.
	Includes emphysema (damage to the air sacs in the lungs) and chronic bronchitis.		
	Poor air flow is the result of small airways disease and emphysema. Chronic bronchitis is a type of COPD that includes bronchi inflammation and is defined as cough with phlegm for at least 3 months per year for 2 years or more. Underlying mechanism is an increase in mucus-secreting glands and alterations in characteristics of the mucus.	Chronic bronchitis symptoms include coughing up sputum, wheezing, shortness of breath, and chest pain.	Enhanced by indoor air pollutants.

SBS is a group of symptoms that are linked to the physical environments of specific buildings [80]. Poor ventilation, dampness, and high temperature tend to increase the probability of SBS [81].

The SBS symptoms tend to worsen as a function of the exposure time and include:

- Mucous-membrane irritation (eye, throat, and nose irritation);
- Neurotoxic effects (headaches, irritability, and fatigue);
- Asthma and asthma-like symptoms (chest tightness and wheezing);
- Skin irritation and dryness; and
- Gastrointestinal problems, among others.

BRI comprises the illnesses and symptoms with an identified causative agent directly related to exposure to a poor air quality in buildings. BRI symptoms include fever, chills, chest tightness, muscle aches, and cough. Major mechanisms of BRI symptoms are irritant, immunologic, infectious, and toxic. Usually, the first reaction is the irritant effect, followed

by toxic, allergic, or infectious mechanisms, the severity being dependent on the individual susceptibility and the pollutant [63,82].

Indoor environment may potentially have influence on health, particularly on chronic respiratory symptoms of older people living in elderly centers [83]. Further studies in the elderly population are needed in order to define causal relationships between exposures to indoor air pollution and underlying mechanisms in this sub-population [38].

Concerning elderly residences, where cough and sputum are the major respiratory symptoms and allergic rhinitis is the main reported illness, in some studies, no association was found between indoor air chemical and biological contaminants and respiratory symptoms [16].

According to Bentayeb [7], although mean concentrations of air pollutants did not exceed the standards in the elderly nursing homes studied, excess risks for breathlessness and cough were directly correlated with elevated PM₁₀ and nitrogen dioxide. PM_{0.1} leads to higher risk of wheeze, and formaldehyde correlates with chronic obstructive pulmonary disease and exhaled carbon monoxide. Breathlessness and cough were also associated with higher carbon dioxide, and relative humidity was inversely related with wheeze and usual cough. Therefore, even at low levels, indoor air quality affected respiratory health in elderly people permanently living in nursing homes. Moreover, these effects appear to be modulated by ventilation. However, further studies need to be performed in order to understand the mechanisms of these effects [7]. On the other hand, another study [16] concluded that high levels of PM₁₀ were associated with increased probability of allergic rhinitis. However, no association was found between indoor air chemical and biological contaminants and respiratory symptoms.

In regards to biological contaminants, Belo et al. [38] found a direct association between exposure to total bacteria and the presence of a restrictive ventilator pattern. The study of Karottki et al. [84] found similar results; however, to our knowledge, no more data are available concerning the impact of microbiological exposure on lung function, mainly in older people.

Concerning thermal comfort, elderly people with chronic diseases are at greater risk, as body thermal regulation is directly dependent on cardiovascular response. However, a direct correlation between indoor thermal comfort (ITC), indoor air quality (IAQ), and cardiovascular diseases (CVD) is not easy to achieve. It seems that elderly people with CVD respond to ITC and IAQ in a significantly intense manner. However, several factors influence this response. Therefore, designers of indoor environments for elderly people should be aware of the joint influence of thermal environment and air quality on the physiological response of elderly people [85].

5. Ventilation and Thermal Comfort

5.1. Managing Thermal Comfort and Ventilation in Buildings

Ensuring proper thermal comfort in buildings is recommended to prevent amenable deaths attributable to thermal stress, particularly in vulnerable population groups, such as the elderly [2]. Thermal comfort is a subjective concept because, being a sensory experience [86], it varies from person to person, and it is quite complex to model due to the high interdependence of variables. The main factors that influence thermal comfort include both individual characteristics, such as metabolic rate and clothing insulation, and conditions of the indoor environment, such as air and radiant temperature, air speed associated with ventilation (natural or mechanical), and air relative humidity [87]. The conditions of an acceptable thermal comfort zone may be achieved by optimizing all these six variables together and considering the influence of atmospheric air conditions, which depend on the climate zone and the season. Generally, the model for determining the thermal comfort conditions in residential building is based on 'Predicted Mean Vote (PMV)' [87,88], originally defined by Fanger in 1970 [89]. Accordingly, the PMV model applies heat balance principles to relate the six above-mentioned variables. In addition, the thermal comfort perceived by space occupants based on the average responses obtained by a questionnaire

with a seven-level scale from cold (3 negative points) to hot (+3 points) is considered in the model [87].

Usually, residential indoor spaces do not need devices for controlling air humidity, because the indoor environment is determined by human occupation, and often, air relative humidity levels are in the acceptable range of 30% to 60% [88]. However, normal household activities in kitchens, laundries, and hygiene rooms are relevant sources of water vapor in the indoor air in addition to human respiration, so these spaces demand dehumidifying strategies, which may be as simple as a mechanical air-extraction system. High humidity levels favor the development of microorganisms, in particular fungi, which are the cause of some pneumonia types, in addition to other respiratory and skin illnesses [90,91]. Fungi growth in walls or ceilings of poorly ventilated spaces may constitute sources of organic and biological pollutants including particulate matter, microbial volatile organic compounds (MVOCs), mycotoxins, allergens, and pathogens [92,93]. Low levels of humidity, typically below 30%, are also associated with respiratory and ocular infections due to dryness of eye and airways' mucous membranes, hampering the role of these important immunological defenses.

The tolerance to humidity varies with the environmental temperature. Regarding temperature and observing that the indoor environment of elderly care centers can be classified as category I (corresponding to a high level of expectation for thermal comfort), the average range of temperatures is assumed to be between 21 °C and 25 °C for cold seasons and between 23.5 °C and 25.5 °C for warmer seasons [88]. However, these temperature ranges were established for average adults and not particularly the elderly. The physiological models of human thermoregulation are based on the average person's characteristics [94]. Besides varying from person to person, thermal sensation is also dependent on age. With ageing, the response of biological functions become slow; therefore, in healthy elders, thermoregulation is affected by the reduction in capacities for sweating, vasomotor responses to cold or hot, metabolism, or blood circulation to the skin and to body limbs [95].

Studies, carried out in different climate regions of the globe, resulted in diverse findings with regard to the temperature range in which are considered to exist conditions of thermal comfort or thermal preference for the elderly. This means that, for each person, there is a process of adaptation to the temperature and humidity conditions, which is influenced by that person's life experience. With time, a healthy person tends to get used to the climate conditions of the region where she lives. Elderly lifetime experience and adaptation to a certain climate may present an additional factor to be considered in the evaluation of thermal comfort. In an exploratory study carried out during the winter in center Mongolia, focusing on the thermal comfort of rural mutual-help elderly care facilities, authors [96] found that elders' age influences their thermal sensation and that the thermal expectation temperature is 21.1 °C, slightly lower than the standardized range. On the other hand, a study carried out in the Mediterranean climate and during summer season found that the mean comfort temperature for the elderly was 24.4 °C, within the limits of the standard range but higher than the value obtained for non-elderly adults: 23.5 °C [97].

Globally, the capacity to adapt to thermal discomfort conditions depends on individual health, including cardiovascular stability, metabolism, muscle strength, vascular reactivity, and sweating capacity, which may vary in addition to the normal human diversity, but also on the existence of certain diseases or medication that may affect heat transfer through the body [98].

The detrimental effect of thermal stress on health is worsened by polluted air [99]. Therefore, the adequate management of indoor air quality and thermal comfort in elderly care centers is not only a matter of wellbeing but a health determinant as well [100]. Managing thermal comfort and ventilation in buildings is a multidisciplinary problem that has been addressed mainly by civil, mechanical, and electric engineers and architects, over seven decades, focusing on the advancement of technologies to improve systems' performance while enhancing energy efficiency and reducing energy consumption. In addition to buildings design and construction characteristics, thermal comfort and ventila-

tion are provided by climatization systems, usually abbreviated as AHU—Air Handling Unit, or HVAC—Heating, Ventilating and Air Conditioning (although technically these two designations are not interchangeable), which comprise air pumps and mixing chambers to combine atmospheric air with indoor air, heat exchangers for air heating and cooling, a network of ducts for air flow into and out of an indoor space, and filters to remove dust. AHUs can become more complex in buildings with high-air-quality specifications such as hospitals and health care centers, research laboratories, archives, data center rooms, or high-technology industries. In these environments, standards for air quality can be quite restrictive, imposing not only filtration of fine particles but disinfection as well. AHUs' capacity to treat air can be dimensioned for very large buildings with centralized air climatization systems that commonly include air renovation, filtration, humidity, and temperature correction.

Air renovation of an indoor space (rooms, floors) or even an entire building, through climatization systems, involves pumping air out of the space, mixing it with a supply of atmospheric air, and returning the air mixture inside. This process is called mechanical ventilation to distinguish it from natural ventilation, where the renovation of air in a room is obtained by the opening of windows and doors to let atmospheric air inside by convection (wind). In old buildings, natural ventilation may also occur from breaches in window frames, doorcases, or even very poor wall joints. These conditions of poor construction are not acceptable in buildings for elders' residence, and the natural ventilation by opening windows and doors generally is not sufficient to properly renovate the indoor air, especially during cold seasons, and may not be possible depending on elders' health condition. Presently, with the technical advances in construction materials and the improvement of construction procedures, modern buildings have increased insulation and air tightness, preventing air infiltration through the building envelope, so buildings require the support of mechanical ventilation systems to renovate indoor air.

5.2. Technical and Legal Frameworks to Manage Energy Efficiency, Energy Consumption, and Thermal Comfort in Residential Buildings for Elderly Care: Where to Fit Indoor Air Quality?

There is a considerable wealth of guidelines, standards, and regulations that define buildings' construction characteristics concerning thermal isolation and energy efficiency [101–103] and specifications for climatization equipment and installation for residential buildings [88,102]. In the EU context, residential and services buildings take about 40% of the final energy consumption [104], so the need to reduce energy consumption and improve energy efficiency in buildings is a priority in the EU energy policy translated in several official documents: the European Green Deal [24], the Renovation Wave for Europe [104], the EED—Energy Efficiency Directive [105], the RED—Renewable Energy Directive [106], and the EPDB—Energy Performance of Buildings Directive [102]. The common goal of these regulations is to improve buildings' energy efficiency and to reduce energy consumption while increasing thermal comfort through climatization systems. Globally, the share of buildings' energy utilization in HVAC systems accounts for around 38% of final energy consumption [107]. The current EU energy policy foresees an 18% energy reduction in buildings' energy parcel used in HVAC systems with the implementation of a regulations update to be approved with the recast of EPDB, EED, and RED directives. Consequently, AHU equipment and installation efficiency must be improved to comply with the defined targets. However, the calculation of the exact ventilation rate required for a specific indoor space continues to be under technical discussion [108], while models to estimate thermal comfort conditions are continuously under development [109].

In mechanical ventilation, the outdoor air flow entering an indoor space (as volume per unit of time— Q , expressed in m^3/s) is designated as the ventilation rate of that space [88]. The global volumetric flow of air admitted into a room or building is the sum of external air (fresh air) and recirculated indoor air flows.

The proportion of the air flow admitted to a space and the corresponding room volume is called the air-change rate (ACH) of a room, representing the number of times per hour

that the volume of air in a space is totally removed and replaced. Building users (tenants, caregivers, and staff) are responsible to promote the daily natural ventilation of interior spaces. To avoid thermal discomfort and/or save energy, natural ventilation routines are usually reduced in winter, especially in buildings lacking centralized heating systems. To complement natural ventilation, buildings may have mechanical ventilation, or heating, ventilation, and air conditioning (HVAC) systems, which may promote fresh-air admission and controlled air-changes per room. Usually, the air-changes rate should be related to the level of activity and the number of occupants in each space. Thus, overcrowded rooms and facilities or buildings not originally projected to be elderly centers may fail to achieve the appropriate air renovation.

In most commercially available HVAC systems for residential buildings, including nursing homes, the renovation air flow is either a fixed or variable rate depending on the targets for minimization of energy consumption for heating or cooling needs. One of the common ways to reduce energy consumption in HVAC systems is to reduce the ventilation flow rate, which is to say, to reduce the volume fraction of atmospheric air introduced into a space.

In addition to conservation targets for energy consumption in climatization systems, additional factors contribute to common practices for low-renovation-rate adoption in HVAC systems operation: climate conditions, season, and polluted atmospheric air. Most elderly care centers are in cities, where atmospheric pollution is a common situation. Consequently, the air admitted to an indoor space is seldom 100% atmospheric air but rather a fraction of atmospheric air flow mixed with a fraction of indoor air that is being recycled back into the space.

In the scope of energy-saving goals, this procedure is logical, because the recycling of indoor air consumes less energy to condition temperature and humidity than adjusting the same variables to a flow of fresh air from outdoors. Therefore, this procedure is well-established among HVAC operators. However, sometimes, this energy-saving strategy in HVAC systems does not consider the need to ventilate indoor air by replacing this stuffy and polluted air with new, atmospheric, air.

Several elderly care centers tend to operate at full capacity, complying with the minimum areas for spaces set by the law, so often, building areas are at the legal limit. Densely occupied indoor spaces with poor ventilation typically have high carbon dioxide (CO₂) and humidity concentrations as result of human respiration. These stuffy, saturated indoor air conditions favor the colonization of microorganisms, mainly bacteria and fungi, and the transmission of air-borne infections. Atmospheric air is also reported to be the source of bio-contaminants, mainly bacteria [58]. Commercially available climatization solutions for residential buildings, such as elderly centers, usually do not have air-purification systems to inactivate microorganisms or to remove CO₂ from indoor air, because most HVAC devices are equipped with filters that have no positive influence in reducing CO₂ concentration and, eventually, a limited capacity to reduce microbial pollutant charge. Air-purification devices need to be installed into HVAC systems to reduce the number of microorganisms in the air. Air-purification devices may operate through different technologies: catalytic oxidation, electrostatic precipitation, ultraviolet radiation, ion generators such as ozone, physical and chemical adsorption, creation of gaseous plasmas, or a combination of the mentioned technologies [110,111].

CO₂ concentration can easily be reduced by dilution with atmospheric air either by natural or mechanical ventilation. Nevertheless, especially in urban centers due to traffic and industrial pollution sources, atmospheric air may be polluted with nitrogen oxides (NO_x), particulate matter (PM₁₀, PM_{2.5}), ozone (O₃), or volatile organic compounds (VOCs); therefore, in severe polluted regions, admission of atmospheric air to indoor spaces may represent a threat to health.

The increase in indoor air recirculating rates in climatization systems aiming to reduce energy consumption for heating or cooling needs has detrimental effects on indoor air quality, because existing indoor air pollutants are being recirculated inside. Therefore,

high indoor air-recycling rates through climatization systems further increase the concentration of pollutants by returning them to the same indoor space where they are being generated [112].

The regulation of indoor spaces' ventilation based on indoor pollutants concentration measured in real time using multiple sensors for different air parameters is available in the high-technology environments mentioned previously, because these automated systems are costly and require adequate technical maintenance. In certain highly polluted areas, such as car parks, CO sensors activate the admission of atmospheric air to renovate the indoor air and reduce the pollutant level. However, these automated systems are not yet widely available for a set of important indoor air pollutants inside residential buildings. In addition, the installation of sensors for chemical pollutants, such as CO₂ or VOC, in elderly care centers' indoor air would also benefit from the inclusion of filtration and disinfection devices in their AHUs or the adoption of individual air-cleaner systems, at least in treatment rooms or in dining rooms. Notwithstanding, AHUs with automation systems including multiple pollutant sensors and fine filtration and disinfection devices are still expensive equipment that demand more regular and specialized maintenance. In addition, such systems for complete air treatment consume more energy than basic ones, hampering the established goals for energy saving.

6. Conclusions and Future Trends

The quality of indoor air in ECCs and other similar settings for the elderly can be significantly affected by a myriad of factors. As reported in this work, the characteristics of the buildings (namely related to the construction and services), the introduction of indoor sources, and polluted outdoor air can be major determinants of exposure to indoor pollutants. For instance, the existing studies aiming at characterizing IAQ in ECCs show that the elderly population can be exposed to levels of some contaminants (such as PM, chemicals, and biological agents) at higher-than-desirable concentrations in some of these facilities. The scarce epidemiological data on investigating associations between the air-pollution levels in ECCs and the risk of health effects on the occupants also demonstrate that the indoor environment may have an important influence on elderly people's health, particularly on development of respiratory symptoms. Further environmental and epidemiological studies are definitely needed in order to obtain more comprehensive data to define causal relationships between exposures to indoor air pollution and health outcomes as well as to broaden the knowledge of the underlying biological mechanisms.

The recent COVID-19 pandemic contributed immensely to raising awareness of the importance of breathing air with quality for human health and of the fact that indoor air is a vector for airborne infections and poisoning. While IAQ has attracted the interest of scientists in the public health sector, more work is needed to support further urgent policies and ensure healthy indoor environments, in particular in settings for vulnerable population groups. The urgent need for incorporating more restrictive measures on IAQ in energy, public health, and environment policies should represent an opportunity to establish more ambitious standards for the quality of air that we breathe indoors, to promote awareness, and, fundamentally, to protect human health and wellbeing.

At present, the implementation of actions for ensuring healthy IAQ in ECCs can be compromised by the lack of robust national/local legislation for controlling levels of air pollutants and ensuring compliance with the respective guidelines. In the case of facilities with HVAC systems, IAQ can also sometimes be compromised by the establishment of common technical procedures that are needed to comply with energy-saving targets in the installation and operation of climatization systems. Therefore, the management of ECCs to achieve a healthy indoor air quality requires a holistic approach that should consider:

- Conception, design, and construction of buildings for elderly care that must consider the regional climate and the specific needs and typical activities for heating and cooling of vulnerable residents.
- Use of adequate and low-emitting materials (in both construction and renovation works).

- Implementation of comprehensive IAQ assessment plan to ensure that the pollutant levels are in compliance with the recommended limit values.
- Establishment of awareness campaigns for informing all relevant stakeholders (including ECC building managers and staff) of good and low-cost practices that can be implemented to promote healthy IAQ (e.g., improving ventilation in the indoor spaces during/after an emission event such as drawing activities, opening the windows outside of typical high-traffic hours, avoiding declared indoor sources of pollution (e.g., incenses), etc.).
- When a building is adapted to be an ECC, it is important to consider a comprehensive building-evaluation approach in order to ensure that the building characteristics are adequate for the new use, occupancy density, and activities, in order to protect the occupants from avoidable environmental risks.
- As technical solutions, the following should be considered:
 - a. Adoption of automated systems to manage air-flow recirculation rates in climatization systems, based on real-time evaluation of IAQ parameters (as CO₂) through the permanent use of sensor devices.
 - b. Installation of air cleaners as a complementary action if the levels of PM cannot be reduced to safe concentrations by source-control and/or ventilation corrective measurements.

In summary, to protect this particularly vulnerable group of people, it is of utmost importance that ECC buildings are designed, constructed, and maintained by environmentally conscious and properly informed people.

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