SIRCULAR

DELIVERABLE 1.4:

Health, IAQ and construction materials correlations report WP1

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OVERVIEW	
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Abbreviations and Acronyms

ACRONYM	DESCRIPTION
AgBB	Ausschuss zur gesundheitlichen Bewertung von Bauprodukten
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CARB	California Air Resources Board
CDPH	California Department of Public Health
CDW	Construction and Demolition Waste
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CEN/TS	European Technical Specification (developed by CEN)
CFD	Computational Fluid Dynamics
DfD	Design for Disassembly
DIBT	Deutsches Institut für Bautechnik
ECHA	European Chemicals Agency
EPD	Environmental Product Declaration

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EN	European Norm (Standard)
EU	European Union
FSC	Forest Stewardship Council
GWP	Global Warming Potential
HQ	Hazard Quotient
IAQ	Indoor Air Quality
IARC	International Agency for Research on Cancer
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCR	Lifetime Cancer Risk
LEED	Leadership in Energy and Environmental Design
MVHR	Mechanical Ventilation with Heat Recovery
PM	Particulate Matter
PM2.5 / PM10	Fine and coarse particulate matter (≤2.5µm / ≤10µm)
REACH	Registration, Evaluation, Authorization, and Restriction of Chemicals (EU regulation)
SCAQMD	South Coast Air Quality Management District
VOC	Volatile Organic Compounds
WELL	WELL Building Standard
WHO	World Health Organization

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Background: About the SIRCULAR project

SIRCULAR is coordinated by RINA-C and combines the expertise of 22 partners from six European countries, including universities, SMEs, NGOs, and industries. During the next three-and-a-half-years, SIRCULAR will transform the building sector into a circular and sustainable industry, aligned with the Built4People partnership principles.

We will test and demonstrate innovative technologies and services across four regional clusters: initially in Estonia and Spain, followed by Germany and Greece. These clusters will engage construction companies, housing companies, universities, and local administrative entities, focusing on buildings owned or occupied by vulnerable population groups, in line with the SIRCULAR just and affordable transition approach.

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Executive Summary

The SIRCULAR project aims to promote a circular and sustainable transformation of the building sector, aligning with the Built4People partnership principles. This deliverable provides a comprehensive assessment of the relationship between construction materials, indoor air quality (IAQ), and occupant health, with a particular focus on materials derived from Construction and Demolition Waste (CDW). The study establishes an evaluation framework integrating sustainability, health, and safety considerations while ensuring compliance with international IAQ standards. It addresses key challenges in sustainable construction, such as the impact of pollutant emissions from building materials, the role of ventilation and environmental factors, and the application of circular economy principles in material selection. The deliverable adopts a multi-criteria assessment framework that combines an extensive literature review on IAQ determinants and pollutant emissions, standardized testing protocols (e.g., EN ISO 16000, CEN/TS 16516) to evaluate material emissions, real-time IAQ monitoring in pilot buildings to validate laboratory findings, and the definition of Key Performance Indicators (KPIs) for material selection, ensuring compliance with health-focused construction standards. The findings highlight the complex interplay between construction materials and IAQ, emphasizing that CDW-based materials can be beneficial if properly processed, though residual contaminants and moisture-related degradation require careful management. Volatile Organic Compounds (VOCs), formaldehyde, and particulate matter (PM2.5/PM10) remain key pollutants, with emissions varying based on material composition and environmental factors. Moreover, ventilation and humidity control play a crucial role in mitigating IAQ risks, especially in airtight, energy-efficient buildings, while the European Union's regulatory framework provides essential guidelines, although additional standardization is necessary to support the large-scale adoption of circular materials. To ensure optimal IAQ and sustainability, the report suggests strengthening regulatory compliance and certification requirements for recycled materials, enhancing material testing methodologies to include long-term performance and emissions stability, promoting best practices in material selection based on climate-specific IAQ considerations, and encouraging further research on next-generation bio-based and low-emission materials. These findings support the broader objectives of the SIRCULAR project, contributing to healthier and more sustainable built environments while fostering circularity and decarbonization in the construction industry.

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1. Introduction

This deliverable provides a detailed analysis of Indoor Air Quality (IAQ) and its correlation with construction materials, particularly focusing on the impact recycled and Construction and Demolition Waste (CDW)-based materials proposed in SIRCULAR project have on occupants health. The study explores pollutants associated with these materials and their potential health effects, while also outlining key frameworks and indicators used for IAQ evaluation in the SIRCULAR project.

1.1 Objectives of the Deliverable

The objective of this deliverable is to provide a comprehensive assessment of the impact of construction materials, particularly those derived from CDW-based sources, on IAQ. The report aims to establish a structured evaluation framework that integrates sustainability, health, and safety considerations while ensuring compliance with existing IAQ standards and best practices. By identifying key pollutants emitted from construction materials, this deliverable will contribute to understanding their long-term effects on human health and building environments. A key aspect of this deliverable is the development of evaluation methodologies that assess IAQ performance. The study continues the review of existing frameworks and regulations started in D1.1 with the BREEAM and LEED frameworks, reviewing the WHO IAQ guidelines[1], EN ISO 16000 standards, CEN/TS 16516, and ASHRAE ventilation requirements, to provide a scientifically grounded basis for assessing the safety and viability of materials in sustainable construction. The deliverable also examines how different construction material properties, including emissions of volatile organic compounds (VOCs), formaldehyde, particulate matter, and other hazardous substances, impact IAQ. Furthermore, the deliverable suggests a set of Key Performance Indicators (KPIs) to measure the suitability of materials concerning IAQ. These indicators are classified into mandatory, recommended, and optional categories, ensuring a flexible but structured approach for material selection in various building contexts. This document is intended to provide stakeholders with clear guidelines for integrating IAQ

[1] https://www.who.int/publications/i/item/9789289041683

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considerations into sustainable construction practices. Ultimately, this deliverable serves as a valuable resource for industry professionals, policymakers, and researchers, offering insights into optimizing construction material choices to enhance IAQ while advancing circular economy principles. The findings will support the broader objectives of the SIRCULAR project, promoting healthier and more sustainable built environments.

1.2 Structure of the Document

The document is structured as follows:

- Introduction and Objectives, which outline the purpose of the deliverable, focusing on assessing the impact of construction materials, particularly recycled and CDW-based materials, on Indoor Air Quality (IAQ) and occupant health. It also defines the evaluation framework integrating sustainability, health, and safety considerations.
- Theoretical Background, which provides an overview of IAQ determinants, pollutants associated with construction materials, and their potential health impacts.
- SIRCULAR Construction Materials, describing the types, properties, and comparative analysis of recycled/CDW-based materials versus conventional ones in terms of IAQ impact.
- Guidelines and KPIs, which define key performance indicators for material selection, compliance with IAQ regulations, and recommendations for optimizing IAQ in sustainable buildings.
- Conclusions, summarizing key findings and proposing strategies for integrating IAQ considerations into circular construction practices.

1.3 Relation to Project Documents

D1.4 builds on the analysis performed in D1.1, particularly regarding the evaluation of IAQ frameworks and KPIs. D1.1 thoroughly examines IAQ frameworks such as BREEAM and LEED, which are also referenced in this deliverable. The document identifies key IAQ-related KPIs and methodologies for their assessment, which serve as a foundation for the evaluation methods presented in D1.4. Moreover, D1.1 discusses protocols and standards that influence the assessment of IAQ in sustainable

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building environments. The methodologies presented in D1.4 for assessing IAQ solutions in pilot projects are derived from these findings, reinforcing the integration of standardized evaluation criteria throughout the project.

This document is aslo directly linked to the development and validation of SIRCULAR materials, particularly through WP3 (SIRCULAR Materials and Solutions) and WP4 (Demo implementation).

As for the connection to WP3 SIRCULAR Materials and Solutions, WP3 focuses on the development, characterization, and optimization of innovative construction materials that integrate circularity principles and IAQ-enhancing properties. The key aspects covered include:

- Material Composition and Circularity: Evaluating recycled Construction and Demolition Waste (CDW)-based materials, bio-based alternatives, and hybrid solutions.
- Health and Environmental Performance: Ensuring materials meet IAQ standards, with a focus on VOC emissions, particulate matter release, and microbial resistance.
- Standardized Testing Protocols: Establishing methodologies to assess materials' thermal behavior, emissions, and long-term degradation under simulated environmental conditions.

The D1.4 framework provides the criteria and methodologies used in WP3 to evaluate and refine materials before their real-world application. It ensures that only materials meeting IAQ, sustainability, and durability requirements proceed to the demonstration phase.

The Demo Implementation phase (WP4) is where the materials developed and validated in WP3 are tested in real building environments to assess their practical performance. This phase focuses on:

- Deployment in Pilot Buildings: Integrating SIRCULAR materials into existing or newly constructed buildings to evaluate their actual impact on IAQ and occupant comfort.
- Long-Term Monitoring & Data Collection: Using sensors and IAQ measurement tools to track pollutant emissions, thermal behavior, and material interactions with indoor environments.
- Performance Validation: Comparing laboratory results (WP3) with real-world data to assess the effectiveness of the materials in improving indoor environmental quality while maintaining circularity and sustainability goals.

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The D1.4 document serves as a key reference for this phase, ensuring that the assessment methodologies developed for material evaluation are consistently applied both in controlled conditions (WP3) and real-world scenarios (WP4).

1.4 Overall Approach

The methodology employed involved a comprehensive and structured approach to assessing the impact of construction materials on Indoor Air Quality (IAQ) and occupant health. The process began with an extensive literature review to establish a theoretical foundation for understanding IAQ determinants and the pollutants associated with construction materials. This was followed by the development of a multi-criteria assessment framework, integrating sustainability, health, and safety considerations. Key Performance Indicators (KPIs) were defined to evaluate material composition, performance metrics, impact on IAQ, recycling and end-of-life considerations, and compliance with relevant certifications. The framework will be applied to SIRCULAR construction materials, through standardized testing protocols and real-time IAQ monitoring. Preliminary information was gathered from material developers to ensure the accuracy and relevance of the assessment. This deliverable serves as a valuable resource for stakeholders, offering insights into enhancing IAQ while advancing circular economy principles.

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2. Theoretical Background

This chapter will provide a comprehensive theoretical foundation for understanding Indoor Air Quality (IAQ) and its relationship with construction materials and occupant health. It will explore the key determinants of IAQ, the pollutants associated with building materials, and the potential health impacts of exposure. Special attention will be given to the role of recycled and Construction and Demolition Waste (CDW)-based materials, assessing their emissions and how they interact with environmental factors such as temperature, humidity, ventilation, and light exposure.

Additionally, the discussion will also cover existing European regulations and guidelines, ensuring that material selection aligns with sustainability and health priorities.

2.1 Understanding Indoor Air Quality (IAQ) and its determinants

IAQ refers to the condition of the air within buildings and structures, significantly influencing the health, comfort, and well-being of occupants. It is a complex and interdisciplinary field that involves environmental science, material science, chemistry, and human health studies. The assessment of IAQ extends beyond the simple measurement of pollutants; it requires an understanding of how chemical, biological, and physical factors interact within a built environment. IAQ is influenced by both endogenous sources (such as emissions from building materials and human activities) and exogenous sources (such as outdoor air pollution that infiltrates indoor spaces).

Given that individuals spend a substantial portion of their time indoors (approximately 90% of time), IAQ has become a critical focus area for environmental health and sustainable construction. Various factors, including building materials, ventilation systems, outdoor air infiltration, human activities, and the presence of pollutants, collectively determine IAQ. Poor IAQ is associated with well-being and a range of health issues, from short-term effects like headaches and allergic reactions to long-term consequences such as respiratory diseases, cardiovascular conditions, and cancer. Short-term effects include headaches, allergic reactions, and symptoms of Sick Building Syndrome (SBS), such as runny nose, dry throat, and fatigue. These symptoms can significantly impact an individual's well-being and

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productivity[2]. Long-term exposure to indoor air pollutants, however, poses more severe health risks. Respiratory diseases such as asthma and chronic obstructive pulmonary disease (COPD) are common outcomes of prolonged exposure to pollutants like particulate matter (PM), volatile organic compounds (VOCs), and microbial spores. Cardiovascular conditions, including heart disease and stroke, have also been linked to poor IAQ, as pollutants can enter the bloodstream and cause systemic inflammation and oxidative stress. Furthermore, certain indoor air pollutants have been associated with various cancers, including lung cancer and nasopharynx cancer[3,4] .

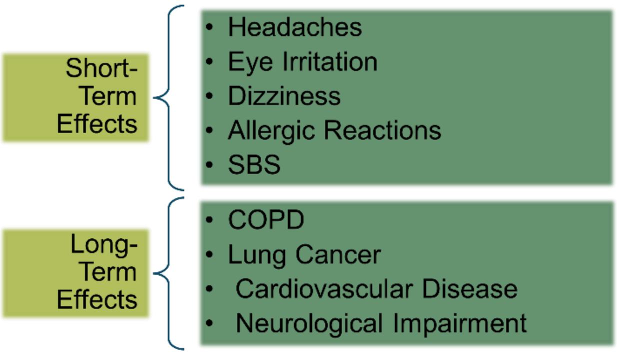

Figure 1- Most common Health effects of Poor IAQ Across Different Exposure Durations

Certain groups are particularly susceptible to the adverse effects of poor IAQ, these vulnerable populations include children, the elderly, and individuals with pre-existing health conditions. Children are more vulnerable due to their developing respiratory systems and higher breathing rates relative to their body size[5]. Exposure to toxic gases, PM, and volatile organic compounds (VOCs) can adversely affect their respiratory health, leading to conditions such as asthma, respiratory infections, and other

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[2] https://ec.europa.eu/health/opinions/en/indoor-air-pollution/index.htm
[3] Asikainen, A., Carrer, P., Kephalopoulos, S. et al. Reducing burden of disease from residential indoor air exposures in Europe (HEALTHVENT project). Environ Health 15 (Suppl 1), S35 (2016). https://doi.org/10.1186/s12940-016-0101-8
[4] Kumar, P., Singh A.B., et al. Critical review on emerging health effects associated with the indoor air quality and its sustainable management. Science of The Total Environment, Volume 872, 2023, 162163. https://doi.org/10.1016/j.scitotenv.2023.162163.
[5] Maung, T.Z.; Bishop, J.E.; Holt, E.; Turner, A.M.; Pfrang, C. Indoor Air Pollution and the Health of Vulnerable Groups: A Systematic Review Focused on Particulate Matter (PM), Volatile Organic Compounds (VOCs) and Their Effects on Children and People with Pre-Existing Lung Disease. Int. J. Environ. Res. Public Health 2022, 19, 8752. https://doi.org/10.3390/ijerph19148752

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respiratory diseases. Additionally, prenatal exposure to indoor air pollution can result in poor pregnancy outcomes, including low birth weight and preterm birth, which are significant risk factors for mortality and disability. Older adults are more likely to be affected by indoor air pollution due to their decreased mobility and the higher likelihood of having pre-existing health conditions. The elderly are particularly susceptible to cardiovascular and respiratory issues caused by pollutants such as PM, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). These pollutants can exacerbate conditions like COPD, heart disease, and stroke. Furthermore, the elderly may experience ocular problems, such as cataracts and glaucoma, due to prolonged exposure to indoor air pollutants[2]. People with pre-existing health conditions, such as asthma, cardiovascular diseases, and compromised immune systems, are at a higher risk of experiencing severe health effects from poor IAQ. Indoor air pollutants can trigger or worsen symptoms of these conditions, leading to increased hospital admissions and a higher likelihood of complications. For example, individuals with asthma may experience more frequent and severe asthma attacks when exposed to indoor allergens and pollutants[2]. Addressing IAQ is of paramount importance to protect these vulnerable populations as well as highlighting the need for effective interventions and policies to reduce indoor air pollution and its associated health risks.

One of the primary factors affecting IAQ is ventilation, adequate ventilation is crucial for maintaining optimal IAQ. It facilitates the exchange of indoor and outdoor air, thereby diluting indoor pollutants and controlling humidity levels. Insufficient ventilation can lead to the accumulation of contaminants, resulting in adverse health effects. A systematic review of studies conducted in European settings between 2013 and 2023 highlighted that inadequate ventilation is a prevalent issue, especially in educational institutions, leading to elevated concentrations of indoor pollutants[2,6]. Temperature and humidity are also integral components influencing IAQ. They affect the survival and proliferation of biological contaminants such as mold and bacteria. High humidity levels, in particular, create conducive environments for mold growth, which can release spores and mycotoxins into the air, posing health risks. Conversely, low humidity can cause respiratory discomfort and exacerbate

[6] Honan, David; Gallagher, John; Garvey, John; Littlewood, John (2024). Indoor air quality in naturally ventilated primary schools: A systematic review of the assessment & impacts of CO2 levels. University of Limerick. Journal contribution. https://doi.org/10.34961/researchrepository-ul.28151087.v1

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conditions like asthma. Maintaining indoor relative humidity between 30% and 50% is generally recommended to minimize these risks[7]. Chemical pollutants and biological contaminants should be also included for a proper evaluation. Chemical pollutants encompass a wide range of substances emitted from various sources within indoor environments. VOCs, for instance, are released from building materials, furnishings, cleaning agents, and combustion processes. Common VOCs include formaldehyde, benzene, and toluene, which can cause symptoms like eye, nose, and throat irritation dizziness, and headaches[8]. For instance, formaldehyde and benzene are recognized carcinogens; chronic exposure to these compounds can increase the risk of developing cancers, including leukemia and nasopharyngeal cancer[9]. Biological contaminants include mold, bacteria, viruses, pet dander, dust mites, and pollen. These organisms can trigger allergic reactions, respiratory issues, and other health problems. Damp and humid conditions, often resulting from inadequate ventilation or water leaks, promote the growth of mold and bacteria. Exposure to these biological contaminants has been associated with increased prevalence of respiratory symptoms, allergies, and asthma[10]. Mold testing in reused construction materials is a critical process to ensure the safety, durability, and sustainability of building projects. Furthermore, microbial pollution involves numerous species of bacteria and fungi that can perturb the immunological system[11]. Finally, PM refers to a mixture of solid particles and liquid droplets suspended in the air such as dust, fibers, and combustion-related particles that affect respiratory health. Indoor sources of PM include cooking, smoking, burning candles, and the use of fireplaces or wood-burning stoves. Fine particles, known as PM2.5, can penetrate deep into the respiratory tract, leading to health issues such as aggravated asthma, decreased lung function, and increased risk of cardiovascular diseases[12]. The European Environment Agency reported that in 2021,

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[7] https://epha.org/wp-content/uploads/2024/04/epha-towards-better-indoor-air-quality-in-the-european-residential-context-_-final.pdf
[8] https://iaqscience.lbl.gov/vocs-and-cancer
[9] Xiong, Y., Du, K. & Huang, Y. One-third of global population at cancer risk due to elevated volatile organic compounds levels. npj Clim Atmos Sci 7, 54 (2024). https://doi.org/10.1038/s41612-024-00598-1
[10] https://iris.who.int/handle/10665/164348
[11] WHO Guidelines for Indoor Air Quality: Dampness and Mould. Geneva: World Health Organization; 2009. 1, Introduction. Available from: https://www.ncbi.nlm.nih.gov/books/NBK143944/
[12] Juginović, A., Vuković, M., Aranza, I. et al. Health impacts of air pollution exposure from 1990 to 2019 in 43 European countries. Sci Rep 11, 22516 (2021). https://doi.org/10.1038/s41598-021-01802-5

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exposure to PM2.5 led to approximately 253,000 attributable deaths in EU Member States. Also building materials significantly influence IAQ through the emission of various pollutants. Materials such as paints, adhesives, sealants, and certain types of flooring can emit VOCs over time. The selection of low-emission materials is essential to minimize indoor air pollution[13]. A comprehensive review of European legislation emphasized the need for stringent regulations to control emissions from building materials, aiming to protect occupant health. Scientific approaches to studying IAQ can be categorized into experimental studies, epidemiological research, computational modeling, and real-time monitoring systems. These methodologies help establish correlations between airborne pollutants, environmental conditions, and health outcomes. Recent advancements in sensor technology, data analytics, and exposure assessment frameworks have provided deeper insights into IAQ and its impact on human well-being.

[13] Ruiz-Jimenez, J., Heiskanen, I., Tanskanen V. et al. Analysis of indoor air emissions: From building materials to biogenic and anthropogenic activities. Journal of Chromatography Open, 2, 100041 (20222). https://doi.org/10.1016/j.jcoa.2022.100041

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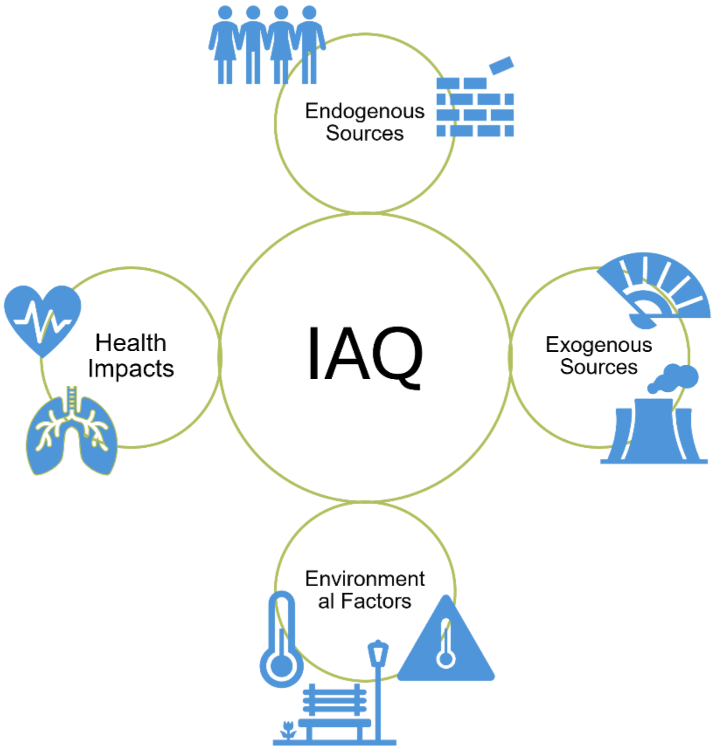

Figure 2- Key Determinants of Indoor Air Quality (IAQ)

In the European regulatory landscape, IAQ is governed by a range of standards and guidelines that include the World Health Organization (WHO) IAQ guidelines, European Norm (EN) standards (e.g., EN 16798-3 for ventilation), and ISO 16000 series for air sampling and indoor pollutant analysis. The integration of these regulations ensures that construction materials meet health and safety requirements, particularly in low-carbon and circular economy projects[14].

2.2 Overview of pollutants associated with construction materials

The construction industry plays a crucial role in shaping modern built environments, but, as anticipated in the previous paragraph, it also significantly influences indoor IAQ through the materials

[14] Settimo, G.; Manigrasso, M.; Avino, P. Indoor Air Quality: A Focus on the European Legislation and State-of-the-Art Research in Italy. Atmosphere 2020, 11, 370. https://doi.org/10.3390/atmos11040370

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it employs. The reuse of construction and demolition (C&D) materials is a cornerstone of sustainable construction practices. It helps reduce waste, conserve natural resources, and minimize the environmental impact of building projects. While the primary goal of construction materials is to provide durability, insulation, and aesthetic appeal, many materials unintentionally contribute to indoor pollution by releasing hazardous substances over time. These pollutants can originate from raw materials, chemical treatments, or degradation processes, affecting both short-term comfort and long-term health risks for occupants. As the demand for sustainable and energy-efficient buildings rises, industry is increasingly incorporating new materials, including recycled and bio-based alternatives. However, despite their ecological benefits, these materials can introduce new challenges related to pollutant emissions, such as residual VOCs or unexpected chemical interactions with indoor environments. Understanding the nature of these pollutants, their sources, and their effects on human health is essential for making informed material choices that balance sustainability with indoor environmental quality. To address these concerns, regulatory bodies such as the World Health Organization (WHO), the European Chemicals Agency (ECHA), and the International Organization for Standardization (ISO) have established guidelines to monitor and control emissions from construction products. Standards like EN ISO 16000 and CEN/TS 16516 provide frameworks for testing and evaluating material emissions, ensuring that building components contribute to safe and healthy indoor environments.

Materials can release various harmful substances, including:

- **Volatile Organic Compounds (VOCs):** VOCs originate from paints, adhesives, sealants, and composite wood products. Prolonged exposure to VOCs like benzene, toluene, and xylene can cause respiratory issues, neurological damage, and liver or kidney dysfunction (World Health Organization, 2022).
- **Formaldehyde:** This chemical is commonly found in pressed-wood products, insulation materials, and coatings. Recognized as a human carcinogen by the International Agency for Research on Cancer (IARC, 2020), formaldehyde exposure is linked to respiratory irritation and increased cancer risks.

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- **Particulate Matter (PM2.5 and PM10):** Construction dust, material degradation, and airborne particles contribute to indoor PM pollution, which can exacerbate lung diseases and cardiovascular conditions (European Environment Agency, 2023).
- **Heavy Metals (Lead, Cadmium, Mercury):** Some older paints, insulation materials, and plumbing systems contain heavy metals that can cause severe neurological disorders, particularly in children (European Chemicals Agency, 2023).
- **Radon:** A radioactive gas that naturally emanates from certain soils and construction materials, radon is one of the leading causes of lung cancer in Europe (European Commission, 2022).
- **Carbon Monoxide (CO) and Nitrogen Dioxide (NO2):** These gases are produced from combustion-based heating systems and can result in dizziness, cognitive impairment, and severe respiratory issues (ASHRAE, 2023).
- **Mold:** Reused construction materials, such as wood, drywall, and insulation, are often exposed to moisture during their lifecycle, making them susceptible to mold growth. Mold can compromise indoor air quality, cause health issues, and weaken structural integrity. Mold damage in demolition construction materials requires careful handling to protect both human health and the environment. The most common mold species found on demolition construction materials include Aspergillus, Penicillium, Cladosporium, Stachybotrys chartarum, Alternaria, Chaetomium, and Fusarium. These molds thrive in damp, organic-rich environments and pose significant health risks. Proper identification, containment, and remediation are essential to mitigate these risks during demolition activities. Referencing guidelines from organizations like the EPA[15], OSHA[16], and IICRC[17] ensures compliance with best practices and regulations.

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[15] EPA Mold Remediation Guidelines
[16] OSHA Mold Safety
[17] IICRC S520 Standard

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Table 1- Health effects associated with pollutants

Pollutant	Common Sources	Health Effects
VOCs	Paints, adhesives	Respiratory issues, neurological effects
Formaldehyde	Pressed-wood, insulation	Carcinogenic, irritation
PM2.5/PM10	Construction dust	Lung disease, cardiovascular risk
Heavy Metals	Old paints, insulation	Neurological damage
Radon	Soil, building materials	Lung cancer risk
CO & NO2	Combustion appliances	Dizziness, respiratory issues
Mold	Reused construction materials (wood, drywall, and insulation)	Respiratory issues (particularly for individuals with asthma or weakened immune systems), allergic reactions

The interaction between construction materials and IAQ is studied using both direct and indirect assessment techniques. Direct techniques involve air sampling and chemical analysis, whereas indirect techniques rely on longitudinal health studies and exposure modeling. Understanding the behavior of pollutants within indoor environments is crucial for designing mitigation strategies.
Experimental studies on indoor pollutants from construction materials typically involve:

- Emission chamber testing: Small-scale environmental chambers are used to quantify the release of VOCs, formaldehyde, and particulate matter from building materials over time.
- Field monitoring studies: Real-world IAQ data is collected from residential and commercial buildings using sensor-based air monitoring (e.g., CO_2, PM2.5, and VOC detectors).
- Material degradation studies: The chemical breakdown of materials under different conditions (e.g., temperature fluctuations, humidity exposure) is examined to predict long-term emission trends.

These methods provide insights into the dynamic behavior of pollutants and how they are influenced by environmental factors such as ventilation rates, humidity, and occupant behavior.
Correlating IAQ with health risks involves a combination of epidemiological studies, which track health conditions in populations exposed to specific IAQ conditions, toxicological studies, which determine

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the dose-response relationship of pollutants and finally computational exposure modeling, which predicts human inhalation exposure using airflow dynamics simulations (e.g., CFD - Computational Fluid Dynamics models). Understanding these relationships is crucial for defining acceptable exposure limits for different pollutants, as established by EU directives such as REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) and the European Environmental Agency's IAQ recommendations.

2.3 The impact of recycled and CDW-based materials on IAQ and health

Construction and Demolition Waste (CDW) encompasses waste generated from construction, renovation, and demolition activities, including a variety of materials such as concrete, wood, glass, metals, plastics, and insulation. CDW represents a significant fraction of total waste production worldwide. In the European Union (EU), CDW accounts for approximately 25-30% of all waste generated, making it one of the largest waste streams in the region (European Commission, 2023). Given the environmental footprint of CDW, its management, recycling, and safe reintegration into construction have become central to EU policies promoting sustainability and circular economy principles. Recognizing the need to reduce landfill waste and carbon emissions, the EU has implemented various directives and regulations aimed at encouraging CDW recycling and reuse. These include:

- The Waste Framework Directive (2008/98/EC): Establishes a hierarchy for waste management, prioritizing prevention, reuse, recycling, and recovery over disposal.
- The Construction Products Regulation (305/2011/EU): Ensures that recycled construction materials meet safety, performance, and environmental standards before being reintroduced into buildings.
- EU Green Deal & Circular Economy Action Plan: Aims to increase the use of secondary raw materials, setting a goal to recover and recycle at least 70% of CDW by weight.

While CDW-based materials offer substantial environmental benefits, such as reducing raw material extraction, energy consumption, and landfill waste, concerns remain regarding their impact on IAQ

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and occupant health. Unlike virgin materials, recycled materials may retain residual contaminants, alter air exchange properties, and degrade unpredictably over time. Potential IAQ issues with recycled materials concern:

- **Residual Contaminants:** Some recycled materials, particularly insulation panels and composite boards, may still contain VOCs, heavy metals, or microbial residues from prior use. Studies have shown that untreated recycled insulation boards can release toxic compounds (CEN/TS 16516, 2023).
- **Emission Rates:** The decomposition of recycled materials can alter their emissions of particulates and gases. Tests conducted on CDW-based concrete show increased formaldehyde emissions when exposed to high humidity levels (EU Construction Materials Report, 2023).
- **Chemical Interactions:** Some recycled materials react with indoor air elements, increasing pollutant concentrations. Research highlights that recycled gypsum board releases higher concentrations of sulfur compounds than virgin gypsum (ISO 16000-9, 2023).

Key research findings indicate that CDW-based materials can be safe if properly processed and tested under EN ISO 16000-9 and CEN/TS 16516.

While the emission of VOCs, particulate matter, and formaldehyde is a primary concern when using recycled and CDW-based materials, other environmental factors also play a crucial role in influencing indoor air quality (IAQ) and occupant health. Temperature and thermal stability are important considerations, as recycled materials often have different thermal properties compared to conventional materials, which can affect indoor temperatures. For instance, recycled concrete aggregates may exhibit altered thermal mass properties, impacting heat retention and overall indoor comfort. Additionally, high temperatures can accelerate the off-gassing of VOCs and other chemical emissions from recycled materials, increasing exposure risks. Ventilation and airflow are also critical, as the placement and composition of CDW-based materials can influence how air circulates within a building. Some recycled insulation materials, such as cellulose-based insulation, tend to trap more humidity than conventional alternatives, increasing the risk of mold growth. In poorly ventilated spaces, recycled materials that contain residual chemicals may contribute to a buildup of indoor pollutants, leading to prolonged exposure. Moisture and humidity control present another challenge,

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particularly with recycled materials derived from organic waste, such as wood, textiles, and paper, which often have higher moisture absorption rates. Excess humidity not only enhances pollutant emissions but also creates a favorable environment for microbial growth, including mold and bacteria, which further degrades IAQ. Light exposure can also affect material performance and IAQ. Certain CDW-based plastic composites degrade more rapidly under UV light, releasing microplastics or harmful degradation by products. Moreover, natural lighting can influence the behavior of some materials; for example, rubberized recycled materials used in flooring may release more VOCs when exposed to direct sunlight. Given these considerations, recycled materials must be evaluated not only for their pollutant emissions but also for their interactions with environmental factors such as temperature, humidity, ventilation, and light exposure. Without proper IAQ management, even low-emission recycled materials can contribute to poor indoor conditions if they trap moisture, overheat, or disrupt airflow patterns.

2.4 Relationship between construction materials, IAQ, and occupant health

The relationship between construction materials and indoor air quality (IAQ) is a critical factor in determining occupant health and well-being. Poor IAQ, often exacerbated by emissions from building materials, has been linked to a range of health issues, from short-term discomfort and irritation to long-term chronic diseases. Good indoor environment requires that indoor air issues are considered at all stages of design, construction, and operation. Part of this process is the use of low-emitting building materials and fixtures, which helps to achieve good indoor air quality. However, IAQ is influenced not only by the emissions of pollutants but also by environmental conditions, including temperature, humidity, ventilation, and light exposure, which can alter how pollutants behave within an indoor space.

Many building materials release volatile organic compounds (VOCs), formaldehyde, particulate matter (PM), and heavy metals, which can accumulate indoors, particularly in poorly ventilated environments. These chemical and particulate emissions are known to cause respiratory conditions, neurological effects, cardiovascular diseases, and even cancer. VOCs, commonly emitted from paints, adhesives, and composite wood products, have been associated with headaches, dizziness, and

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irritation of the respiratory tract[18]. In addition to chemical emissions, construction materials also interact with temperature and humidity, further influencing indoor air quality (IAQ). For example The Finnish M1 Emission Classification of Building Materials has successfully helped to improve indoor air quality for almost 30 years. The M1 Emission Classification, introduced in 1996, was created to promote the development and use of low-emitting building materials, fixed furniture, and office furniture. Recycled and CDW-based materials, such as cellulose insulation and reclaimed wood, often absorb and retain moisture, creating an ideal environment for mold and bacterial growth. High humidity levels can also accelerate chemical off-gassing, increasing the concentration of airborne pollutants, while low humidity can lead to respiratory system irritation, exacerbating conditions like asthma and allergies. To mitigate these risks, maintaining an indoor humidity level between 30-50% is recommended[19].

Ventilation and outdoor air change further determine how construction materials impact IAQ. Sealed surfaces and prefabricated insulation panels minimize uncontrolled airflow, preventing pollutants to infiltrate to indoor spaces. To counteract reduced airflow caused by certain material choices, mechanical ventilation systems must be guaranteed. EN 16798-1:2019 has replaced EN 15251 and it focuses on parameters at Indoor Climate Category I, II, III level – sometimes also level IV (level I is best, III / IV is worst) for thermal environment, indoor air quality, lighting and acoustics. The IICC II represents the normal expectations for new buildings and major renovations. The standard explains how to use these parameters for building system design and energy performance calculations.

Another key factor affecting IAQ is light exposure, which influences the way materials degrade and release emissions. Certain plastics and rubber composites break down under UV light, releasing microplastics or other harmful byproducts into the air. Additionally, some synthetic flooring materials emit increased levels of VOCs when exposed to direct sunlight, particularly in buildings featuring large glass facades or areas with high solar heat gain[20]. These combined factors highlight the need for a

[18]https://www.who.int/publications/i/item/9789240047693#:~:text=Pollutants%20for%20which%20new%20guidelines,lower%20than%20the%20previous%20guideline.
[19] https://www.ashrae.org/file%20library/technical%20resources/covid-19/i-p_s16_ch22humidifiers.pdf
[20] https://www.eea.europa.eu/publications/europes-air-quality-status-2023

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holistic approach to material selection, considering not only chemical composition but also environmental interactions to ensure a healthy indoor environment.

The combined effect of pollutant emissions and environmental factors directly contributes to various health conditions, categorized as respiratory, cardiovascular, neurological, and allergic disorders.

- **Respiratory Diseases:** Poor IAQ caused by VOCs, formaldehyde, and particulate matter increases the risk of asthma, bronchitis, and chronic obstructive pulmonary disease (COPD)[21].
- **Neurological Effects:** Long-term exposure to certain pollutants, such as benzene and formaldehyde, can cause headaches, fatigue, and cognitive impairment[22].
- **Cardiovascular Risks:** Research from the European Heart Journal (2023) indicates that fine particulate matter (PM2.5) is linked to increased risks of hypertension, heart disease, and stroke[23].
- **Allergic Reactions:** Biological contaminants such as mold, dust mites, and fungi commonly found in construction materials exacerbate allergies and skin irritations[24] (European Respiratory Society, 2023).

The health effects of IAQ pollutants are assessed using various frameworks that help quantify exposure risks and their potential long-term impact on human health. Hazard Quotient (HQ) and Lifetime Cancer Risk (LCR) calculations are commonly used to estimate long-term exposure risks by evaluating pollutant concentrations in relation to established safety thresholds. Additionally, building-occupant exposure models simulate the dose-response relationship of pollutants based on real-world activity patterns, allowing researchers to predict how different materials and environmental

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[21]https://www.eea.europa.eu/publications/status-of-air-quality-in-Europe-2022/europes-air-quality-status-2022/world-health-organization-who-air

[22] How Air Pollution Affects Our Brains | Harvard Magazine

[23] Liuzzo G., Volpe M., Weekly journal scan: every breath you take, air pollution impacts your cardiovascular health, *European Heart Journal*, Volume 45, Issue 24, 21 June 2024, Pages 2116–2118, https://doi.org/10.1093/eurheartj/ehae230

[24] Indoor environment: mould and dampness | European Environment Agency's home page

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conditions influence human exposure. Furthermore, advancements in wearable exposure sensors and bio-monitoring technologies enable real-time personal exposure assessments, providing more precise data on individual pollutant intake. By integrating these methodologies, researchers can establish evidence-based guidelines for selecting low-emission construction materials, ensuring that sustainable building projects prioritize both environmental and human health considerations. Moreover, the study of IAQ is rapidly evolving with technological advancements in sensor-based real-time monitoring, machine learning-based predictive modeling, and health-based material certification frameworks. Innovations in this field include IoT-enabled IAQ monitoring devices, which track pollutant levels in real-time and enable adaptive ventilation control to maintain optimal indoor air conditions. Additionally, AI-driven material selection tools use big data analytics to predict the IAQ performance of construction products, aiding in the selection of low-emission and health-conscious building materials. Another significant development is in bio-based material research, which explores natural antimicrobial and self-cleaning surfaces to reduce pollutant accumulation and microbial contamination. Looking ahead, future research will focus on developing a unified IAQ assessment framework that integrates environmental impact, health metrics, and material life cycle performance, ensuring that sustainable construction practices align with both environmental responsibility and human health priorities.

Table 2- Health Implications of Poor IAQ and Construction Material Emissions

Health Condition	Primary IAQ Factors	Common Construction-Related Pollutants	Aggravating Environmental Factors
Respiratory Diseases (Asthma, COPD, bronchitis)	Poor IAQ, exposure to airborne pollutants	VOCs, PM2.5, mold spores, formaldehyde	High humidity (mold growth), inadequate ventilation
Cardiovascular Conditions (Hypertension, heart disease, stroke)	Long-term exposure to fine particulates	PM2.5, nitrogen dioxide (NO_2), carbon monoxide (CO)	High temperatures (increases oxidative stress), poor air circulation
Neurological Effects (Headaches, cognitive impairment, fatigue)	Chemical exposure from off-gassing	Benzene, toluene, lead, heavy metals	Light exposure (UV degradation of plastics), extreme

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			temperatures (affects neurotoxins)
Allergic Reactions & Skin Irritation (Rhinitis, dermatitis)	Airborne biological contaminants	Dust mites, mold, formaldehyde, latex from building materials	Poor ventilation (allergen accumulation), high humidity

To mitigate these risks, the construction industry must prioritize good heating and ventilation systems and materials that are low-emission and compliant with health-focused building standards, such as BREEAM and LEED certifications and must adopt a range of mitigation strategies that combine material selection with environmental control measures to ensure optimal indoor conditions. These strategies will be further discussed in Chapter 4.

IAQ is a crucial determinant of occupant health in sustainable construction. While recycled and CDW-based materials present significant environmental benefits, they also pose risks that must be carefully managed. The correlation between poor IAQ and respiratory, neurological, and cardiovascular diseases underscores the need for stringent material selection, rigorous emissions testing, and proactive air quality monitoring. Future advancements in material science and green construction practices will play a pivotal role in mitigating these risks while fostering a more sustainable built environment.

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3. SIRCULAR Construction Materials: Types and Properties

3.1 Overview of SIRCULAR construction materials and technologies

The SIRCULAR project is dedicated to the transformation of the building sector through the development and implementation of circular and sustainable construction materials and technologies. The initiative aims to reduce the carbon footprint of buildings by integrating recycled and repurposed materials while ensuring optimal IAQ and compliance with sustainability standards. The selection of materials is driven by key considerations, including durability, energy efficiency, recyclability, and environmental impact and the work is still ongoing in WP3.

One of the core principles of SIRCULAR is the prefabrication of renovation components, enabling the use of industrialized methods to minimize waste and maximize efficiency. The project ensures a reduction in onsite construction time, labor requirements, and disruption for building occupants by focusing on prefabricated offsite solutions. This approach also enhances material reuse, reducing reliance on virgin resources. Prefabrication and modularity are particularly important in deep renovation projects targeting cold climate regions, where energy efficiency plays a critical role in achieving carbon neutrality.

SIRCULAR prioritizes the use of low-carbon materials, emphasizing the incorporation of CDW into new building components. Innovative materials are explored such as bio-based insulation, low-carbon concrete, and repurposed timber, ensuring that each material meets the necessary performance criteria in terms of structural integrity, thermal insulation, and IAQ considerations. In line with the circular economy principles, SIRCULAR materials are designed for recyclability and ease of disassembly at the end of their lifecycle. This ensures that buildings are not only sustainable during their operational phase but also contribute to long-term resource efficiency when they reach the end of their lifespan. Moreover, IAQ is a key factor in material selection, ensuring that low-emission and non-toxic materials are prioritized to create healthier indoor environments.

To evaluate and optimize the performance of these materials, SIRCULAR applies a multi-criteria assessment framework that includes:

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- **Material Composition & Intended Application**: Detailed analysis of material components and their intended function.
- **Performance Metrics**: Evaluation of thermal efficiency, durability, and environmental impact.
- **Impact on IAQ**: Assessment of emissions, including volatile organic compounds (VOCs) and other pollutants.
- **Recycling & End-of-Life Considerations**: Analysis of circularity aspects, including recyclability and disposal strategies.
- **Certifications & Compliance**: Consideration of relevant sustainability and health certifications.

These criteria serve as a foundation for selecting and refining materials within the SIRCULAR project, ensuring alignment with European sustainability policies and construction standards. Below is an in-depth look the key materials and entire solutions that are being developed within SIRCULAR.

Please note that the material solutions are still not in their final release since the project is currently at M10, and some changes could occur during the project lifetime. Indeed, as we are still in the early stages, it has not been possible to have a complete overview of the proposed solutions for each pilot, which is why some are described in more detail than others. Additionally, modifications may also occur during the project for the materials described in the following chapters.

3.2 Prefabricated offsite circular deep renovation solution incorporating reused elements for in cold climate region

The Estonian demo project uses modern timber frame facade elements that cover the building facade without removing previously installed layers. The layers included in the element are:

1. 8mm cement fiberboard Swisspearl Patina;
2. 13mm mineral wool wind barrier board
3. 45x195mm C24 timber frame, 600mm pitch
4. Between it 150mm ISOVER Standard mineral wool (λ_d =0.035 W/m²K)

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5. air and vapor barrier membrane

6. 50mm compensation wool ISOVER Standard (λ_d =0.040 W/m²K)

In addition, the element has PVC windows (including insect screens, vapor and wind barrier tape, water sheeting under the window, sheet metal above the window). There is a ventilation pipe between the layers of the element, which connects the exhaust from the kitchens and the supply to the rooms.

Material Composition & Intended Application:

- **Swisspearl Patina fiber cement board (8mm):** Swisspearl Patina is a high-tech cement fiberboard with natural minerals, the surface of which is coated with a colored mass paint, which ensures long-term protection against weathering. The board is largely made of recycled and local materials (minimizing the transport footprint). In addition, the cellulose fibers contained in the cement come from responsibly managed forests. Thermal conductivity (λ-value): Swisspearl Patina has a relatively low thermal conductivity, typically λ = 0.32 W/m·K, depending on the thickness. This helps to reduce heat loss and heat management problems. Moisture conductivity: As it is a cement fiber material, it is quite resistant to moisture, but not completely moisture-proof. The material does not absorb moisture, but at the same time its moisture conductivity is moderate, which means it can manage the risk of mold and condensation. Strength and durability: Cement fiberboard is extremely resistant to weather conditions, UV radiation, mold and corrosion. It is perfect for exterior cladding and can withstand various mechanical loads.
- **Mineral wool wind barrier plate (13mm):** Mineral wool is a non-flammable, lightweight and flexible insulation material with very good thermal insulation properties. Thermal conductivity (λ-value): Mineral wool has a thermal conductivity of λ = 0.036 W/m·K, which means that it provides excellent thermal insulation and helps maintain the energy efficiency of the building. Moisture conductivity: Mineral wool is a relatively good moisture conductor, which helps prevent excessive moisture accumulation in insulation materials, while it is important to keep moisture-sensitive materials dry. Product: Paroc WAB 10t. Rigid and thin wind barrier board. Belongs to fire reaction class A1 and has a long-term water permeability rating (Wlp) ≤ 3

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kg/m². The fire resistance properties of stone wool do not change over time. The Eurofire class of the product depends on the organic content of the product. The insulation properties of stone wool do not change over time. Experience has shown that the fiber structure of the wool is permanent and the space between the fibers is filled only with the surrounding gas.

- **Wooden frame (45x195mm C24 timber, 600mm pitch)**: The wooden frame is made of C24 grade wood, which is a high-quality and strong building material. Strength and load-bearing capacity: C24 grade wood is strong and can withstand heavy loads, making it ideal for framing. The wooden frame provides the necessary support and structure for the wall, ensuring long-term stability. Moisture conductivity: Wood is a natural material with average moisture conductivity, but it can also absorb and release moisture, thereby ensuring a healthy indoor climate. Heavy-grade S2S C24 wood: The C in the classification indicates that it is coniferous wood and the number 24 refers to the strength class. Since 2007, wood used in construction has been required to carry the CE mark, which is also guaranteed for the product we use. S2S indicates that both sides of the wooden element have been processed
- **Isover STANDARD mineral wool (200mm, λ = 0.035 W/m·K):** Isover mineral wool is a thermal insulation material with very low thermal conductivity and excellent fire resistance. Thermal conductivity (λ-value): Isover Standard mineral wool has a λ-value of 0.035 W/m·K, which ensures high insulation performance. With this layer, we can effectively reduce heat loss. Moisture conductivity: Mineral wool has moderate moisture conductivity, helping to keep materials dry and prevent mold growth.
- **Air-and vapor barrier film (0.2mm):** Air- and vapor barrier film is a synthetic film that prevents moisture from moving into insulation layers to prevent condensation and moisture problems. Moisture conductivity: Since the vapor barrier film is specially designed to prevent moisture movement, its moisture conductivity is practically zero. The water vapor permeability of this product is 100*1 g/m 2 /24h. The vapor resistance value is 0.2*20m.
- **Compensation wool Isover Standard (50mm, λ = 0.04 W/m·K)**: Compensation wool fills the gaps between the insulation layers and provides additional insulation. Thermal conductivity (λ-value): Compensation wool is an insulation material with a λ-value of 0.04 W/m·K. This provides additional insulation and helps maintain a high level of energy efficiency.

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- **PVC windows (triple glazing, U-value 0.9 W/(m²·K)):** PVC windows are made of high-quality PVC, which has excellent insulation properties. U-value: The average U-value of PVC windows is 0.92 $W/m^2 \cdot K$, which indicates that they offer good insulation. The window construction includes a triple glazing unit, which significantly reduces heat loss and ensures energy efficiency. Sun protection: PVC windows have a sun protection feature, where the glass has a G-value of at least 0.4, which helps reduce overheating of the indoor climate in summer.
- **Ventilation**: Zehnder ComfoTube Flat 51 is a flat plastic ventilation pipe with a height of only 51 mm. It is a flexible ventilation pipe that is very suitable for installation in tight spaces. The ComfoTube Flat 51 ventilation pipe has an antistatic dirt-repellent inner surface that reduces the accumulation of dust and dirt and allows for easy cleaning. ComfoTube Flat 51 ventilation pipe installation is easier and faster than alternative options. It is a ventilation system with a "Plug & Play" design that does not require metal processing or on-site sealing and insulation. Recommended air flow rate per ventilation pipe: <13 l/s

Performance Metrics:

Thermal insulation: All layers provide strong thermal insulation, especially mineral wool (λ = 0.035 W/m K) and the U-value of PVC windows of 0.9 W/m^2 K indicates low heat loss. The combination of materials gives the greatest effect as a whole.

Durability: All materials used in the element, including Swisspearl Patina cement fiberboard, mineral wool, wooden frame and PVC windows, are resistant to all kinds of mechanical loads, weather conditions and UV radiation. The wooden frame offers excellent mechanical strength (class C24), while the Swisspearl Patina board protects the building facade for a long time from sun, wind, rain and other factors, including the layers below it, such as wool, pipes, etc., which are less resistant to direct contact with the environment.

Moisture management: All layers (e.g. mineral wool, vapor barrier) are able to regulate moisture and ensure that the building structure remains dry and free from mold. This ensures a long life for the structure and protects the interior surfaces from the spread of mold. The ventilation system is securely located between the layers of the element to ensure a long life and protect against external influences.

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Impact on Indoor Air Quality:

All materials, including PVC windows, Swisspearl Patina cement fiberboard and mineral wool, have a very low content of volatile organic compounds (VOCs), which is safe for the environment. Mineral wool insulation ensures minimal heat loss and guarantees low heating costs. Sealing windows with vapor and wind barrier tape minimizes heat loss at joints, and ventilation ducts in the elements allow you to regulate the air quality in all apartments through fresh air valves and ceiling fans. Regulated air circulation in the room and minimal heat loss are the basis for a good indoor climate.

Recycling & End-of-Life Considerations:

The materials used in the element are all recyclable. For example, PVC windows are made into crushed stone in Estonia. Swisspearl Patina cement fiberboard is a long-lasting material with low maintenance requirements but can be suitably processed and reused. For example, in the construction of formwork, as fillers for foundations and drainage systems, because of crushing and screening for the production of new cement, for the production of composite materials. The use of Swisspearl products also has a positive impact on buildings that want to obtain the LEED label, which proves the sustainability and environmental friendliness of these materials.

The recycling of mineral wool is versatile: It is used to produce biofuels, as an insulation material in buildings with lower requirements, and in masonry, it is also mixed into the mixture as a filler.

Window flashings and pipes can be melted/cut and reprocessed and used to make new products. In short, all products can be recycled, thus guaranteeing an endless cycle.

3.3 Low-carbon precast insulated concrete façade panels with recycled material

Hormipresa aims to develop a low-carbon concrete mix that meets the required characteristics for use in precast concrete manufacturing, ensuring sufficient early strength to allow prestressing and demolding within 12 to 16 hours. The new concrete mix will be used initially for manufacturing reinforced concrete elements, such as bearing walls, cladding, and columns, in standard precast structures. These elements do not require as much strength as prestressed ones.

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Material Composition & Intended Application:

In this initial stage, the new concrete mix will be used exclusively for manufacturing reinforced concrete elements, which do not require as much strength as prestressed ones. These include bearing walls, cladding, and columns, which can be used in standard precast structures without any further considerations. This decarbonized mix will be achieved by incorporating the following raw materials:

- **Cement with partial clinker substitution (~20%)**

Early strength requirements significantly limit the use of cement with a clinker substitution higher than 10%. However, Hormipresa aims to push these limits by testing new cements available on the market that can meet the required performance. In this case, CEM II-B/V-L is used, where clinker is partially replaced by fly ash (V) and limestone (L).

- **Internally recycled aggregates**

Concrete manufacturing generates systematic concrete waste, which can be crushed and reused as aggregate for new concrete. These recycled aggregates, sourced from mid-to-high strength concrete (+50 MPa), are suitable for significantly replacing natural aggregate. In this initial stage, only coarse aggregate will be replaced, with up to 50% substitution.

- **Carbonated aggregates**

The recycled aggregates mentioned above have the potential to sequester CO_2 through carbonation. Since they are primarily composed of crushed concrete, the calcium oxide in the cement paste can react with CO_2, forming calcium carbonate and thus permanently capturing the CO_2 in a solid state. Additionally, this process reduces the porosity of the carbonated aggregates, positively impacting concrete strength.

- **Polypropylene fiber reinforcement**

The goal is to replace as much steel reinforcement as possible. Steel is susceptible to corrosion, which compromises concrete durability.

- **Next-generation admixtures**

The aim is to minimize water consumption. This can be achieved using superplasticizers that enhance concrete flowability while maintaining self-compacting properties despite the reduced water content.

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In parallel, UPC is developing a bio-based insulation material intended for use at the Spanish demo site. Its composition includes hemp shiv, recycled cardboard, and a vegetal coating (likely colophony).

Performance Metrics:

Two key environmental characteristics of the new concrete mix will be evaluated:

- **Durability:** This property can be assessed either experimentally—through chloride penetration (EN 12390-11) and water penetration (EN 12390-8)—or numerically, using a model proposed by Spanish regulations. The goal is to achieve a service life of over 50 years.
- **Global Warming Potential (GWP):** GWP will be measured through an Environmental Product Declaration (EPD).
- **Thermal efficiency** will be responsibility of the recycled bio-based insulation developed at UPC. The initial tests suggest that the thermal conductivity of the insulation material ranges between 0.03 and 0.04 W/m K. In an accelerated durability test, the material was exposed to ambient conditions for two years and showed no degradation of its properties. A life cycle analysis will be conducted in the project using the final composition, but initial studies indicate significant potential for a lower environmental footprint compared to commercial materials such as rockwool

Impact on Indoor Air Quality:

Concrete, in general, does not affect indoor air quality. Hormipresa never uses aggregates containing silicon, ensuring that concrete elements can be drilled and cut safely. As for the material developed by UPC, it has zero impact on indoor air quality. However, if the coating is not applied correctly, ambient moisture may lead to fungal growth.

Recycling & End-of-Life Considerations:

This concrete will be 100% recyclable. Whenever possible, structural elements will be designed for disassembly, allowing them to be either relocated or crushed for use as aggregates in future concrete. While UPC material can be recycled up to 90%.

Certifications & Compliance:

A Life Cycle Assessment (LCA) will be conducted as part of the project framework. Moreover, it is planned to certificate the thermal efficiency of the material and ITEC will produce a life cycle analysis.

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3.4 Innovative prefabricated circular renovation components

NTUA is developing a low TRL universal prefabricated module based on steel and aluminum. The module will be designed but not constructed within the project. Two different sizes will be tested:

The materials used for the smaller unit (i.e., 0.44 by 0.44) will be:

1. Aluminum Thermal broken profile;
2. EPDM EXPANDED 601-SPONGE (λd=0.055W/mK);
3. Nomatec closed cells LDPE foam profile (λd=0.038W/mK);
4. Socket screw type ISO4762 TX type C;
5. Allen Screw EX-7629651901 ALLEN 5,5x19 A2;
6. Siga airtightness hygrobryd membrane – Majrex200 (sd: 0.8-35);
7. Knauf - NaturBoard VENTACUSTO Mineral Wool (λd=0.034W/mK);
8. Knauf - AQUAPANEL® Cement Board Thermobase 8.

The materials used for the larger unit (i.e 2m by 3m) will be:

1. Steel 12mm (Steel rod – w=0.89kg/m);
2. Rowmat board as thermal brake between system and wall connection (λd=0.033W/mK);
3. Siga airtightness hygrobryd membrane – Majrex200 (sd: 0.8-35);
4. Knauf - NaturBoard VENTACUSTO Mineral Wool (λd=0.034W/mK);
5. MVHR – Wolf CWL-2 (size depending on the building);
6. Pipework inside the system DIN75 – Wolf antibacterial;
7. Windows – Uf < 1W/m2K, Ug < 0.6W/m2K, g – depending on the study;
8. Airtightness membranes between window and wall – Siga Fentrim;
9. Knauf - AQUAPANEL® Cement Board Thermobase 8.

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In addition, the element has PVC windows (including insect screens, vapor and wind barrier tape, water sheeting under the window, sheet metal above the window). There is a ventilation pipe between the layers of the element, which connects the exhaust from the kitchens and the supply to the rooms.

Material Composition & Intended Application:

- **Steel or Aluminum as structural elements (variety of geometry)**

Material: Steel and Aluminum produced locally provide a variety of options regarding craftmanship from local manufacturers. There is an important difference between these materials in cost and weight. Aluminum profiles are more expensive, lighter but cannot exceed a specific depth (i.e., more than 10cm of insulation) as a panel because it is designed to carry windows or door panels. Steel can be treated differently and according to the geometry and the design will be the main structural material for the larger unit. According to the needs the construction can change the depth (i.e., from 10cm to 30cm of insulation) keeping the same structure and the same 2D size (i.e., 2m by 3m)

Maintenance and Durability: Aluminum offers superior corrosion resistance compared to steel, which may require protective coatings or treatments to prevent rust. This inherent resistance can result in lower maintenance costs over the module's lifespan when using aluminum

Weight: Steel is significantly heavier than aluminum, with a density of 7.85 g/cm^3 compared to aluminum's 2.7 g/cm^3. This means aluminum is nearly three times lighter than steel for the same volume. In a prefabricated insulation module, choosing aluminum can reduce overall weight, making transportation and installation easier. However, steel offers higher strength and durability, which may be necessary for load-bearing structures. The choice between the two depends on the balance between weight, strength, and cost efficiency for the specific application

- **NaturBoard VENTACUSTO Mineral Wool**

Material: Mineral wool is a non-flammable, lightweight, and flexible insulation material with excellent thermal and acoustic properties.

Thermal Conductivity (λ-value): With a thermal conductivity of 0.034 W/m·K, mineral wool provides high energy efficiency by minimizing heat transfer and maintaining indoor temperature stability.

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Moisture Conductivity: Mineral wool has good moisture conductivity, helping to prevent excessive moisture accumulation while allowing vapor permeability, which protects moisture-sensitive materials and reduces the risk of condensation.

- **Siga Majrex200**

Material: SIGA Majrex 200 is a high-performance vapor control membrane made from a combination of polyethylene (PE) and polypropylene (PP), reinforced with PET fibers. This construction provides the membrane with exceptional strength and flexibility, making it suitable for a variety of building applications. Its durable composition ensures that it performs effectively in both residential and commercial environments, offering reliable protection against moisture infiltration.

Hygrobrid® Technology: The membrane is equipped with Hygrobrid® technology, which allows it to adjust its vapor permeability based on moisture direction. This unique feature enables the SIGA Majrex 200 to release internal moisture from the building while preventing external moisture from penetrating the structure. By regulating vapor flow, it helps maintain a dry, energy-efficient building envelope and prevents the accumulation of condensation or mold.

Performance: SIGA Majrex 200 offers a Moisture Vapor Transmission Rate (MVTR) ranging from 0.097 to 4.25 US perms, depending on environmental conditions and the direction of vapor flow. This dynamic vapor control capability makes it adaptable to various climates and construction needs, ensuring optimal performance in maintaining indoor air quality and protecting against moisture-related issues. Additionally, the membrane passes air barrier tests, contributing to enhanced airtightness in building assemblies.

Installation: The SIGA Majrex 200 is designed for easy and efficient installation. It is supplied in rolls measuring 1.5 meters wide and 50 meters long, making it convenient to cover large areas. The membrane's surface includes printed guidelines for precise cutting, and its flexibility ensures a smooth application without wrinkles. This ease of installation, combined with its high durability, allows contractors to achieve optimal results with minimal effort.

- **MVHR – Wolf CWL-2**

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Material: The Wolf CWL-2 is a central domestic ventilation unit designed to provide efficient and quiet air exchange in residential settings. Its compact design and advanced features make it suitable for various building sizes, with air handling rates ranging from 225 to 600 m^3/h, depending on the specific model chosen.

Heat Recovery Efficiency: Equipped with an enthalpy heat exchanger, the CWL-2 achieves a heat recovery rate of up to 95%, significantly reducing energy consumption by reclaiming heat from exhaust air to precondition incoming fresh air.

Performance: Designed for whisper-quiet operation, the CWL-2 ensures minimal noise disruption while supplying fresh, filtered air to the home. Its precise flow rate measurement system allows for optimal ventilation performance, adapting to the specific needs of the building.

Installation and Maintenance: The unit's compact size facilitates flexible installation options, fitting seamlessly into various residential spaces. Its design emphasizes ease of maintenance, with accessible components and straightforward servicing procedures to ensure long-term reliability and performance. Installation can be performed outside the thermal envelope and the pipework will be inside the prefab elements (larger unit).

- **Windows**

Material: Windows with $U_f < 1$ W/m^2K and $U_g < 0.6$ W/m^2K can be constructed using various frame materials, such as PVC, aluminum, fiberglass, or wood. Each material offers unique advantages depending on the specific needs of the building. PVC windows are widely known for their excellent thermal insulation properties and low maintenance requirements. Aluminum frames, while offering strength and durability, are often fitted with thermal breaks to improve insulation performance. Fiberglass windows are lightweight, strong, and highly energy-efficient, making them a great choice for both thermal and structural performance. Wood provides natural insulation and aesthetic appeal, offering a traditional look with solid thermal resistance when properly treated.

Thermal Performance: These windows achieve superior energy efficiency due to their high-performance thermal insulation properties. The Uf value of < 1 W/m^2K ensures that the window frame minimizes heat transfer, while the Ug value of < 0.6 W/m^2K ensures the glazing helps retain heat within the building. Combined, these values prevent heat loss during the winter and reduce heat gain during

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the summer, significantly improving the energy efficiency of the building. The g value (solar heat gain coefficient) is adjustable depending on the study or project needs, allowing customization to optimize solar heat gain.

Performance: These windows not only excel in thermal insulation but also offer soundproofing benefits and air tightness, contributing to an overall more comfortable and energy-efficient indoor environment. Whether using PVC, aluminum, fiberglass, or wood, each material offers its own benefits, from low-maintenance to aesthetic flexibility, while still delivering excellent thermal performance and durability. They also help reduce the need for artificial heating and cooling, lowering energy consumption and costs.

Installation and Maintenance: High-performance windows made from these materials require precise installation to ensure airtightness and prevent heat loss through gaps. Regular maintenance, such as checking the seals and cleaning the glass, will help maintain their efficiency. PVC and fiberglass windows are typically low-maintenance, while aluminum may require periodic care to ensure its thermal break performance, and wooden frames may need occasional treatment to prevent weathering, but all offer long-term benefits when properly maintained.

- **Knauf Aquapanel**

Material: Knauf AQUAPANEL® Cement Board Thermobase 8 is a high-performance cement-based insulation board designed for exterior use in construction. The board is ideal for use in both wet and dry areas, providing a stable and strong base for thermal insulation systems and external wall cladding. Its cement composition ensures it is non-combustible, making it a safe choice for a wide range of building applications.

Moisture Resistance: The board is specially designed to withstand high humidity environments, such as those found in external cladding applications or wet areas like bathrooms or kitchens. Its unique composition ensures it remains stable and resistant to mold and mildew growth, providing long-term durability even in challenging environmental conditions.

Installation and Maintenance: Knauf AQUAPANEL® Cement Board Thermobase 8 is designed for easy installation, with pre-marked edges and a lightweight structure for simple handling. It can be quickly fixed to a variety of substrates, ensuring a secure and reliable fit. The board's low-maintenance nature

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is another advantage; its cement core and moisture-resistant properties ensure that it remains durable over time with minimal upkeep. Regular cleaning and checking for any potential surface damage are sufficient to maintain its performance and integrity throughout the lifespan of the building.

Performance Metrics:

Thermal Efficiency: The prefabricated aluminum system is designed to achieve U-values between 0.20 and 0.09, ensuring high thermal efficiency. This allows for excellent insulation, reducing heat loss and improving energy performance. The system effectively maintains indoor comfort while minimizing the need for heating and cooling, leading to lower energy costs and improved environmental performance.

Durability: With its robust aluminum frame, the system offers exceptional strength and corrosion resistance, making it highly durable in various environmental conditions. Aluminum’s natural resistance to moisture, UV exposure, and temperature changes ensures the system maintains its structural integrity and insulation performance over time with minimal maintenance.

Moisture Control: The system is designed with built-in features to effectively manage moisture, preventing condensation and mold growth. This ensures that the insulation remains effective and energy-efficient while promoting a dry and healthy indoor environment.

Environmental Impact: The prefabricated aluminum system is designed with sustainability in mind, using recyclable materials such as aluminum, which can be 100% recycled without losing quality. In addition to the aluminum frame, the system incorporates eco-friendly insulation materials, chosen for their high performance and low environmental impact. These materials contribute to energy efficiency, helping reduce heating and cooling demands. The system also features smart connections that allow for easy disassembly, ensuring that all components, including insulation, can be reused or recycled at the end of their life cycle. This approach minimizes waste, reduces the need for new raw materials, and supports a circular economy by making the entire system more sustainable throughout its life.

Impact on Indoor Air Quality:

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The prefabricated aluminum system is designed with a strong focus on maintaining high indoor air quality. Integrated moisture control features, such as vapor barriers and precise sealing, prevent moisture accumulation within the walls, which helps to avoid issues like mold growth and condensation. The inclusion of a Mechanical Ventilation with Heat Recovery (MVHR) unit ensures that fresh, filtered air circulates throughout the building while retaining heat, promoting a continuous flow of clean air without introducing harmful pollutants or volatile organic compounds (VOCs). The system's design also eliminates thermal bridges, preventing cold spots where moisture can accumulate and mold can thrive. With excellent airtightness and effective moisture management, the system keeps the interior dry and healthy, reducing the risk of pollutants and ensuring a comfortable and sustainable living environment.

Recycling & End-of-Life Considerations:

The prefabricated metal system is designed for a circular lifecycle, focusing on recyclability and easy disposal. The aluminum frame is fully recyclable, allowing it to be reused in future applications without compromising material quality. The system features modular components and smart connections, which facilitate straightforward disassembly, making it easier to separate and recycle individual parts at the end of the building's life. Insulation materials used in the system are also chosen for their recyclability, reducing the amount of waste generated during demolition. This approach ensures minimal environmental impact, supporting sustainable building practices and a closed-loop system where materials are continually reused.

Certifications & Compliance:

The prefabricated metal system is aiming for Passivhaus component certification, ensuring it meets high standards of energy efficiency and thermal performance. The system is also developed to be in line with LEED and WELL certification requirements, focusing on sustainable materials, energy use, and indoor environmental quality. The materials selected for the system are chosen with these standards in mind, helping to reduce environmental impact and support healthier indoor spaces. By aligning with these certifications, the system is designed to contribute to more sustainable and energy-efficient building practices.

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3.5 Preliminary design studies on timber reuse with focus on sustainable deconstruction

The virtual demo case in Germany focuses on renovation solutions for building envelopes using reused timber, in line with the principles of circularity and non-destructive dismantling. The renovation strategy for the virtual demo building, a university building in Karlsruhe, will be developed by systematically comparing various approaches in a matrix to identify the optimal solutions.

Material Composition & Intended Application:

In this initial stage, the renovation will focus on integrating reused timber into the building envelope of the university building. The aim is to address several challenges associated with the reuse of timber, including adapting processing methods and equipment, certification issues, escaping the waste chain when harvesting timber, and managing wood preservatives. An innovative strategy for waste wood harvesting and processing will be developed within Task 3.3. Eventually, a detailed facade system will be designed for the renovation of the virtual demo building, incorporating reused timber to enhance its environmental sustainability.

Performance Metrics:

It is expected that the thermal insulation of the building will be improved through the renovation, but many different factors will be considered in order to determine the optimal balance between different aspects, like grey energy of the intervention, waste production, future energy savings, etc.

Impact on Indoor Air Quality:

The reuse of timber, especially timber that has been treated in the past, poses potential risks for indoor air quality. The main challenge here is the safe integration of formerly treated timber into the building envelope, as it may release volatile organic compounds (VOCs) or other pollutants if not managed properly. The research will focus on identifying and mitigating these risks to ensure a healthy indoor environment.

Recycling & End-of-Life Considerations:

The solution will be following the principles of circularity by incorporating reused material but also by anticipating further reuse. Connections will be designed to facilitate non-destructive dismantling,

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ensuring that components can be reused again at the end of their life cycle, contributing to the reduction of waste and promoting sustainable practices in construction.

Certifications & Compliance:

While no specific certifications are planned for the virtual demo, relevant aspects of certification systems will guide decisions throughout the project. These include adherence to sustainability standards, as well as technical approvals for the reuse of timber and the safety of the materials used.

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4. Guidelines for Enhancing IAQ Through Material Selection

This chapter provides comprehensive guidelines for selecting construction materials that optimize Indoor Air Quality (IAQ) and occupant health. Key performance indicators (KPIs) are outlined for evaluating the impact of construction materials on IAQ and health, including VOC emissions, formaldehyde levels, particulate matter, durability, and recyclability. Recommendations are provided for selecting materials to optimize IAQ, emphasizing the importance of certifications such as EU EcoLabel, FSC, GREENGUARD, LEED, and WELL. Best practices for material use in different building types and climates are discussed, highlighting the need for materials that prevent mold growth in humid climates and provide thermal insulation in cold climates. Strategies for integrating IAQ considerations into the design and construction process are presented, supported by international standards like ISO 16000, CEN/TS 16516, and WHO IAQ guidelines. By following these guidelines, stakeholders can ensure that construction materials contribute to healthier indoor environments while advancing circular economy principles,

4.1 Key performance indicators (KPIs) for evaluating construction materials' impact on IAQ and health

Valuation framework integrates KPIs across three categories to ensure balanced material selection. The proposed KPIs, in addition to those proposed in D1.1, provide a structured methodology for assessing materials based on their composition, performance, and environmental impact. The KPIs are categorized into mandatory, recommended, and optional criteria, ensuring a flexible yet comprehensive approach to material selection.

1. **VOC Emissions**

The measurement of VOC emissions from materials follows standardized protocols, such as CEN/TS 16516, to ensure compliance with indoor air quality (IAQ) requirements. To determine VOC emissions, materials are typically tested in controlled environmental chambers, where gas

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chromatography and mass spectrometry (GC-MS) analysis are used to quantify the concentration of emitted compounds. The threshold for compliance is set at <0.3 mg/m³ (reference defined in D1.1 has been kept), in line with EU standards for low-emission materials. However, accurately assessing VOC emissions can be complex, as direct chamber testing is often resource-intensive and may not always be feasible. In such cases, alternative approaches, including the use of conversion factors, may be applied to estimate emissions from other available data sources. These conversion factors enable the derivation of VOC values based on related parameters, such as material composition, known emission characteristics, or secondary data from similar tested materials.

$$VOC_{est} = \frac{EF \times A \times t}{ACH \times V}$$

Where:

- $VOC_{est,env}$ = Estimated VOC concentration in the air (mg/m³);
- EF = Emission Factor (µg/m²·h) from material tests or databases or literature data
- A = Exposed surface area of the material (m²);
- t = Duration of emission measurement or exposure time (h);
- ACH = Air changes per hour (1/h), based on ventilation in the pilot environment;
- V = Room or building volume where the material is installed (m³).

While this method can provide useful approximations, it requires careful validation to ensure reliability and consistency with chamber test results. Therefore, when calculating VOC emissions, it is recommended to consider both direct measurement techniques and scientifically validated estimation methods to achieve accurate and regulatory-compliant assessments.

2. **Formaldehyde Emissions**

The assessment of formaldehyde emissions from materials follows regulatory guidelines established by the WHO and European standards (EN 717-1), which set a threshold limit of <0.1 mg/m³. The standard methodology for measuring formaldehyde emissions involves chamber testing, where controlled environmental conditions are maintained, and the emitted formaldehyde is quantified using photometric or chromatographic analysis. In case direct chamber

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testing is not feasible e.g. when large-scale assessments or preliminary evaluations are required, alternative approaches can be applied to estimate formaldehyde emissions based on material properties, known emission characteristics, or secondary data from similar tested materials. In these cases the estimation of emissions is made using parameters such as resin content, wood composition, and historical emission data from comparable materials.

$$HCHO_{est} = \frac{Q \times A \times t}{V \times (1 + ACH \times t)}$$

Where:

- $HCHO_{est}$ = Estimated formaldehyde concentration in indoor air (mg/m³);
- Q = Formaldehyde emission rate of the material (µg/m²·h) based on emission characteristics of similar materials;
- A = Exposed surface area of the material (m²);
- t = Exposure time (h);
- ACH = Air changes per hour (1/h), based on ventilation in the pilot environment;
- V = Room or building volume (m³).

If you have the resin content in the material, you can look for specific data on the formaldehyde release rate (Q) for that type of material, you can find average emission rates in the literature. If this specific data is not available, the next step would be to estimate a value based on experiments or common trends for the material you are considering. Note that while this method can offer practical insights, their accuracy depends on the reliability of the input data and the appropriateness of the assumptions made.

3. **Particulate Matter (PM) Emissions**

Evaluation of particulate matter emissions, including PM2.5 and PM10, to prevent respiratory issues and other health risks. According to the European Union's air quality standards, the threshold values for PM emissions are set at PM2.5 < 25 µg/m³ and PM10 < 50 µg/m³. These standards aim to limit the concentration of fine particles that can penetrate deep into the

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respiratory system and cause long-term health issues. The most common method for measuring PM emissions involves gravimetric analysis, where particulate matter is collected on filters and then weighed, or using real-time particle counters, which directly measure the concentration of particles in the air. Alternative estimation approaches, in case it is not possible to perform direct measurements, may be applied. Calculation of PM emissions can be performed from other sources, based on material properties, known emission characteristics, or using data from similar tested materials.

$$PM_{est} = \frac{E \times t}{(1 + ACH \times t) \times V}$$

Where:

- PM_{est} = Estimated PM concentration in indoor air (μg/m³ or mg/m³);
- E = Emission rate of particulate matter from the source (μg/h);
- t = Exposure time (h);
- ACH = Air changes per hour (1/h), based on ventilation in the pilot environment;
- V = Room or building volume (m³).

If the emission rate E is not known directly, it can be estimated based on factors such as: emission rate per unit area (for building materials, furniture, carpets, etc.); specific activities (e.g., cooking, smoking, use of printers or photocopiers); experimental models or literature data.

4. **Mold growth**

Critical moisture level should be known. Knowing the critical moisture condition of the materials in a building envelope makes it possible to assess the risk of mould growth when exposed to moisture. Samples of the building materials can be inoculated with mold spores and incubated in climate chambers at different relative humidities and temperatures; the growth of mold will be analysed weekly for at least 12 weeks. If the critical moisture level for a material is not known, 75% RH is to be used.

Recommended KPIs

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1. **Moisture Absorption**

To measure this, ISO 12571 provides the standard protocol, with a commonly set threshold for moisture absorption of less than 5% by weight. The typical testing method is the hygroscopic sorption test, which involves measuring the amount of moisture a material can absorb under controlled humidity and temperature conditions. However, when considering the application of materials in a real-world environment, it may be difficult or impractical to conduct this test on all materials or during every phase of construction. In these cases, moisture absorption can be estimated using empirical formulas that derive from the material's known characteristics, such as its porosity and surface area, which directly affect moisture uptake.

$$Moisture = M_0\left(1 - e^{-k\cdot t}\right)$$

Where:

- $Moisture$ = Moisture content at time t (kg of moisture absorbed per kg of material);
- M_0 = Maximum moisture content the material can absorb at equilibrium (kg of moisture per kg of material);
- k = Absorption rate constant, which depends on material properties (1/h);
- t = Time of exposure (h).

2. **Thermal Efficiency**

Thermal insulation properties are typically assessed in accordance with EN ISO 6946, a standard that defines the methods for determining the thermal resistance and thermal transmittance of building components. The threshold for effective thermal insulation is typically set with a thermal conductivity value of less than 0.05 W/(m·K), as lower thermal conductivity ensures better insulation and energy efficiency. The most common measurement method is the heat flow meter method, which involves using specialized equipment to measure the heat transfer through a material under controlled conditions, enabling the calculation of its thermal conductivity.

$$\lambda = \frac{Q \cdot d}{A \cdot \Delta T}$$

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Where:

- $\lambda =$ Thermal conductivity (W/(m·K))
- $Q =$ Heat flow rate (W)
- $d =$ Thickness of the material (m)
- $A =$ = Area through which heat flows (m²)
- $\Delta T =$ = Temperature difference across the material (K or °C)

Optional KPIs

1. **Heavy Metal Content**

The evaluation of heavy metal content in construction materials is essential to prevent potential health and environmental risks associated with toxic elements such as lead (Pb), cadmium (Cd), and mercury (Hg). Regulatory guidelines, including EPA 3052 and ISO 11885, establish testing protocols and threshold limits for these metals to ensure compliance with safety standards. The acceptable concentrations are typically set at Pb < 0.01%, Cd < 0.001%, and Hg < 0.0005%.

The standard laboratory method for determining heavy metal content involves Inductively Coupled Plasma Mass Spectrometry (ICP-MS), which provides highly precise quantification. However, in a real pilot environment, direct laboratory testing may not always be feasible. Instead, alternative estimation approaches based on material properties, known contamination sources, and environmental exposure can be applied.

$$HeavyMetal_{est} = \frac{E_{PM} \times f_M \times t}{V \times (1 + ACH \times t) \times C_{PM}} \times 100$$

Where:

- $HeavyMetal_{est}$ = Estimated heavy metal content in the environment (%);
- $E_{PM} =$ Emission rate of particulate matter from the source (μg/h);
- $f_M =$ Fraction of the heavy metal in the particulate matter (from experimental data or literature, e.g., Pb = 0.1 - 1%);

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- t = Exposure time (h);
- V = Volume of the room or environment (m³)
- ACH = Air changes per hour.
- C_{PM} = Total concentration of particulate matter in the air (µg/m³).

If you know the emission source, you can find values for E_{PM} and $f_M$in scientific literature or from experimental measurements.

2. **Certifications and Compliance**

Ensuring that construction materials meet sustainability and health certifications is essential for verifying their environmental impact, safety, and overall performance. Certifications such as EU Ecolabel, LEED, or BREEAM provide standardized criteria to assess material sustainability, emissions, resource efficiency, and indoor air quality contributions. The evaluation process typically involves certification audits, where third-party assessors verify compliance with relevant standards. For further details on the suggested emission certifications, please refer to the table in Chapter 4.4.3.

$$Certifications = \sum_i Certification_i$$

Incorporating these KPIs and testing methods can ensure that the SIRCULAR project construction materials are selected and refined to optimize IAQ, enhance occupant health, and align with sustainability and circular economy principles.

4.2 Recommendations for selecting construction materials to optimize IAQ

When selecting building materials, to ensure good indoor air quality (IAQ), it is essential to consider several factors. In addition to what has already been discussed in this document, it is necessary to choose products certified for their sustainability and that comply with international safety standards. Below are some of the most relevant certifications/standards:

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1. **EU EcoLabel:** it identifies products and services that have a reduced environmental impact. EcoLabel certifications can vary by country, but generally cover broad categories of products, from building materials to cleaning products.
2. **FSC (Forest Stewardship Council):** for wood materials, this certification guarantees that the wood comes from sustainably managed forests, thus contributing to a greener supply chain and reducing environmental impact.
3. **GREENGUARD e GREENGUARD Gold:** these certifications evaluate indoor emissions of VOCs and other chemicals to ensure that materials are safe for indoor use. GREENGUARD Gold certification offers additional assurance, meeting even more stringent standards, especially relevant for vulnerable environments such as schools and daycares.
4. **EUROFINS GOLD:** guarantees that the products and construction materials used have low harmful emissions and formaldehyde quantities lower than 10 micrograms/m3.
5. **LEED (Leadership in Energy and Environmental Design):** this certification system recognizes buildings designed with sustainable practices and green materials. The materials used in LEED certified buildings must meet specific requirements regarding indoor air quality, as explained in the following paragraphs.
6. **BREEAM (Building Research Establishment Environmental Assessment Method):** similar to LEED, BREEAM evaluates the sustainable performance of buildings, including aspects related to IAQ. Using BREEAM certified materials can help achieve higher scores in the certification process.
7. **WELL Building Standard:** this certification focuses primarily on human well-being and the comfort of occupants inside a building. Indoor air quality is one of the main factors taken into consideration, and for this reason the WELL protocol includes specific requirements to reduce concentrations of VOCs and formaldehyde in built environments.
8. **ASHRAE 62.11010:** ventilation standard for acceptable Indoor Air Quality in residential buildings, which defines the physical and chemical parameters that ensure the well-being of the inhabitants

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9. **Cradle to Cradle Certified:** This certification evaluates the sustainability of materials based on various criteria, including safety for human health and the environment, circularity and responsible use of resources.

To optimize indoor air quality, it is therefore advisable to check that the materials chosen to have one or more of these certifications, thus ensuring that they have been tested and approved for indoor use. It is advisable to consult the product data sheets and speaking with suppliers can provide further information on the certifications and their relevance to the specific project.

4.3 Best practices for material use in different building types and climates

As previously stated, the choice of materials has an impact not only on energy efficiency and environmental sustainability, but also on the well-being of the occupants, especially regarding the quality of the air they breathe. It is therefore important in this context to consider various factors, including climatic characteristics, material properties and ventilation technologies.

1. **Material Selection Based on Climate**

   In buildings located in humid climates, such as coastal or tropical areas, materials must be chosen to prevent mold growth and bacterial proliferation. For instance, treated wood or breathable materials like porous concrete or natural stone are preferable, as they allow moisture regulation and reduce risks of condensation and microbial growth. The use of eco-friendly paints, free from VOCs, is essential to avoid the release of harmful chemicals into the air.

   In cold climates, the priority is thermal insulation, but without compromising indoor air quality. Materials like solid wood, natural fibers (such as cellulose fiber), or insulation based on hemp and coconut fiber are excellent choices for maintaining energy efficiency while avoiding toxic emissions. In these environments, ventilation is particularly important, as highly insulating materials can reduce natural airflow, increasing the risk of moisture buildup and the accumulation of pollutants. The adoption of mechanical ventilation systems with heat recovery (MVHR) is essential for ensuring proper air quality.

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In warm climates, it is fundamental to select low-emitting materials resistant to ultraviolet (UV) radiation for preserving their integrity and appearance in warm contexts. For instance, teak wood and slate ensure that structures and surfaces remain durable and visually appealing in sunny climates and low-emitting UV-Protective Paints formulated with UV-resistant compounds can protect surfaces from sun damage, maintaining color and preventing degradation.

2. **Low-Impact and Non-Toxic Materials**

Regardless of the climate, selecting materials with low VOC emissions is crucial to prevent indoor air pollution. Also, non-toxic materials do not release harmful chemicals into the air. Hypoallergenic materials reduce the risk of allergic reactions and are particularly important for individuals with sensitivities. The use of natural materials such as untreated wood, cork, stone, bamboo, or hemp is highly recommended, as these materials are not only biodegradable and environmentally friendly but also contribute to better indoor air quality due to their humidity-regulating properties and resistance to pathogen growth.

3. **Importance of Ventilation and Humidity Control**

Alongside material selection, ventilation and moisture safety are critical aspects. In this regard, advanced technologies such as mechanical ventilation with heat recovery (MVHR), which filters the air and controls humidity levels, are particularly effective. Additionally, materials with hygroscopic properties, such as stone and wood, help maintain a balanced humidity level in the indoor environment, preventing excessive dryness or condensation buildup.

4. **Materials and Design for Occupant Health**

The integration of natural materials with advanced technologies can significantly improve indoor air quality and the health of building occupants. For example, in residential or educational buildings, the use of non-toxic materials that encourage breathability is essential for long-term health protection. The incorporation of plants and biofiltration systems in the indoor environment, alongside materials that naturally regulate air quality, such as wooden panels or terracotta tiles, can further enhance air quality and create healthier spaces.

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Ultimately, in any building, careful design that combines natural, low-impact materials with efficient ventilation systems can make a significant difference in creating healthy and comfortable spaces, minimizing health risks associated with indoor air quality.

4.4 Strategies for integrating IAQ considerations into the design and construction process

Integrating IAQ considerations into the design and construction process has become a critical priority for ensuring healthy and comfortable environments for building occupants. Effective strategies for incorporating IAQ throughout the lifecycle of a building must be supported by **international standards** and **guidelines** that define minimum requirements and best practices. Among the key reference standards are ISO 16000, CEN/TS 16516, and the World Health Organization (WHO) IAQ Guidelines, which are described below.

4.4.1 International standards

ISO 16000

The ISO 16000 series is a set of international standards developed by the International Organization for Standardization (ISO) that focuses on indoor air quality. These standards provide guidelines for the measurement and analysis of various pollutants in indoor environments, with the primary goal of ensuring the health and well-being of people in buildings. The quality of indoor air is a key factor in preventing respiratory issues, allergies, and other health problems, especially in spaces like homes, offices, schools, and healthcare facilities.

The ISO 16000 series is divided into several parts, each dealing with specific aspects of indoor air quality. These parts provide detailed methods for sampling and analyzing pollutants, as well as guidelines for interpreting results. Some of the key sections include:

1. **ISO 16000-1:** General principles and guidelines for measuring indoor air quality. It outlines the procedures for sampling and analyzing indoor air pollutants and defines terms and conditions related to indoor air quality.

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2. **ISO 16000-2:** Formaldehyde is a chemical compound that can be present in indoor air at elevated concentrations due to building materials, furniture, and cleaning products. This section describes the measurement methods for formaldehyde in indoor air, which is a critical contaminant to monitor, especially in residential and commercial spaces.
3. **ISO 16000-3:** Focuses on measuring VOCs in indoor air. VOCs are a wide range of chemical substances that can be released from building materials, furniture, paints, cleaning products, and other sources. The presence of VOCs in indoor air is often linked to Sick Building Syndrome (SBS), which can cause symptoms like headaches, fatigue, and respiratory irritation.
4. **ISO 16000-4:** This part provides guidelines for air sampling for chemical analysis, detailing how to collect representative air samples for various pollutants, including VOCs, formaldehyde, carbon monoxide, ozone, and others. Proper sampling is essential for obtaining accurate and reproducible results.
5. **ISO 16000-5:** Ozone is another pollutant that may be present in indoor environments, especially in spaces with air conditioning or ventilation systems. This section outlines methods for measuring ozone, which can be harmful to health at high concentrations.
6. **ISO 16000-6:** This part deals with the microbiological quality of indoor air, including the measurement of bacteria, mold, and other microorganisms that can proliferate in damp or poorly ventilated environments. These microorganisms can cause allergies, respiratory issues, and other health problems.
7. **ISO 16000-9:** This section provides detailed methods for sampling and analyzing formaldehyde in indoor air. As a known irritant and potential carcinogen, measuring formaldehyde is critical to ensure levels remain within safe limits.
8. **ISO 16000-11:** Radon is a naturally occurring radioactive gas that can seep into buildings from the ground. It is a known carcinogen, and measuring its concentration in indoor air is essential, especially in areas where radon levels are higher. This section focuses on the methods for measuring radon.

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The primary objective of ISO 16000 is to protect human health and improve well-being in indoor environments by regulating the quality of indoor air. The standards provide a scientific framework for measuring and assessing indoor air pollutants, which helps organizations ensure that their spaces are safe and healthy for occupants. They are also used to guide decisions about ventilation, air purification, and overall indoor environmental management.

The ISO 16000 series cover several pollutants that are commonly found in indoor air, including:

- **Volatile Organic Compounds (VOCs):** these include substances like benzene, toluene, xylene, and others that can be released from paints, adhesives, building materials, furniture, and industrial processes.
- **Formaldehyde:** a well-known irritant for the respiratory system and a potential carcinogen.
- **Ozone:** while beneficial in the upper atmosphere, ozone at ground level can be harmful to human health.
- **Particulate matter:** Fine particles that may be emitted from smoke, cooking, or combustion processes in indoor environments.
- **Bacteria and mold:** microorganisms that can grow in poorly ventilated or damp areas and contribute to health problems such as allergies and respiratory infections.
- **Radon:** a radioactive gas that can enter buildings from the soil and is associated with an increased risk of lung cancer.

The ISO 16000 standards are used by various professionals for a range of purposes:

- **Public health professionals:** to monitor and evaluate the impact of indoor air quality on human health.
- **Architects and building engineers:** to design and manage buildings that promote good indoor air quality and ensure proper ventilation.
- **Manufacturers and industry stakeholders:** to ensure that materials and products on the market do not emit harmful pollutants into indoor air.
- **Regulatory authorities:** to establish exposure limits and environmental regulations concerning indoor air pollutants.

CEN/TS 16516

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It is a technical specification developed by the European Committee for Standardization (CEN) that provides guidelines for the measurement of volatile substance emissions from building materials and indoor products, such as paints, flooring, furniture, and other components used in buildings. The standard primarily focuses on the emissions of volatile organic compounds (VOCs) and formaldehyde, both of which are known to impact indoor air quality and human health.

The main goal of this standard is to ensure that materials used in buildings do not release hazardous substances into indoor air, especially those that can affect the health of people living or working in these spaces. Indoor air quality is a crucial factor for occupant well-being, and prolonged exposure to substances like formaldehyde or VOCs can cause respiratory problems, allergies, skin irritation, headaches, and in extreme cases, serious diseases such as cancer (in the case of formaldehyde). With the growing concern about health and sustainability, CEN/TS 16516 addresses the need to create safer indoor environments.

Details of the CEN/TS 16516 standard:

1. **Testing Methods for Emission Measurement**

   The standard defines methods to measure the emissions of volatile substances from building materials under controlled laboratory conditions. Key testing methods include:

- **Emission testing in chambers with controlled temperature and humidity**: Materials are tested in simulated environments that replicate indoor conditions, such as a room in a building. The chemicals released from the materials are monitored over time, with data collected on the concentrations of VOCs and formaldehyde.
- **Sampling and analysis techniques**: Sophisticated instruments like gas chromatographs and mass spectrometers are used to accurately measure the quantities of chemical compounds in the air. These techniques allow for precise identification and quantification of volatile substances emitted from materials.

2. **Substances Monitored by the Standard**

   The standard specifically focuses on two major categories of substances:

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- **Volatile Organic Compounds (VOCs)**: VOCs include a wide range of chemical substances, such as benzene, toluene, xylene, acetone, and others. These can be released from paints, adhesives, building materials, flooring, furniture, and other products. VOCs are known to cause irritation of the respiratory system, skin, and eyes, and they can also have neurotoxic effects with prolonged exposure.
- **Formaldehyde**: Formaldehyde is a highly irritating substance classified as a carcinogen. It is commonly released by building materials like pressed wood panels, MDF, paints, adhesives, and other products. It is particularly concerning indoor environments, where it can accumulate and reach harmful concentrations.

3. **Emission Limits and Material Classification**

CEN/TS 16516 not only defines testing methods but also sets emission limits for volatile substances in building materials. These limits are designed to ensure that concentrations of harmful substances in indoor air do not exceed levels that could compromise the health of occupants. Materials that exceed these limits are considered unsafe for indoor use.

Furthermore, the standard provides a classification system for materials based on the amount of volatile substances they emit. This classification system helps consumers and industry professionals choose low-emission materials, thereby improving indoor air quality.

4. **Applications and Regulatory Relevance**

This standard is relevant to several sectors:

- **Construction Industry**: Manufacturers of building materials, flooring, furniture, and interior finishes must comply with this standard to ensure their products do not release harmful levels of volatile substances. Compliance with CEN/TS 16516 is essential for achieving quality certification and meeting European safety and health regulations.
- **Regulatory Authorities**: Local and national authorities can use CEN/TS 16516 as a basis to establish exposure limits for emissions from building materials and to create more precise regulations regarding indoor air quality.

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- **Designers and Architects**: Architects and designers can use this standard to select low-emission materials when designing new buildings or during renovations. This helps improve indoor air quality and reduce health risks for occupants.
- **Public Health Sector**: Indoor air quality is a key element of public health. By adhering to CEN/TS 16516, the risks of respiratory diseases, allergies, and other illnesses related to indoor air pollution can be minimized.

CEN/TS 16516 is crucial because it ensures that building materials and indoor products do not release hazardous chemicals into the air, improving the quality of life and health of those who live and work in buildings. As the focus on health and sustainability increases, this standard responds to the need for creating safer indoor environments.

Additionally, compliance with CEN/TS 16516 is increasingly required by European and international regulations that aim to create safer and healthier indoor environments. This has led many companies to seek quality certification for their products in response to the needs of consumers and building professionals.

WHO IAQ guidelines

The World Health Organization (WHO) guidelines for indoor air quality have been developed to address the importance of air quality in enclosed spaces and reduce exposure to pollutants that can harm human health. Indoor air can contain a variety of contaminants originating from internal sources, such as household activities, building materials, heating systems, ventilation systems, and even human behavior (e.g., smoking and cooking). The health effects resulting from poor indoor air quality include respiratory and cardiovascular diseases, eye and skin irritation, and even neuropsychiatric disorders.

WHO's indoor air quality guidelines are based on scientific evidence and establish concentration limits for several pollutants. The main pollutants addressed are:

1. **Particulate Matter (PM):** Suspended particles, such as PM2.5 and PM10, are among the most harmful to human health. WHO recommends that PM2.5 concentrations in indoor environments should not exceed 10 µg/m³ as an annual average and 25 µg/m³ as a daily average.

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2. **Nitrogen Dioxide (NO_2):** This gas can irritate the airways and worsen conditions like asthma. WHO advises that NO_2 concentrations should remain below 40 µg/m³ for an annual average and below 200 µg/m³ for a one-hour average.

3. **Formaldehyde:** A volatile organic compound (VOC) that can cause eye, throat, and respiratory irritation. WHO recommends a maximum formaldehyde concentration of 0.1 mg/m³.

4. **Carbon Monoxide (CO):** A hazardous gas that can impair oxygen transport in the blood. CO concentration should not exceed 9 mg/m³ as an 8-hour average and 25 mg/m³ as a one-hour peak.

5. **Volatile Organic Compounds (VOCs):** Besides formaldehyde, various VOCs (such as benzene, toluene, and xylene) are harmful to health, and WHO recommends concentration limits for each of these in indoor environments.

Other key WHO recommendations include:

- **Ventilation:** Proper ventilation is essential to reduce the concentration of indoor pollutants. WHO suggests adopting adequate ventilation practices to ensure sufficient air exchange and prevent the buildup of harmful substances.
- **Control of pollution sources:** WHO advises reducing pollution sources such as cigarette smoke, fossil fuel combustion (e.g., stoves and fireplaces), and the use of chemical products containing VOCs (paints, cleaners, etc.).
- **Monitoring and managing air quality:** Regular monitoring of indoor air quality is crucial, particularly in sensitive environments such as schools, hospitals, and homes of vulnerable individuals (e.g., children and the elderly).

In summary, WHO's indoor air quality guidelines aim to protect public health by preventing exposure to atmospheric pollutants that can have harmful effects in both the short and long term. By promoting healthy indoor environments and implementing preventive measures, WHO seeks to reduce the health risks associated with indoor air quality.

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4.4.2 Guidelines

The growing attention to the environmental impact and indoor air quality of buildings has led to the adoption of energy-environmental certification protocols such as LEED (Leadership in Energy and Environmental Design) and WELL. These protocols aim to promote sustainability, health and well-being of building occupants by introducing rigorous criteria for the use of construction materials. Among the most critical factors for certification are emissions of volatile organic compounds (VOCs) and formaldehyde, chemicals known for their impact on human health and the environment.

This section explores the emission limits of VOCs and formaldehyde provided by the LEED and WELL protocols, analyzing how these standards influence the selection of construction materials and design practices.

The Tasks of LEED and WELL Protocols in Emissions Control

Both LEED and WELL certification protocols focus on improving the built environment, but with a slightly different approach. LEED focuses more on energy efficiency and the overall environmental impact of the building, while WELL places a particular emphasis on the well-being of the occupants. Specifically:

LEED (Leadership in Energy and Environmental Design) is one of the most widely used certification systems for sustainable buildings. It considers various aspects related to construction, energy efficiency and environmental impact. In terms of VOC emissions, LEED promotes the use of low-emitting materials by establishing specific limits for VOCs and formaldehyde in certain building materials. The goal of these guidelines is to reduce indoor air pollution and help improve air quality, which is essential for the comfort and health of occupants.

The WELL Building Standard is instead a certification that focuses primarily on human well-being and the comfort of occupants inside a building. Indoor air quality is one of the main factors taken into consideration, and for this reason the WELL protocol includes specific requirements to reduce concentrations of VOCs and formaldehyde in built environments. For example, the WELL system promotes the use of materials that do not release harmful chemical compounds, including VOCs, and establishes stringent limits for formaldehyde, with the aim of creating healthy indoor environments.

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LEED Guidelines for Low-Emitting Materials

LEED specifies VOC and formaldehyde emission limits for several building materials, such as paints, sealants, adhesives, flooring, and siding. LEED prohibits the following guidelines:

- **VOCs (Volatile Organic Compounds)**: LEED requires that materials used meet certain VOC emission limits to prevent indoor pollution and improve air quality. VOC emission limits vary by material type, and are defined for different product categories, such as paints, sealants, and adhesives. For example, for sealants and adhesives, LEED requires that products do not exceed 50 g/l of VOC (grams per liter), a value that is further reduced based on the specific material categories. This goal is intended to minimize VOC emission in the early years of the building's life, when indoor concentration levels are highest.
- **Formaldehyde**: for this material, LEED provides a specific set of limits for wood-based materials, which commonly contain formaldehyde in the form of resins. Wood materials, such as plywood and medium-density fiberboard (MDF), must meet specific formaldehyde emission standards, typically less than 0.05 ppm (parts per million) to receive the Indoor Air Quality credit. This standard aligns with the Environmental Protection Agency (EPA) and European guidelines for limiting formaldehyde emissions.

To demonstrate compliance of a product or layer with the emission limits, the following requirements must be met, as applicable.

Inherently Non-Emitting Sources: products that inherently do not emit VOCs (stone, ceramic, powder-coated metals, anodized or chrome-plated metal, glass, concrete, clay brick, and untreated or untreated hardwood flooring) are considered compliant in the absence of VOC emission testing unless they include organic coatings, binders, or sealants.

General Emissions Assessment: construction products shall be tested and assessed in accordance with the California Department of Public Health Standard Method v1.1–2010 (CDPH Standard Method v1.1 2010), using the exposure scenario for the specific case. The reference scenario is a private office. The manufacturer or third-party certification shall indicate the exposure scenario used to determine compliance. Declarations of compliance for freshly applied products shall indicate the amount applied by mass per surface area.

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The above manufacturer's declarations of conformity shall also indicate the range of total VOCs after 14 days (336 hours), measured according to CDPH Standard Method v1.1:

- 0,5 mg/m3 or less
- between 0.5 and 5.0 mg/m3
- 5,0 mg/m3 or more

Projects outside the United States may use products that have been tested and found to be compliant with CDPH Standard Method 2010 or German AgBB Test and Evaluation Methodology 2010.

Products must be tested in accordance with the following standards: CDPH Standard Method 2010, AgBB Test and Evaluation Methodology 2010, or ISO 16000-3: 2010, ISO 16000-6: 2011, ISO 16000-9: 2006, ISO 16000-11:2006 or in conjunction with AgBB, or in accordance with French VOC emission class labeling legislation, or (4) DIBt Test Method 2010. If the test method used does not provide specific details for a product group covered by the CDPH Standard Method, use the specifications in the CDPH Standard Method.

Additional Requirements for VOC Content in Wet-Applied Products: in addition to meeting the general requirements for VOC emissions above, for the health of installers and other workers exposed to them, wet-applied products must not contain excessive levels of VOCs. To demonstrate compliance, a product or finish must meet the requirements below, as applicable. The VOC content must be declared by the manufacturer. All laboratory testing must follow the test methodology required by applicable regulations.

- All wet-applied paints and coatings on site must meet the VOC limits set forth in the California Air Resources Board (CARB) guidelines, Suggested Control Measure (SCM) for Architectural Coatings, 2007, or the South Coast Air Quality Management District (SCAQMD) Rule 1113 effective June 3, 2011.
- All wet-applied, on-site adhesives and sealants must meet the chemical content requirements of SCAQMD Rule 1168, dated July 1, 2005, Adhesive and Sealant Applications, tested using the method specified in Rule 1168. This rule does not apply to adhesives and sealants subject to state or federal regulations for VOC emissions limits for consumer products.

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- For projects outside the United States, all wet-applied, on-site paints, coatings, adhesives and sealants must meet the technical requirements of the above regulations or comply with applicable local VOC regulations, such as the European Directive 2004/42/EC "Decopaint", the Canadian VOC Concentration Limits for Architectural Coatings, or the Hong Kong Air Pollution Control (VOC) Regulation.
- If applicable regulations exclude exempt compounds, any exempt compound content intentionally added in amounts greater than 1% by weight by mass (total exempt compounds) must be declared.
- If a product cannot be tested as specified above, the VOC content assessment must be in accordance with ASTM D2369-10; ISO 11890 Part 1; ASTM D6886-03; or ISO 11890-2.
- For projects in North America, methylene chloride and perchloroethylene must not be intentionally added to paints, coatings, adhesives, or sealants.

Composite Wood Products Compliance: composite wood, as defined by the CARB Airborne Toxic Measure to Reduce Formaldehyde Emissions from Composite Wood Products, must have low formaldehyde emissions per CARB requirements for ultra-low-formaldehyde emitting (ULEF) resins or no formaldehyde added.

Reclaimed or reused woodwork older than one year at the time of occupancy is considered compliant, provided it meets all requirements for site-applied paints, coatings, adhesives, and sealants.

Testing standards

- *CDPH Standard Method v1.1*

  The "California Department of Public Health (CDPH) Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environmental Chambers, v. 1.1–2010" is used for the **emissions testing and requirements of all products and materials except furniture**. The method, widely recognized as a leadership standard for its stringent scientific criteria and detailed specificity, was developed through an open, consensus process. It uses the chronic reference exposure levels established by the California Office of Environmental Health Hazard Assessment, which include some of the most stringent

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criteria in use. It also adopted and incorporated the first edition of the ANSI/BIFMA M7.1 standard test method for furniture.

There is no **total volatile organic compound** (TVOC) pass-fail requirement in the CDPH standard, which focuses on measuring and limiting individual VOCs. However, this credit requires manufacturers using the CDPH standard to also disclose the range of TVOC for each product, a requirement intended to provide greater transparency for project teams, especially when they are comparing similar materials. Though TVOC alone is a crude measurement not suitable for health-based determinations of acceptability, it is useful as a general indicator in combination with individual VOC measurements, since higher TVOC may suggest the need for additional investigation.

- *CARB ATCM composite wood formaldehyde regulation*

  The "California Air Resources Board (CARB) 93120 Airborne Toxic Control Measure (ATCM) for formaldehyde emissions from composite wood products" provides a way to determine the **compliance of composite wood materials** used in products not covered by full VOC testing in other categories. CARB 93120 ATCM is required in California but widely used internationally.

  LEED doesn't use the minimum requirements of the CARB 93120 ATCM but the more stringent requirements for ultra-low-emitting formaldehyde (ULEF) resins or no added formaldehyde-based resins, as defined in the CARB ATCM. These criteria are some of the strongest available for formaldehyde emissions from composite wood.

  Although composite wood compliance with the CARB formaldehyde criteria is beneficial, chamber testing for a broader range of individual VOCs emitted from assembled products that include composite wood in combination with other components can provide a better determination of a product's potential effect on indoor air quality.

  Therefore, the composite wood criteria of this credit do not apply to composite wood covered by the full VOC testing of other categories.

- *ANSI/BIFMA standards*

  The second edition of the "ANSI/BIFMA M7.1–2011 Standard Test Method for Determining VOC Emissions from Office Furniture Systems, Components and Seating" incorporates important advances that include defining an emissions factor approach for compliance,

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refining the mathematical estimation procedures for no measured time points, and adding specific, highly detailed surface area calculation requirements to ensure consistency.

LEED also requires furniture to comply with the low-emitting requirements in the ANSI/BIFMA e3–2011 Furniture Sustainability Standard. This standard includes both the historical VOC emissions requirements for furniture from earlier versions of LEED and the health-based requirements from the 2010 version of the CDPH standard, both as concentration limits and as maximum emissions factors. These emissions factor limits effectively increase the stringency of the standard and make it easier for furniture component suppliers to modify their products for compliance.

- *International standards*

  Recognizing the need for additional compliance options for projects outside the U.S., this credit also references select international standards, which can be used only under specific conditions because of the complicated nature of air quality standards.

The German AgBB Testing and Evaluation Scheme (2010) is a leading industry standard that can be used for this credit, with some limitations. The AgBB standard does not represent a European consensus but does share common attributes with several European counterparts. It addresses six times more individual VOC requirements than the CDPH standard, and it specifies TVOC and total semivolatile organic compound (TSVOC) limits for all nonregulated substances. However, the standard has limitations, including the following:

- The formaldehyde limit value of 10 µg/m³ at 28 days must also be met when using the AgBB alternative, as specified for class A+ in French compulsory VOC emissions class labeling.
- The AgBB requirements use different exposure scenario conditions than CDPH. Because VOC emissions from building materials generally decrease over time, the point in time for determining compliance is critical. The more time there is for off-gassing to occur, the easier it may be to meet the standard, even though in many cases the difference is minor (most emissions decay within the first week). CDPH requires compliance at 14 days; the full AgBB requirements apply at three or 28 days, which this credit does not take into account.

Similarly, LEED allows the use of the ISO 16000 series standards when combined with the AgBB standard, the cited French legislation (Decree no 2011-321 and arrêté of 19 April 2011), or the DIBT

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method (German Institute for Building Technology, Principles of Health Assessment of Construction Products in Indoor Environments, 2010 dibt.de/de/ data/Aktuelles_Ref_II_4_6.pdf). The ISO 16000 series standards do not contain enough detail to be cited alone for testing in this credit. The same requirements for formaldehyde also apply in each of these cases.

For composite wood, LEED allows the use of EN-717-1, CEN/TS 16516 and the ISO 16000 series provided that a formaldehyde limit of 0.05 ppm (0.06 mg/m2-h when expressed as emission rate) is met. This is the same limit required to meet CARB ATCM requirements for ultra-low-emitting formaldehyde resins (ULEF). EN 717-1 was established by the Comité Européen de Normalisation (CEN) as a consistent standard for determining formaldehyde emissions from wood-based panels and is used primarily for assigning E1 and E2 classifications to wood products.

- *Referenced mass VOC regulatory standards*

  The U.S. regulatory system for adhesives and sealants captures a limited range of listed product categories and excludes small packages intended for consumer use. The leading CARB and SCAQMD regulations are well ahead of other state and national regulations. Historically, CARB has developed the suggested control measure (SCM) coatings regulatory framework later adopted by some U.S. states and Canada. SCAQMD created a widely cited regulatory system for sealants and adhesives packaged and designed for commercial applications.

LEED includes requirements for all product categories found in the referenced standards. Product categories that are not listed do not need to be tracked. The credit incorporates various district, state, and national regulations limiting the overall VOC content in coatings, sealants, and adhesives. These regulatory limits serve as a minimum requirement, in addition to emissions testing standards listed in the general emissions requirements.

Because of divergent regulatory development processes, the coatings categories, category definitions, and VOC limits vary between CARB SCM and SCAQMD Rule 1113. Suppliers should provide information on the proper categorization of their materials consistent with definitions in the referenced regulations.

For projects outside the U.S., existing national VOC regulations may serve as the credit requirement. The Canadian VOC Concentration Limits for Architectural Coatings and the Hong Kong Air Pollution

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Control (VOC) Regulation are examples of local regulations deemed equivalent to the CARB SCM and SCAQMD Rule 1113. Project teams should contact USGBC to determine additional equivalent regulations. Establishing parity or a direct comparison with cited U.S. regulations is difficult, given varying definitions of product categories, the VOC status of specific solvents, and varying applications of the less-water and exempt-solvent approaches.

Information on any VOC compounds exempt from regulation is required for credit compliance. Cited regulatory limits do not include the VOC content of colorants added to coatings at the point of sale. Pretinted flat, nonflat, industrial maintenance coatings and stains include the VOC content of all ingredients, including colorants.

WELL Guidelines for Low-Emitting Materials

The WELL Building Standard sets even more stringent limits than LEED for VOC and formaldehyde emissions, with a greater focus on the health and well-being of occupants. The WELL protocol, in its air quality section, sets specific limits for VOC and formaldehyde concentrations in building materials.

- **VOC**: WELL defines that VOC concentrations in indoor environments should not exceed certain limits. Specifically, the VOC concentration limit for indoor air is set at 500 µg/m³ for the sum of all VOCs (micrograms per cubic meter). This limit is considerably lower than the LEED standards, reflecting WELL's emphasis on occupant health. Additionally, WELL encourages the use of materials that emit minimal amounts of VOCs, such as low-solvent paints, certified low-emitting adhesives and sealants.
- **Formaldeide**: for formaldehyde, WELL imposes very strict limits. The concentration of formaldehyde in indoor air must not exceed 27 µg/m³ (micrograms per cubic meter), a value that is well below the limits required by international regulations. The WELL protocol also applies standards for building materials, encouraging the use of products with low formaldehyde emissions, such as those made with wood treated with low-emitting resins.

There are then other values to consider, reported in the table below.

Table 3- Gases Evaluated for the WELL Building Standard

CHEMICAL SUBSTANCE	LIMIT FOR PASSING TEST

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Formaldehyde	< 27 ppb
Total Volatile Organic Compounds	< 500 µg/m³
Carbon Monoxide	< 9 ppm
PM2.5	< 15 µg/m³
PM10	< 50 µg/m³
Ozone	< 51 ppb
Radon	< 50.148 Bq/L

The limit values of the Finnish M1 Emission Classification are based on (area) specific emission rate (SER). These classification criteria are presented in Table below.

Table 4 SER-based limit values of the M Classification for building materials and furniture[25].

Parameter	Emission Class M1	Emission Class M2
Total Volatile Organic Compounds (TVOC) Emissions [mg/m²h]	≤ 0.2	≤ 0.4
Emission of Volatile Compounds (VOC) [µg/m³]	≤ EU-LCI	≤ EU-LCI
Formaldehyde Emission [mg/m²h]	≤ 0.05	≤ 0.125
Ammonia Emission [mg/m²h]	≤ 0.03	≤ 0.06
Emissions of CMR compounds [mg/m³][26]	≤ 0.001	≤ 0.001
Odour[27]	acceptable	acceptable

1) excluding formaldehyde and acetaldehyde, 2) result of the sensory evaluation ≥ 0.0

[25] https://ymparisto.rakennustieto.fi/en/emission-classification-of-building-materials/emission-classification-of-building-materials-testing-and-classification-criteria
[26] excluding formaldehyde and acetaldehyde
[27] result of the sensory evaluation ≥ 0.0

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Newly installed interior wet-applied paints, coatings, adhesives, and sealants must meet the following:

1. All products are tested to meet methods and thresholds established in one of the following standards and/or regulations for VOC content:
   - SCAQMD Rule 1168 (Adhesives and Sealants, 2017),GB 33372-2020 (Adhesives),
   - 2019 CARB SCM for Architectural Coatings,
   - EU Ecolabel for indoor and outdoor paints and varnishes,
   - HJ 2537-2014 (Paints),
   - Any other compliance path listed in the 'VOC content evaluation' section of the 'Low-Emitting Materials' credit of the LEED v4.1 standard.
2. At least 75% of products (by surface area or volume) are tested by a third-party laboratory to meet testing methods and thresholds established in one of the following standards and/or regulations for VOC emissions:
   - California Department of Public Health (CDPH) Standard Method v1.2,
   - AgBB,
   - European Union LCI VOC thresholds following EN 16516-1:2017 testing methods,
   - Any compliance path accepted to meet the VOC emission requirements of the 'Low-Emitting Materials' credit of the LEED v4.1 standard.

Furniture, Architectural and Interior Products must be:

1. Tested per methods and VOC emission thresholds established in one of the following:
   - California Department of Public Health (CDPH) Standard Method v1.2,
   - AgBB,
   - European Union LCI VOC thresholds following EN 16516-1:2017 testing methods,
   - ANSI/BIFMA e3-2014, sections 7.6.1 or 7.6.2 (Furniture),
   - Any compliance path accepted to meet the VOC emission requirements of the 'Low-Emitting Materials' credit of the LEED v4.1 standard.

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2. Made exclusively with one or a combination of (without organic additives): metal (including powder-coated, plated and anodized materials), untreated wood and plant products, glass, ceramic, concrete or stone.
3. If custom-made or refurbished, wet-applied and wood-based materials used in fabrication or refurbishing meet the following:
   - All paints, coatings, sealants and adhesives applied to the product are verified as low-VOC emitting by one of the applicable standards listed in Part 1,
   - All composite wood panels, including medium-density fiberboard, plywood and particle wood panels meet the 'Formaldehyde emissions evaluation' criterium of the 'Low-Emitting Materials' credit of the LEED v4.1 standard, or meet one of the following: US EPA TSCA Title VI, Europe E1, Japan Four-star.
4. Installed for at least 6 months before enrollment or the start of subscription or manufactured and unmodified at least one year before enrollment or the start of subscription.

Implications for Building Materials Selection

LEED and WELL protocols significantly influence the selection of building materials, especially regarding indoor air quality. In fact, construction companies and designers must select certified products that comply with these limits to meet the certification criteria.

Certifications such as Greenguard or EcoLabel can facilitate the selection of materials that comply with the emission limits established by the LEED and WELL protocols. In addition, FSC (Forest Stewardship Council) certifications for wood ensure that wood-based materials are produced sustainably and with a minimum formaldehyde content.

The growing concern for the health and well-being of occupants, together with the need to reduce the environmental impact of buildings, has driven the adoption of certification protocols such as LEED and WELL. These standards set stringent limits for VOC and formaldehyde emissions in building materials, helping to create healthier and less polluted indoor environments. Using low-emitting materials, exposure to harmful chemicals can be significantly reduced, improving air quality and occupant comfort.

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Selecting building materials that meet LEED and WELL requirements is a key step in creating sustainable and healthy buildings that meet environmental and human well-being challenges.

Countries currently testing mold contamination of reused constructive materials

The testing of mold contamination in reused construction materials is a growing concern across various countries, particularly as the construction industry increasingly adopts sustainable practices by utilizing recycled materials. Recent research indicates that several countries are actively engaged in developing and implementing testing protocols for biological contamination, including mold. Below is a summary of countries currently involved in this area of research and testing, based on recent literature.

Table 5 Countries testing mold contamination of reused constructive materials

Country	Description
United States	The U.S. has a robust framework for assessing mold contamination in construction materials, primarily through standards set by organizations such as ASTM International. Research has highlighted the prevalence of airborne fungal spores during construction processes, indicating a need for thorough testing protocols to ensure indoor air quality and the safety of reused materials Gallon et al. (2020). The U.S. also emphasizes the importance of identifying specific mold species to inform remediation efforts, as seen in studies focusing on microbial contamination in various contexts. Key Initiatives: • ASTM Standards: ASTM D8219-22 guides microbial sampling for reused materials. EPA Guidelines: Promote mold testing in recycled drywall and wood for indoor air quality.

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European Union Countries	Many EU countries are actively involved in standardizing testing methods for mold contamination in reused construction materials. The European Commission has initiated various projects aimed at promoting circular economy practices, which include the reuse of construction materials. Research has pointed out the need for harmonized standards to facilitate the safe reuse of materials while addressing biological contamination risks (Anastasiades et al., 2021). Countries like Germany and the Netherlands have been at the forefront of developing guidelines for assessing mold resistance in construction materials, reflecting a strong commitment to sustainability and safety. Key Initiatives: • Circular Economy Action Plan (2020): Mandates microbial risk assessments for reused materials, including mold testing. Horizon 2020 Projects: Fund research on bio-contamination in recycled aggregates and timber (e.g., Spain's Life Reusing Posidonia project).
China	Key Initiatives: National Green Building Standards: Require mold screening in recycled concrete and bricks.
Nigeria	Research in Nigeria has highlighted the importance of assessing contaminated materials, particularly in the context of oil-contaminated soil. While this research primarily focuses on soil, the methodologies for evaluating contamination can be relevant for assessing mold in reused construction materials (Ezeokpube et al., 2022). The emphasis on environmental health and safety in

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	construction practices is becoming increasingly important in the region. Reference: Ezeokpube, G., Ahaneku, I., Alaneme, G., Attah, I., Etim, R., Olaiya, B., … & Udousoro, I. (2022). Assessment of mechanical properties of soil-lime-crude oil-contaminated soil blend using regression model for sustainable pavement foundation construction. Advances in Materials Science and Engineering, 2022, 1-18. https://doi.org/10.1155/2022/7207842
Australia	Australia has been proactive in addressing mold contamination in building materials, particularly in the context of public health. Research has shown that airborne mold spores can significantly impact indoor air quality during construction activities. This has led to the development of guidelines and standards for assessing and mitigating mold risks in reused materials. Key Initiatives: • National Construction Code (NCC): Recommends mold testing for reused materials in high-humidity zones. CSIRO Research: Tests reclaimed timber using FTIR spectroscopy to identify mycotoxins (Khalil et al., 2023).
Japan	Key Initiatives: Green Material Certification: Includes mold resistance tests for recycled concrete and steel slag.
Canada	Similar to the U.S., Canada has established guidelines for assessing mold contamination in building materials. The focus on indoor air quality and the health impacts of mold exposure has prompted research into effective testing methods for reused materials.

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	Canadian studies have also explored the relationship between construction practices and mold growth, emphasizing the need for rigorous testing protocols. Key Initiatives: • National Research Council (NRC): Investigates mold risks in recycled cellulose insulation. LEED Canada: Requires microbial testing for reused materials in certified projects.

4.4.3 Application to SIRCULAR solutions

Given that emission limits for materials depend on the type of substance emitted, the type of material, and the final use of the product, it is still possible to identify common limits associated with the most regulated substances due to their health impact according to the previously analyzed standards.

Considering the materials developed, described in paragraph 3, and the location of the DEMO, the guidelines reported in the following table have been selected for SIRCULAR solutions. Each of them reports thresholds for volatile organic compounds (VOCs) and formaldehyde emissions and can be observed to ensure good indoor air quality.

Table 6- Standard / Guidelines and limit values for SIRCULAR solutions

Standard / Guideline	Emissions tested	Limit values	Additional notes
CEN/TS 16516	VOCs	Defined limits depending on product type	Includes specific emissions for construction materials
WHO IAQ Guidelines	VOCs, Formaldehyde	Formaldehyde: <0.1 mg/m³; VOCs: No specific value, but aim to minimize	General guidance for indoor air quality, including health-based targets

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AgBB Test and Evaluation Methodology 2010	VOCs	Specific limits for substances like formaldehyde and TVOCs (e.g., total VOCs < 1 mg/m³)	Focus on low emissions of hazardous air pollutants (HAPs) from building products
French VOC Emission Class Labeling Legislation	VOCs	Class A+ to C (A+ being the best category, emissions < 10 µg/m³ for certain VOCs)	Specific to France, VOC emissions based on product type
DIBt Test Method 2010	VOCs, Formaldehyde	TVOC < 0.5 mg/m³ for certain materials, formaldehyde limit < 0.1 mg/m³	Used for construction and building materials in Germany
Suggested Control Measure (SCM) for Architectural Coatings (2007)	VOCs	VOC limits vary by product type (e.g., flat, non-flat) ranging from 50–150 g/L	Aims to reduce VOC emissions from paints and coatings
European Directive 2004/42/EC (Decopaint)	VOCs	Paints and varnishes: limits vary (e.g., decorative paints ≤ 130 g/L)	Focuses on VOC reduction in decorative paints
EU Ecolabel for Indoor and Outdoor Paints and Varnishes	VOCs, Toxic Emissions	TVOC ≤ 30 g/L for indoor paints, ≤ 75 g/L for outdoor paints	Ensures low environmental and health impact for paints

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5. Conclusion

This deliverable has provided a detailed assessment of the impact of construction materials on Indoor Air Quality (IAQ) and occupant health, with a focus on sustainable and circular solutions in the SIRCULAR project. The analysis confirms that material selection plays a fundamental role in determining IAQ, with key challenges related to pollutant emissions, moisture management, and ventilation efficiency. In particular, recycled and CDW-based materials present both opportunities and risks; while they reduce environmental impact, they can release VOCs, formaldehyde, and other pollutants if not properly treated. Additionally, the interaction between materials and environmental conditions, such as temperature, humidity, and ventilation, is crucial in defining long-term IAQ performance. Despite the current regulations and testing protocols providing a foundation for IAQ assessment, there is a need for further harmonization of standards to facilitate the widespread adoption of circular materials. To ensure a sustainable transition in the construction sector, this report recommends key actions including the standardization and certification of recycled materials through harmonized emission limits and expanded third-party certification schemes, the development of next-generation bio-based materials with enhanced IAQ performance, and the investigation of hybrid solutions that combine CDW-based components with low-emission additives. Furthermore, strengthening policy support and industry adoption through incentives for low-carbon and circular construction practices, as well as fostering knowledge-sharing platforms, will be essential in accelerating the shift towards a healthier and more sustainable built environment. By implementing these actions, the construction industry can align with circular economy principles, promoting healthier indoor environments while achieving climate neutrality goals.

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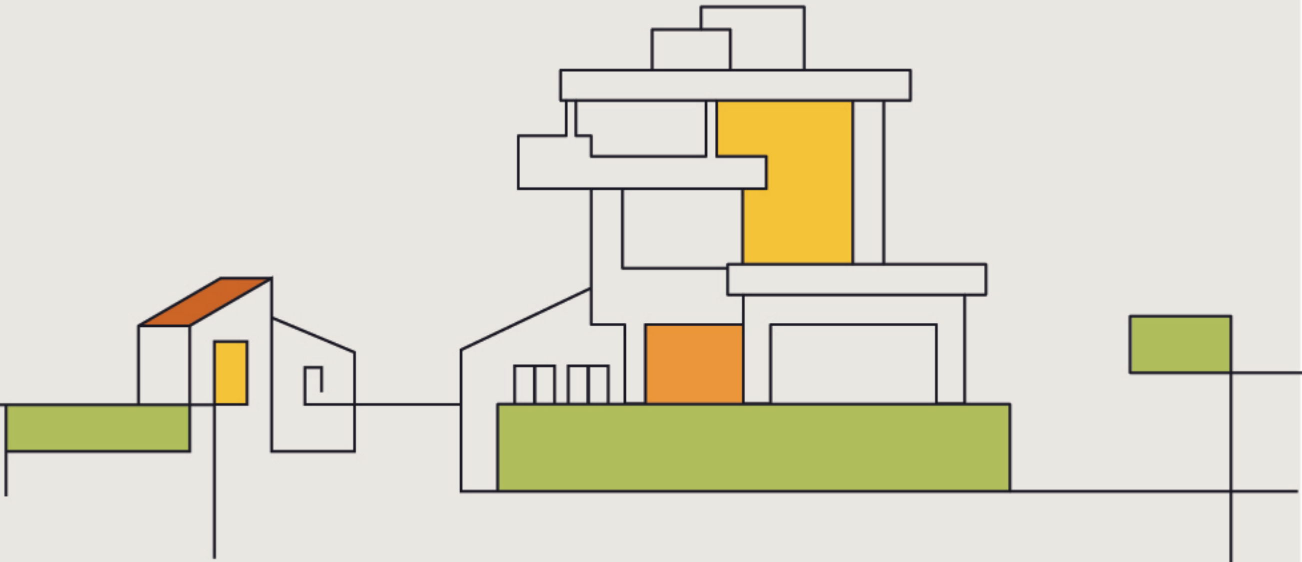

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