

Review

Volatile Organic Compound Emissions from Recycled Interior Finishing Materials: Health Implications, European Regulation and Future Challenges

Andris Stankevics , Sandra Gusta  and Raitis Brencis

Faculty of Forest and Environmental Sciences, Latvia University of Life Sciences and Technologies, Akademijas iela 11, LV-3001 Jelgava, Latvia; sandra.gusta@lbtu.lv (S.G.); raitis.brencis@lbtu.lv (R.B.)

* Correspondence: andris.stankevics@lbtu.lv

Abstract

The transition towards a circular economy has significantly increased the use of recycled construction materials, including products intended for interior applications. While the environmental benefits of material recycling are well recognised, considerably less attention has been devoted to the potential impact of recycled interior finishing materials on indoor air quality through volatile organic compound (VOC) emissions. The objective of this study is to critically review current scientific knowledge, European regulatory frameworks, testing methodologies, and national approaches governing VOC emissions from recycled interior finishing materials, while identifying existing regulatory gaps and proposing directions for future improvement. The study was conducted as a structured literature review and comparative analysis of peer-reviewed scientific literature, European Union legislation, harmonised standards, technical guidance documents, and national VOC emission control systems implemented in selected European countries. Particular attention was given to the Construction Products Regulation (CPR), EN 16516, the ISO 16000 series, EU-LCI values, and national emission classification schemes used in Germany, France, Belgium, Finland, and Latvia. The review demonstrates that Europe has established a comprehensive technical framework for evaluating VOC emissions from construction products. However, current regulatory approaches primarily assess the emission performance of finished products and generally do not explicitly address uncertainties associated with recycled raw materials, including feedstock variability, material traceability, contamination history, manufacturing consistency, and long-term emission behaviour. Furthermore, substantial differences remain between Member States regarding emission classification, product labelling, market surveillance, and practical implementation of VOC control measures. To address these identified gaps, this paper proposes an integrated conceptual framework for VOC risk management in recycled interior finishing materials that combines material traceability, manufacturing quality assurance, emission testing, health-based assessment, regulatory compliance, and market surveillance within a unified decision-making approach. The proposed framework complements existing European legislation by addressing challenges associated with the increasing use of recycled construction materials while supporting both circular economy objectives and the protection of indoor environmental quality. The findings indicate that the principal challenge is not the absence of VOC emission assessment methodologies but the need to adapt existing regulatory approaches to the growing use of recycled construction materials. Strengthening traceability, quality assurance, harmonised emission classification, and market surveillance may improve confidence in recycled construction products while ensuring a high level of chemical safety and human health protection across the European Union.



Academic Editor: William A. Anderson

Received: 5 October 2026

Revised: 14 October 2026

Accepted: 14 October 2026

Published: 17 October 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: volatile organic compounds (VOCs); indoor air quality; recycled interior finishing materials; circular economy; chemical safety; construction products regulation; emission testing

1. Introduction

The transition towards a circular economy has become one of the principal policy objectives of the European Union, aiming to reduce resource consumption, construction and demolition waste, greenhouse gas emissions, and the environmental impacts associated with the extraction of virgin raw materials [1]. Consequently, increasing attention has been devoted to the reuse and recycling of construction materials, particularly those intended for interior applications, where material recovery is considered an essential strategy for improving resource efficiency and reducing the environmental footprint of the construction sector [2].

Cancer remains one of the leading public health challenges in Europe. According to the latest estimates of the International Agency for Research on Cancer (IARC) [3], approximately one in five people will develop cancer during their lifetime, while cancer continues to account for millions of new cases every year across Europe. Although cancer is a multifactorial disease, reducing exposure to avoidable environmental carcinogens represents an important component of modern prevention strategies. Consequently, controlling indoor exposure to hazardous chemicals, including selected volatile organic compounds emitted from construction products, has become an increasingly important objective in public health and environmental policy.

At the same time, people in Europe spend approximately 90% of their time indoors, making indoor environmental quality an important determinant of human health and well-being [4]. Among the factors affecting indoor environmental quality, volatile organic compounds (VOCs) emitted from interior finishing materials have received considerable scientific attention because prolonged exposure to certain VOCs may contribute to respiratory diseases, sensory irritation, reduced comfort, and, in some cases, increased cancer risk depending on the specific compounds and exposure conditions [5–8].

Most European regulations and certification schemes addressing construction products have historically focused either on environmental sustainability or on product performance. Meanwhile, VOC assessment has primarily concentrated on emissions from newly manufactured materials through standardised laboratory testing and voluntary emission classification schemes. Although VOC emissions from recycled building materials have been investigated in several studies [9,10], the available literature remains considerably more limited than that addressing conventional construction products, particularly regarding recycled interior finishing materials and their specific feedstock-related uncertainties.

This situation creates an important policy challenge. On the one hand, European policies actively encourage the increased use of recycled construction materials as part of the circular economy transition. On the other hand, there is limited evidence regarding whether the existing regulatory framework, emission testing procedures, certification systems, and market surveillance mechanisms provide an equivalent level of control over VOC emissions from recycled interior finishing materials. Furthermore, regulatory approaches differ considerably among European countries, while comprehensive control mechanisms remain absent or only partially implemented in several Member States.

These uncertainties are particularly important because indoor occupants are exposed to emissions throughout the service life of construction products rather than only during manufacturing or installation. Therefore, ensuring that recycled materials do not compromise indoor environmental quality is essential for achieving both sustainability and public health objectives.

The aim of this study is to analyse the relationship between circular economy policies and VOC emission control in recycled interior finishing materials by reviewing current scientific evidence, European regulatory approaches, testing methodologies, certification systems, and market surveillance practices. The study also identifies existing regulatory gaps that may limit the effective protection of indoor environmental quality while supporting the continued expansion of circular construction practices.

2. Materials and Methods

This study employed a structured literature review and comparative analysis of scientific literature, international standards, European Union legislation, and national regulatory documents related to volatile organic compound (VOC) emissions from interior finishing materials. The research focused on identifying the current regulatory approaches governing VOC emissions, evaluating the extent to which recycled interior finishing materials are addressed within existing regulatory frameworks, and identifying potential gaps that may affect indoor environmental quality and human health protection.

The literature review included peer-reviewed scientific publications addressing indoor air quality, VOC emissions from construction materials, recycled building products, environmental exposure, and health effects associated with VOCs. Particular attention was given to studies investigating emission characteristics of interior finishing materials, the influence of recycled constituents on emission behaviour, and the relationship between material emissions and indoor environmental quality.

Peer-reviewed scientific literature was identified using the Scopus bibliographic database. The literature search focused on combinations of keywords related to “volatile organic compounds”, “VOC emissions”, “recycled building materials”, “recycled construction materials”, “interior finishing materials”, “indoor air quality”, “feedstock variability”, “contamination history”, “EN 16516” [11], “EU-LCI”, and “VOC regulation”. Priority was given to peer-reviewed journal articles directly addressing VOC emissions, health-related assessment, recycled construction materials, and European regulatory approaches. Publications were selected on the basis of their relevance to the research objectives, with preference given to recent peer-reviewed studies and established scientific sources directly related to VOC emissions, indoor air quality, recycled construction materials, and regulatory assessment.

The literature selection was based on a relevance-oriented screening approach rather than a formal systematic review protocol. Publications were assessed according to their thematic relevance to VOC emissions, recycled interior finishing materials, indoor air quality, and European regulatory requirements. Sources outside the scope of construction materials, indoor emissions, and related regulatory assessment were excluded. The review was intended to provide a structured qualitative synthesis of scientific and regulatory evidence rather than a quantitative meta-analysis. Accordingly, no new experimental measurements or primary datasets were generated. The Scopus search was based on combinations of topic-specific keywords rather than a single predefined systematic search string. Exact search dates, Boolean expressions, and database filters were not systematically recorded; therefore, the literature search should not be interpreted as an exhaustive or fully reproducible systematic search. This methodological limitation may have resulted in the

omission of some relevant publications and should be considered when interpreting the completeness of the literature synthesis and the generalisability of its conclusions.

A structured review of European legislation and technical documents was performed to identify the legal and technical framework governing VOC emissions from construction products. The review included the Construction Products Regulation (CPR), harmonised European standards, the EN 16516 emission testing methodology, the EN 16516 [11], the ISO 16000 series [12], EU-LCI values, European Lowest Concentration of Interest (EU-LCI) evaluation criteria, relevant European Commission policy documents, and selected voluntary certification schemes used within European countries.

To evaluate differences in regulatory implementation, a comparative analysis of selected European national approaches was undertaken. Countries with established VOC emission classification or labelling systems, including Germany, France, Belgium, and Finland, were selected because they represent different regulatory models currently applied within Europe. The analysis examined product testing requirements, emission classification systems, certification procedures, and market surveillance mechanisms.

The regulatory framework applicable in Latvia was analysed separately in order to evaluate the extent to which VOC emissions from interior finishing materials are addressed through national legislation, public procurement requirements, certification practices, and market surveillance. Particular attention was paid to identifying regulatory areas where emission control may be incomplete or absent, especially with regard to recycled construction materials.

The collected information was synthesised using comparative document analysis. The identified regulatory approaches, testing methodologies, certification systems, and scientific evidence were compared in order to determine their similarities, differences, and potential limitations. Based on this analysis, the study identifies existing regulatory and control gaps and proposes recommendations for improving VOC emission management in recycled interior finishing materials while supporting the objectives of the circular economy.

3. VOC Emissions from Interior Finishing Materials

Volatile organic compounds (VOCs) are among the most important chemical pollutants affecting indoor environmental quality. They are released from numerous construction and finishing materials used in residential, commercial, educational, and healthcare buildings and may remain detectable in indoor air for extended periods after installation. The duration and intensity of VOC emissions depend on several factors, including the chemical composition of the product, manufacturing technology, environmental conditions, ventilation rate, temperature, humidity, and material ageing [6,7,13].

Interior finishing materials represent one of the principal sources of VOC emissions because they are typically installed over large surface areas and remain in continuous contact with indoor air throughout their service life [14]. Significant emission sources include paints, varnishes, adhesives, sealants, floor coverings, laminate flooring, wood-based panels, suspended ceilings, insulation products, wallpapers, decorative coatings, and composite construction materials [15]. Many of these products contain organic solvents, synthetic resins, plasticisers, preservatives, curing agents, or other chemical additives capable of emitting VOCs during curing, ageing, or long-term use.

The composition of emitted VOCs differs considerably between product categories and manufacturing processes [16]. Frequently detected compounds include formaldehyde, benzene, toluene, ethylbenzene, xylene, styrene, acetaldehyde, terpenes, and numerous other volatile and semi-volatile organic compounds [17]. Although many VOCs primarily affect odour perception or sensory comfort, several compounds have been classified as

carcinogenic, mutagenic, or toxic to reproduction (CMR), highlighting their importance from a public health perspective.

An important distinction should be made between the VOC content of a construction product and its VOC emissions into indoor air. VOC content refers to the quantity of volatile organic compounds contained within the product itself and is commonly regulated for specific product categories, particularly paints, varnishes, and coatings. In contrast, VOC emissions describe the quantity of chemical substances released from a material into indoor air over time under defined environmental conditions. Indoor air quality is primarily influenced by these emissions rather than by the total VOC content of the product. Consequently, products containing similar amounts of VOCs may exhibit substantially different emission characteristics depending on their chemical composition, curing behaviour, and manufacturing technology.

To assess VOC emissions under reproducible conditions, internationally recognised laboratory methods have been developed. Within Europe, emission testing is primarily performed using environmental chamber methods specified in the ISO 16000 series and EN 16516 [11,18,19]. These standards establish harmonised procedures for determining VOC emissions from construction products intended for indoor applications and provide the technical basis for several European emission classification and certification systems.

Although VOC emissions from conventional construction products have been extensively investigated, scientific evidence specifically addressing recycled interior finishing materials remains comparatively limited. Recent studies have demonstrated that recycled building materials can exhibit material-specific VOC emission characteristics, highlighting the need for further investigation of the influence of recycled constituents and feedstock variability on emission behaviour [9,10]. This knowledge gap becomes increasingly significant as circular economy policies promote the wider use of recycled construction materials within indoor environments. Typical VOC emission sources and associated compounds in selected interior finishing materials are summarised in Table 1.

Table 1. Typical VOC emission sources in interior finishing materials.

Material Category	Typical VOCs/SVOCs	Main Emission Source
Paints and coatings	Toluene, xylene, glycol ethers	Solvents
Adhesives	Formaldehyde, acetaldehyde	Resins and binders
Laminate flooring	Formaldehyde	HDF/MDF core and adhesives
Wood-based panels	Formaldehyde, terpenes	Urea-formaldehyde or phenolic resins
PVC flooring	Residual vinyl chloride monomer (VOC); phthalate plasticisers and DINCH (SVOCs)	Residual monomers, plasticisers and polymer additives
Sealants	Siloxanes, solvents	Polymer curing
Insulation materials	Formaldehyde and other aldehydes (where applicable); potential VOC residues	Mineral wool: phenol-formaldehyde binders; recycled textile/cellulose insulation: residual additives, contaminants or binders

Note: VOCs = volatile organic compounds; SVOCs = semi-volatile organic compounds. TVOC (total volatile organic compounds) represents an aggregate emission parameter determined according to the applicable analytical method and is not reported as a material-specific measured value in this table.

4. Specific Risks Associated with Recycled Materials

The transition towards a circular economy has substantially increased the use of recycled materials in the construction sector [20,21]. While recycling contributes to resource conservation, waste reduction, and lower greenhouse gas emissions, it also introduces new challenges related to the chemical safety of construction products intended for indoor applications [22]. Unlike virgin materials manufactured from controlled raw materials, recycled products frequently incorporate secondary raw materials originating from multiple sources, production processes, and service histories. Consequently, their chemical composition may be considerably more heterogeneous and less predictable [23].

One of the principal challenges associated with recycled interior finishing materials is the limited knowledge regarding the origin and previous use of secondary raw materials. Construction and demolition waste may contain residues of paints, adhesives, sealants, preservatives, flame retardants, plasticisers, cleaning agents, or other chemical substances that were introduced during the original service life of the product. Although recycling processes aim to remove contaminants, complete elimination of all chemical residues cannot always be guaranteed, particularly when recycled feedstock originates from mixed waste streams.

In addition to residual contaminants, recycling itself may alter the chemical characteristics of construction materials. Mechanical processing, crushing, grinding, thermal treatment, or chemical recycling may modify the physical structure of materials or expose previously encapsulated compounds, potentially influencing subsequent VOC emissions. Furthermore, recycled products frequently require the addition of new binders, adhesives, polymers, compatibilisers, or performance-enhancing additives in order to achieve the mechanical properties required for construction applications. These additional substances may themselves become new sources of VOC emissions.

The mechanisms governing VOC emissions from recycled interior finishing materials may involve several interacting physical and chemical processes. Mechanical recycling can increase the exposed surface area of materials and facilitate the release of previously retained volatile compounds. Thermal processing may induce polymer degradation, oxidation, or the formation of low-molecular-weight organic compounds, depending on the material composition and processing conditions. Furthermore, residual adhesives, coatings, plasticisers, and other additives may contribute to secondary emissions during subsequent use. The resulting emission behaviour is influenced by diffusion within the material, partitioning between the material and surrounding air, temperature, relative humidity, and material ageing. Consequently, recycled products with similar nominal compositions may exhibit different VOC emission profiles depending on their feedstock history and processing conditions.

A further distinction should be made between VOC formation during recycling and the transfer of legacy contaminants from previously used materials. During mechanical and thermal reprocessing, thermo-oxidative degradation and polymer chain scission may generate additional low-molecular-weight compounds, including aldehydes and other oxygenated VOCs. The extent and nature of these emissions depend on the polymer type, processing temperature, oxygen availability, and previous material history. In parallel, recycling may transfer legacy additives and contaminants into new products when sorting and decontamination are insufficient. These substances may include phthalate plasticisers previously used in PVC flooring, certain flame retardants and stabilisers, and residues associated with older polymer formulations, including epoxy-based systems. Such substances should not automatically be classified as VOCs, since some are semi-volatile or non-volatile; nevertheless, their presence may affect chemical safety and

contribute to emissions or subsequent release under service conditions [24]. These mechanisms highlight the importance of distinguishing newly formed degradation products from pre-existing contaminants when assessing the chemical safety of recycled interior finishing materials.

Another important consideration is the variability of recycled raw materials. Unlike virgin materials produced under relatively stable manufacturing conditions, the composition of secondary raw materials may vary between production batches depending on the source of recycled feedstock, sorting efficiency, contamination levels, and recycling technologies employed. This variability increases uncertainty regarding the long-term emission behaviour of recycled interior finishing materials and complicates the prediction of indoor VOC exposure.

Recent studies further indicate that VOC emission characteristics of recycled building materials may depend on the composition and origin of the recycled feedstock as well as on the recycling process itself. Experimental investigations have identified emissions of BTEX compounds and carbonyls from recycled building materials, while subsequent research has demonstrated that the transport and emission behaviour of VOCs within recycled building materials may vary according to material-specific characteristics [9,10].

Current emission testing methodologies generally evaluate finished construction products under standardised laboratory conditions without distinguishing whether the product has been manufactured from virgin or recycled raw materials. While this approach provides valuable information regarding measured emissions, it may not fully address the additional uncertainties associated with heterogeneous recycled feedstocks or provide information regarding batch-to-batch variability. Consequently, products demonstrating compliance during initial testing may still exhibit batch-to-batch variability in VOC emission performance, particularly where the composition and origin of recycled feedstocks are not fully consistent.

These uncertainties do not imply that recycled construction materials are inherently less safe than products manufactured from virgin raw materials. On the contrary, many recycled products successfully comply with existing European emission requirements and certification schemes. However, compared with conventional materials, recycled interior finishing products may present additional sources of uncertainty related to material composition, contaminant history, manufacturing variability, and long-term emission behaviour [25]. Therefore, recycled content alone should not be interpreted as evidence of either lower VOC emissions or improved chemical safety; these characteristics require separate emission-based and health-based assessment. As the use of recycled materials continues to increase in support of circular economy objectives, understanding and managing these uncertainties becomes increasingly important for maintaining high standards of indoor environmental quality and human health protection. The pathway from recycled raw materials through manufacturing and VOC emissions to indoor exposure and potential health impacts is summarised in Figure 1.

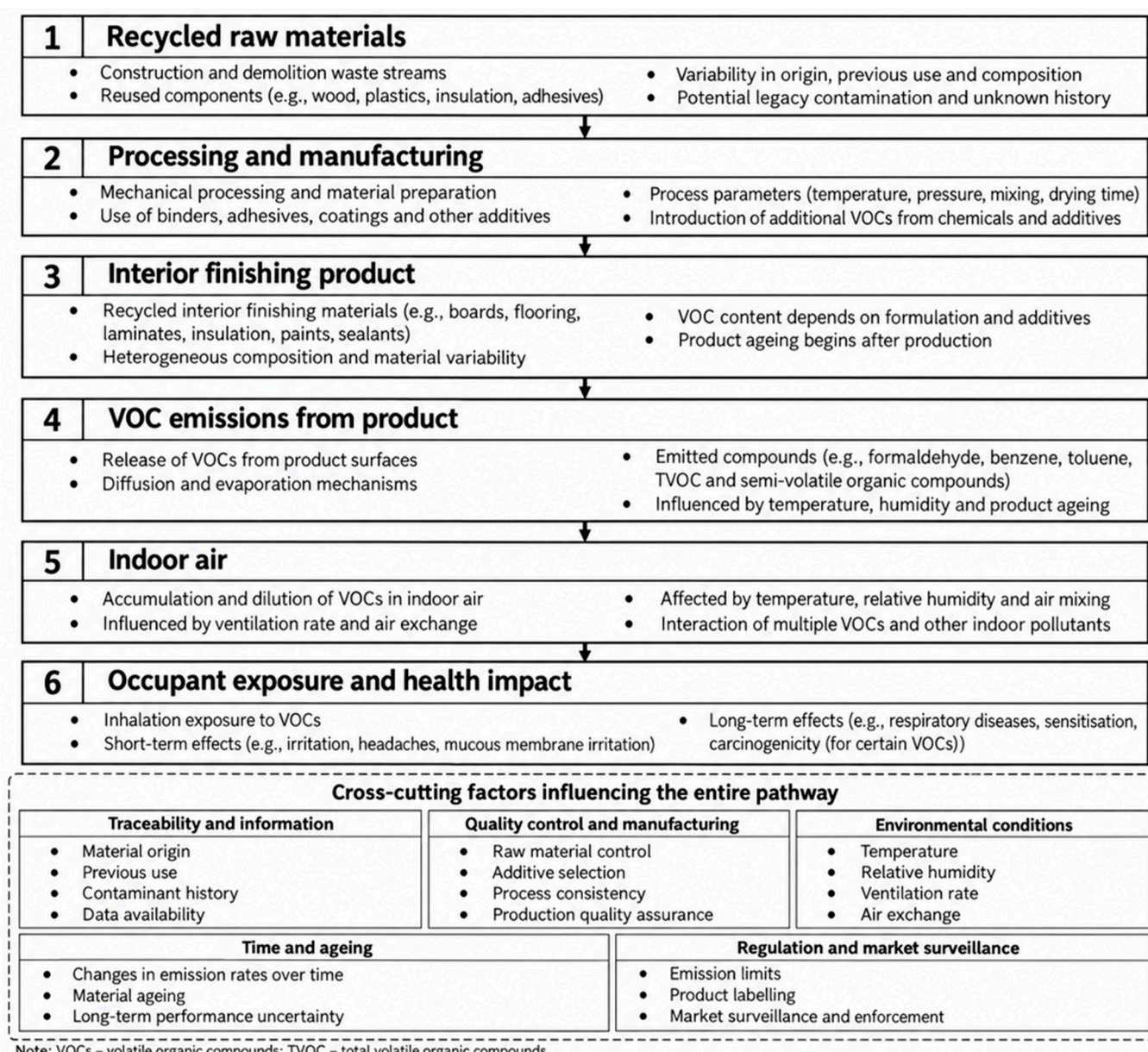


Figure 1. Pathway of VOC emissions from recycled interior finishing materials to occupant exposure and health impacts.

5. Health Significance of VOC Exposure

Volatile organic compounds emitted from interior finishing materials have been widely recognised as an important factor influencing indoor environmental quality and occupant health. Since people in industrialised countries spend approximately 90% of their time indoors, long-term exposure to indoor air pollutants may represent a significant component of total environmental exposure [4]. Although VOC concentrations emitted by individual construction products are often relatively low, simultaneous emissions from multiple materials may contribute to elevated cumulative exposure, particularly in newly constructed or recently renovated buildings [26].

The health effects associated with VOC exposure depend on several factors, including the chemical composition of the emitted compounds, their concentration, exposure duration, individual susceptibility, age, ventilation conditions, and the presence of other indoor pollutants [8,27]. Short-term exposure to elevated VOC concentrations has been associated with eye, nose, and throat irritation, headaches, dizziness, fatigue, unpleasant odours,

and reduced perceived indoor air quality. In sensitive individuals, including children, older adults, and people with respiratory diseases, VOC exposure may aggravate asthma symptoms and other respiratory disorders.

Long-term exposure has received increasing scientific attention because several VOCs commonly detected in indoor environments have been classified as substances of very high concern due to their toxicological properties. Formaldehyde, for example, has been classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen, while benzene is also recognised as a Group 1 human carcinogen [28,29]. Other compounds present in construction products may exhibit mutagenic, reprotoxic, or neurotoxic properties, depending on the specific substance, exposure level, and duration. Consequently, international organisations and regulatory authorities increasingly emphasise the importance of minimising unnecessary indoor exposure to hazardous chemical substances.

It is important to recognise that adverse health effects are generally not caused by a single VOC but rather by prolonged exposure to complex mixtures of chemical compounds originating from multiple indoor sources. Furthermore, indoor environmental quality is influenced not only by construction materials but also by furniture, cleaning products, consumer goods, occupant activities, and outdoor air infiltration. Therefore, the contribution of interior finishing materials should be considered as one component within the broader indoor exposure scenario [30].

From a preventive public health perspective, reducing avoidable chemical exposure remains one of the fundamental principles of indoor environmental management. Because construction materials remain in buildings throughout their service life and continuously interact with indoor air, controlling VOC emissions at the product level represents an important strategy for limiting long-term indoor exposure [4]. This principle becomes particularly relevant in the context of recycled interior finishing materials, where uncertainties regarding chemical composition and emission behaviour may be greater than for conventionally manufactured products.

Current European emission testing methodologies and certification schemes are therefore intended not only to demonstrate product performance but also to reduce the potential health risks associated with long-term indoor exposure. Nevertheless, the effectiveness of these regulatory approaches depends on the extent to which they adequately address the diversity of construction products, including those manufactured from recycled or secondary raw materials.

Although VOC exposure represents only one of many environmental factors influencing human health, the presence of carcinogenic and other hazardous compounds in indoor environments highlights the importance of effective emission control. The following section therefore places VOC management within the broader context of cancer burden in Europe and Latvia, illustrating why prevention of avoidable indoor chemical exposure has become an important public health objective.

6. Cancer Burden in Europe and Latvia

Cancer remains one of the leading causes of morbidity and mortality worldwide and represents a major public health challenge in Europe. According to estimates from the International Agency for Research on Cancer (IARC), globally, approximately one in five people will develop cancer during their lifetime, while the global cancer burden is expected to increase substantially in the coming decades [3]. These trends highlight the importance of effective prevention strategies alongside improvements in cancer diagnosis and treatment.

Recognising this challenge, the European Commission adopted Europe's Beating Cancer Plan, which identifies primary prevention as one of the most effective approaches for reducing future cancer incidence [31]. The strategy emphasises reducing exposure to

avoidable environmental and occupational carcinogens, improving air quality, strengthening chemical safety policies, and increasing public awareness of environmental health risks. Although lifestyle-related factors remain the dominant contributors to cancer incidence, limiting unnecessary exposure to hazardous environmental chemicals has become an increasingly important component of European public health policy.

Indoor environments represent a particularly important area for exposure prevention because people spend the majority of their daily lives inside residential, educational, commercial, and healthcare buildings. Consequently, even relatively low concentrations of hazardous substances may contribute to cumulative long-term exposure when emissions persist over extended periods. Construction and interior finishing materials therefore represent one of several environmental sources that should be considered within broader strategies for improving indoor environmental quality and reducing avoidable chemical exposure.

Several volatile organic compounds detected in indoor environments have been classified by the International Agency for Research on Cancer (IARC) according to their carcinogenic potential. Formaldehyde and benzene, for example, are classified as Group 1 human carcinogens, while additional compounds emitted from construction products may exhibit mutagenic, reproductive, neurological, or endocrine-related effects depending on exposure levels and duration [32]. Although construction materials represent only one component of overall environmental exposure, their contribution is particularly relevant because emissions may continue throughout the service life of the building.

The cancer burden is also highly relevant for Latvia. According to national public health statistics, malignant neoplasms remain among the leading causes of mortality, and cancer incidence has generally increased during recent decades, reflecting demographic changes, improved diagnostics, and continued exposure to multiple risk factors. These trends emphasise the importance of preventive measures aimed at reducing avoidable environmental exposures wherever reasonably achievable [33].

It is important to recognise that cancer is a multifactorial disease resulting from complex interactions between genetic predisposition, lifestyle, occupational exposure, environmental factors, and ageing. Therefore, VOC emissions from construction materials should not be interpreted as a direct cause of cancer incidence at the population level. Nevertheless, where construction products contain or emit substances classified as carcinogenic or otherwise hazardous, minimising unnecessary indoor exposure represents a scientifically justified and precautionary public health measure.

Within this context, effective control of VOC emissions from interior finishing materials becomes relevant not only from the perspective of indoor environmental quality but also as part of the broader European objective of reducing avoidable exposure to hazardous chemicals. As the use of recycled construction materials continues to expand under circular economy policies, ensuring that these products maintain an equivalent level of chemical safety represents an increasingly important regulatory challenge.

7. European Regulatory and Testing Framework

The regulation of volatile organic compound (VOC) emissions from construction products within the European Union is based on a combination of legislative requirements, harmonised technical standards, laboratory testing methodologies, and voluntary certification schemes. Rather than establishing a single European emission limit applicable to all construction products, the current regulatory framework provides harmonised procedures for evaluating product performance while allowing Member States to define their own performance requirements for products intended for indoor use.

The European regulatory framework for construction products is currently undergoing a transition from Regulation (EU) No 305/2011 [34] to the new Construction Products

Regulation, Regulation (EU) 2024/3110 [12]. The new Regulation entered into force on 7 January 2025, with most of its provisions applying from 8 January 2026. During the transitional period, provisions of Regulation (EU) No 305/2011 continue to apply to certain product families and harmonised technical specifications until they are progressively replaced under the new regulatory framework. Both Regulations establish harmonised rules for assessing and declaring construction product performance and for placing construction products on the European market, while Member States retain an important role in determining applicable performance requirements for their intended uses.

Assessment of VOC emissions from construction products intended for indoor use is primarily performed according to EN 16516 [11], which specifies harmonised laboratory procedures for determining emissions into indoor air. The standard defines environmental chamber testing conditions, sampling procedures, analytical methods, and reporting requirements for a broad range of construction products [34]. EN 16516 is closely linked with the ISO 16000 series, particularly those standards addressing chamber testing, air sampling, and analytical determination of volatile organic compounds [12]. Together, these standards provide a common technical methodology that enables comparable emission measurements throughout Europe.

Despite their importance for harmonised emission assessment, standardised chamber testing methods have certain limitations when evaluating recycled interior finishing materials. Emission assessments commonly use a 28-day reference period, which provides a standardised basis for comparing product performance but does not necessarily represent emission behaviour throughout the entire service life of a material. Long-term emissions may be influenced by material ageing, diffusion-controlled release of retained compounds, changes in temperature and relative humidity, and chemical degradation processes. Furthermore, laboratory testing under controlled conditions may not fully reproduce the variability of real indoor environments, including fluctuating ventilation rates and environmental conditions. For recycled materials, variations in feedstock composition, contamination history, and manufacturing processes may additionally result in differences in emission profiles between production batches. Consequently, standardised emission testing should be complemented, where justified by material-specific risks, by appropriate quality assurance, representative batch sampling, and consideration of long-term emission behaviour.

Unlike regulations governing VOC content in certain products, such as paints and coatings, emission assessment focuses on the quantity of chemical substances released into indoor air under standardised environmental conditions. This distinction is particularly important because indoor environmental quality depends primarily on emissions occurring during the service life of construction products rather than on the total amount of VOCs contained within the product itself.

In addition, VOC emission behaviour may be non-linear over time. Changes in temperature and relative humidity can alter the diffusion and release of retained compounds. Such processes are not necessarily captured by a single 28-day chamber test. For heterogeneous recycled materials, differences in composition, ageing, contamination history, and processing conditions may further complicate the extrapolation of short-term measurements to multi-year service life. Therefore, standardised chamber results should be interpreted as measurements under defined test conditions rather than as a complete prediction of long-term emissions.

To facilitate consistent health-based evaluation of measured emissions, the European Commission has supported the development of European Lowest Concentration of Interest (EU-LCI) values. These health-based reference values provide a common scientific basis for interpreting laboratory emission measurements and are intended to improve consistency

among European emission evaluation systems [33,35,36]. However, EU-LCI values are not legally binding exposure limits. Instead, they serve as technical reference criteria used within emission assessment methodologies and by several national certification schemes [36].

Chemical substances used in construction products are additionally regulated under the REACH Regulation (EC) No 1907/2006 [37] and the CLP Regulation (EC) No 1272/2008 [38]. REACH governs the registration, evaluation, authorisation, and restriction of chemical substances placed on the European market, while CLP establishes harmonised rules for classification, labelling, and packaging of hazardous chemicals. Although these regulations contribute significantly to chemical safety through substance hazard classification and risk management, they do not constitute a harmonised product-level methodology for measuring VOC emissions from finished construction products into indoor air.

Consequently, the European regulatory framework relies on several complementary instruments operating simultaneously. Construction product legislation establishes common rules for product assessment and CE marking; harmonised standards provide laboratory testing methodologies; REACH and CLP regulate hazardous chemical substances; and EU-LCI values support health-based interpretation of emission data. Nevertheless, implementation of VOC emission requirements remains largely dependent on national regulatory approaches and voluntary certification systems, resulting in considerable differences between European countries regarding emission classification, product acceptance, and market surveillance [35].

This regulatory structure provides a harmonised technical basis for VOC assessment while allowing flexibility in national implementation. However, it also creates challenges for ensuring consistent protection of indoor environmental quality across the European Union, particularly for innovative construction products incorporating recycled or secondary raw materials, where chemical composition and emission behaviour may be more variable than in conventionally manufactured products. The relationship between the European regulatory framework, harmonised technical assessment, national implementation, and market surveillance is summarised in Figure 2.

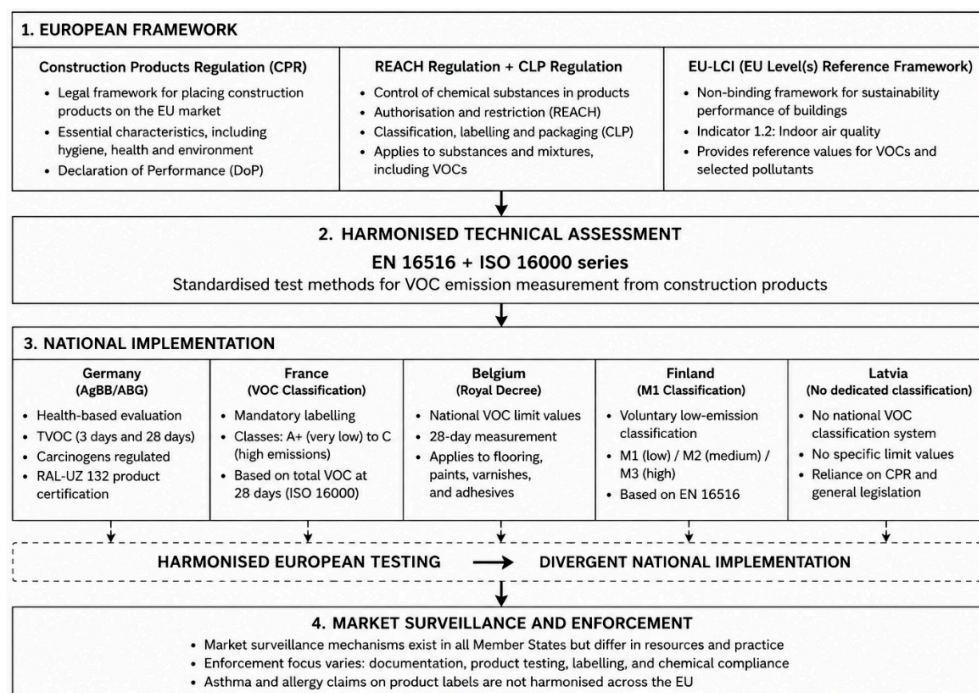


Figure 2. European regulatory and testing framework for VOC emissions from construction products and its national implementation. The arrows indicate the relationship between the European regulatory framework, harmonised technical assessment, national implementation, and market surveillance.

8. National Approaches in Selected European Countries

Although the European Union has established harmonised procedures for measuring VOC emissions from construction products, the implementation of emission requirements remains largely the responsibility of individual Member States. As a result, Europe currently applies a combination of mandatory regulations, voluntary certification schemes, and national emission classification systems that differ considerably in scope, legal status, and enforcement mechanisms.

Germany applies the AgBB (Committee for Health-related Evaluation of Building Products) evaluation scheme for the health-related assessment of VOC emissions from construction products intended for indoor use. The AgBB scheme establishes uniform health-based testing and assessment criteria and evaluates both total VOC emissions and individual emitted substances according to their toxicological relevance. The assessment includes criteria such as LCI values, the R-value, TVOC, TSVOC, and the sum of unidentified or unevaluated VOCs [39].

France has implemented a mandatory VOC emission labelling system for construction and decoration products intended for indoor use. The labelling requirement has been mandatory since 2012 and classifies products according to their emissions of volatile pollutants into indoor air using four emission classes ranging from A+ (very low emissions) to C (high emissions). The label is intended to provide objective information to designers and users and to support product selection according to potential impacts on indoor air quality [40].

Belgium has established mandatory VOC emission requirements for specific categories of construction products intended for indoor use through the Royal Decree of 8 May 2014, which entered into force on 1 January 2015. The regulation establishes emission threshold levels for covered construction products and requires manufacturers to demonstrate compliance before products are placed on the Belgian market. The assessment addresses a broad range of volatile organic compounds and uses health-based criteria linked to European emission assessment methodologies and EU-LCI values [41].

Finland applies the M1 Emission Classification of Building Materials, a voluntary system designed to promote the development and use of low-emitting building materials and improve indoor air quality. M1 classification evaluates emissions from building materials into indoor air and establishes criteria for VOCs, formaldehyde, ammonia, and odour acceptability. Products meeting the M1 criteria are recognised as low-emitting materials, and the classification is widely used as a tool for selecting materials intended for healthy indoor environments [42]. The main characteristics of the selected national VOC emission control approaches are summarised in Table 2.

Romania provides an additional example of a national approach focused on VOC source control and product composition. Government Decisions No. 699/2003 and No. 735/2006 addressed solvent-related VOC emissions from specified activities and VOC content limits for certain paints and coatings, respectively. These measures differ from product emission classification systems based on standardised chamber testing and should not be interpreted as equivalent assessments of long-term indoor VOC emissions [43,44].

Table 2. Comparison of national approaches to VOC emission control for construction products in selected European countries.

Country	Regulatory Approach	Legal Status	Main Assessment/Classification	Technical Basis
Germany	AgBB evaluation scheme	Health-based national assessment framework	LCI values, R-value, TVOC, TSVOC	EN 16516/related European methods
France	VOC emission labelling	Mandatory labelling	A+ to C emission classes	Standardised emission testing
Belgium	National VOC emission requirements	Mandatory for specified product categories	Emission threshold values	European emission assessment methods/EU-LCI
Finland	M1 Emission Classification	Voluntary	M1 low-emission classification	Standardised chamber emission testing
Latvia	No dedicated national VOC classification	No dedicated national classification	Project/procurement-specific requirements	EN 16516/ISO 16000 where specified
Romania	VOC source control and product content limits	Historical national regulatory measures (Decision No. 699/2003 repealed) [11]	VOC content limits; no equivalent indoor emission classification	Government Decisions No. 699/2003 and No. 735/2006

Other European countries have adopted similar national approaches, often combining harmonised European testing standards with country-specific health-based acceptance criteria or voluntary environmental certification systems. Consequently, while laboratory testing methodologies remain largely harmonised across Europe, the regulatory consequences of emission test results differ significantly between Member States.

This diversity reflects the flexibility intentionally provided within the European regulatory framework. However, it also creates inconsistencies in the level of chemical protection afforded to building occupants across the European Union. A construction product demonstrating acceptable performance in one Member State may be subject to different regulatory requirements or market expectations in another despite having been tested according to the same harmonised European standard.

The situation becomes even more complex for recycled interior finishing materials. Existing national emission classification systems generally evaluate finished products without explicitly distinguishing between products manufactured from virgin raw materials and those containing recycled constituents. Consequently, although recycled products are subject to the same emission testing methodologies, current national regulatory approaches rarely address the additional uncertainties associated with heterogeneous secondary raw materials, contamination history, or batch-to-batch variability. The available scientific literature specifically addressing the application of harmonised VOC emission assessment approaches to recycled construction products remains limited and fragmented.

Overall, the comparison of selected European countries demonstrates that significant progress has been achieved in the assessment of VOC emissions from construction products. Nevertheless, differences in national implementation continue to result in unequal levels of regulatory oversight and varying approaches to indoor chemical safety across Europe. These differences become particularly relevant when considering the rapidly increasing use of recycled construction materials promoted under circular economy policies.

9. VOC Control in Latvia

Latvia applies the general European Union regulatory framework governing construction products, including the Construction Products Regulation (CPR), CE marking

requirements, and harmonised technical specifications. Construction products placed on the Latvian market must comply with the applicable European legislation, while market surveillance is carried out in accordance with national regulations implementing the CPR. However, unlike several other European countries, Latvia has not established a dedicated national VOC emission classification or labelling system for interior finishing materials comparable to the German AgBB scheme, the French A+ labelling system, or the Finnish M1 emission classification.

VOC emission performance of construction products may be assessed using established European and international testing methodologies, including EN 16516 and the ISO 16000 series. In Latvia, however, there is no dedicated national VOC emission classification system comparable to the French emission labelling scheme or the Finnish M1 classification. Consequently, the use of VOC emission testing for interior finishing materials depends largely on the applicable product requirements, project specifications, procurement criteria, or voluntary environmental certification rather than on a universal national VOC emission classification requirement.

Green Public Procurement (GPP) has also provided an important policy mechanism for addressing indoor environmental quality in Latvia. Under the former Latvian GPP regulatory framework, specific criteria for construction works included emission limits for selected interior finishing materials, including total volatile organic compounds (TVOC < 300 µg/m³ after 28 days) and formaldehyde (<30 µg/m³). These requirements applied to specified product groups such as ceiling tiles, paints and varnishes, textile floor and wall coverings, laminate and resilient floor coverings, and wood and composite flooring. However, Cabinet Regulation No. 353, which established these GPP requirements, ceased to be in force on 9 June 2026. Consequently, these criteria should be regarded as evidence of previous Latvian policy practice rather than as a currently applicable universal national VOC emission classification system [45,46].

Market surveillance of construction products in Latvia is carried out within the national framework implementing European construction product requirements. The Consumer Rights Protection Centre (PTAC) is the competent market surveillance authority for construction products and verifies compliance with applicable requirements, including product identification, CE marking where required, declared performance, and accompanying documentation. Latvian legislation also provides mechanisms for requesting product samples and conducting laboratory or other examinations when necessary. However, these general market surveillance provisions do not establish a dedicated national programme specifically requiring systematic VOC emission testing of interior finishing materials placed on the Latvian market [47,48].

From the perspective of indoor environmental quality, the Latvian framework therefore relies primarily on applicable European product requirements supplemented by project-specific specifications, procurement criteria, and voluntary environmental certification schemes. In the absence of a dedicated national VOC emission classification system, requirements for low-emitting interior materials may consequently vary between individual projects and procurement contexts.

The increasing use of recycled construction materials introduces additional considerations for indoor environmental quality. Latvian waste legislation promotes the preparation of construction and demolition waste for reuse, recycling, and material recovery and requires recovered materials to comply with applicable technical and environmental requirements. However, no separate VOC emission assessment framework has been identified for interior finishing products specifically on the basis of their recycled material content. Consequently, recycled and conventionally manufactured products are generally subject to the same applicable product and emission assessment requirements, despite

potential differences in raw material origin, contamination history, chemical composition, and emission variability [49,50].

Overall, Latvia has established mechanisms for implementing European construction product requirements and for market surveillance of construction products. However, the regulatory review indicates that Latvia does not currently operate a dedicated national VOC emission classification or mandatory emission-labelling system for interior finishing materials comparable to those applied in several other European countries. VOC-related requirements may instead arise from applicable European product requirements, project specifications, procurement criteria, or voluntary certification schemes. Consequently, the practical level of VOC emission assessment may vary between product categories and individual construction or procurement contexts.

10. Identified Regulatory and Control Gaps

The comparative analysis of European legislation, testing methodologies, national regulatory approaches, and the Latvian regulatory framework indicates that significant progress has been achieved in establishing harmonised procedures for assessing VOC emissions from construction products. Standardised laboratory testing, harmonised analytical methods, and health-based evaluation criteria provide a robust technical foundation for evaluating indoor emissions. Nevertheless, several important regulatory and practical gaps remain, particularly in the context of recycled interior finishing materials.

Although previous studies have addressed VOC emissions from construction products, health-based emission assessment, and the harmonisation of European evaluation approaches, the available evidence addressing recycled feedstock traceability, contamination history, batch-to-batch variability, and regulatory control remains limited and fragmented [51,52]. The present study therefore integrates these dimensions within a unified VOC risk-management framework specifically focused on recycled interior finishing materials.

The first identified gap concerns the relationship between initial product emission assessment and subsequent verification of emission performance. Existing VOC assessment systems are primarily based on testing finished products under standardised conditions, while the extent and frequency of subsequent market surveillance and independent verification vary between national regulatory systems. This may create uncertainty regarding whether declared VOC emission performance remains consistent across production batches and throughout continued market availability, particularly for products incorporating heterogeneous recycled feedstocks.

A second limitation relates to the increasing use of recycled and secondary raw materials. Existing emission testing methodologies evaluate finished construction products without explicitly considering the origin, variability, or previous service history of recycled constituents. While this approach ensures equal treatment of conventional and recycled products during laboratory testing, it does not specifically address the additional uncertainties associated with heterogeneous recycled feedstocks, historical contamination, or variations in recycling technologies.

Another important issue concerns traceability of recycled constituents. Information on the origin, previous use, contamination history, and chemical composition of secondary raw materials may be relevant when evaluating potential VOC emission risks. However, conventional product-level emission assessment does not necessarily provide detailed information on the history and variability of individual recycled feedstocks. Improved traceability of recycled constituents could therefore complement standardised

emission testing and support more comprehensive assessment of potential chemical and VOC-related risks.

Differences between national implementation approaches represent an additional regulatory challenge. While several European countries have introduced mandatory VOC emission labelling systems, national acceptance criteria, or established voluntary classification schemes, others rely primarily on harmonised European standards and project-specific requirements. Consequently, construction products with comparable laboratory emission performance may be subject to different classification, documentation, or acceptance requirements depending on the Member State in which they are placed on the market. This regulatory heterogeneity may complicate consistent interpretation of VOC emission performance and the selection of low-emitting materials across the European construction market.

An additional issue concerns the distinction between VOC content and VOC emissions. VOC content describes the amount of volatile organic compounds present in a product or formulation, whereas emission assessment addresses the release of these compounds from a finished product into indoor air under defined conditions. These parameters are therefore not interchangeable when evaluating potential impacts on indoor air quality. For interior construction materials, emission-based assessment provides information that is more directly relevant to potential indoor exposure than product VOC content alone.

Within Latvia, the absence of a dedicated national VOC emission classification or labelling system means that practical emission control depends primarily on applicable European product requirements, project-specific specifications, procurement criteria, and voluntary certification schemes. Although previous Green Public Procurement regulations included specific VOC emission criteria for selected interior finishing materials, these mandatory requirements ceased to apply to newly initiated procurements after 9 June 2026. This further emphasises the importance of project-level specifications and voluntary use of emission-based criteria when selecting low-emitting interior materials.

Overall, the findings suggest that the current European regulatory framework provides an effective basis for VOC emission assessment but has evolved primarily around conventionally manufactured construction products. As recycled materials become increasingly important within circular economy strategies, future regulatory development may need to place greater emphasis on material traceability, consistency of recycled feedstocks, long-term emission performance, and harmonised approaches to market surveillance. Strengthening these aspects could improve confidence in recycled construction materials while simultaneously supporting both circular economy objectives and the protection of indoor environmental quality. The principal regulatory and control gaps identified through the comparative analysis are summarised in Figure 3.

Taken together, the identified gaps indicate that the principal challenge is not the absence of established VOC emission testing methodologies, but the need to integrate these methodologies more effectively with the specific uncertainties introduced by recycled materials. Circularity alone cannot be regarded as sufficient evidence of environmental or health performance. The increased use of secondary raw materials should therefore be accompanied by appropriate traceability, quality assurance, emission-based assessment, health-based evaluation, and proportionate regulatory verification. In this context, circular economy objectives and the protection of indoor environmental quality should be treated as complementary requirements: material recovery should not be achieved at the expense of chemical safety or human health.

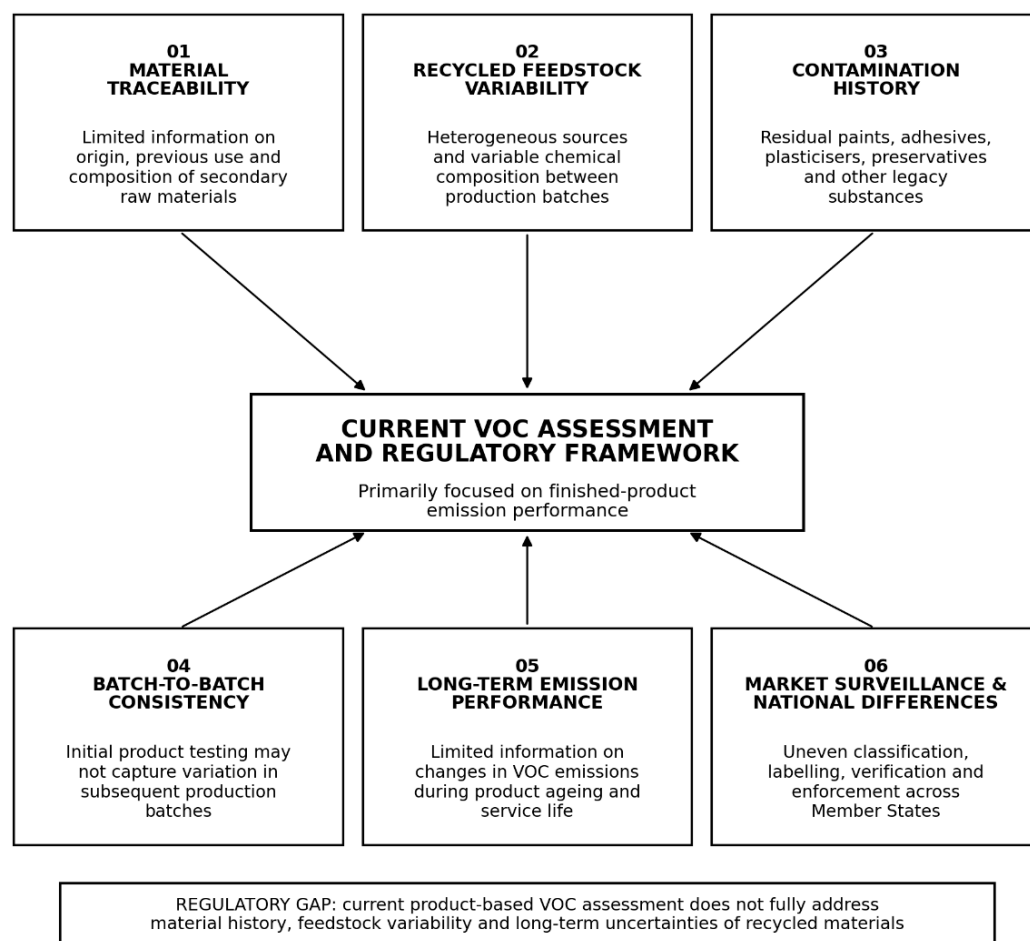


Figure 3. Identified regulatory and control gaps affecting VOC risk management in recycled interior finishing materials.

Conceptual Framework for VOC Risk Management in Recycled Interior Finishing Materials

While the reviewed literature and current European regulatory framework provide established methodologies for assessing VOC emissions from construction products, the present review did not identify an integrated framework that specifically combines VOC emission assessment with the additional traceability, material variability, and chemical safety considerations associated with recycled interior finishing materials. Based on the identified regulatory gaps, the authors propose a conceptual framework for improving VOC risk management while supporting the objectives of the circular economy (Figure 4).

The proposed framework is based on the principle that the chemical safety of recycled construction products should be evaluated through an integrated process extending from secondary raw material origin and manufacturing quality control to finished-product emission testing, health-based assessment, and regulatory verification. It therefore combines material traceability, quality assurance, emission assessment, health-based evaluation, and regulatory oversight within a unified decision-making approach.

Stage 1. Material Origin and Traceability

The first stage focuses on documenting the origin of recycled raw materials, previous applications, recycled content, and available information regarding potential contamination. Improved traceability can reduce uncertainty associated with heterogeneous secondary feedstocks and support more informed assessment and selection of recycled materials.

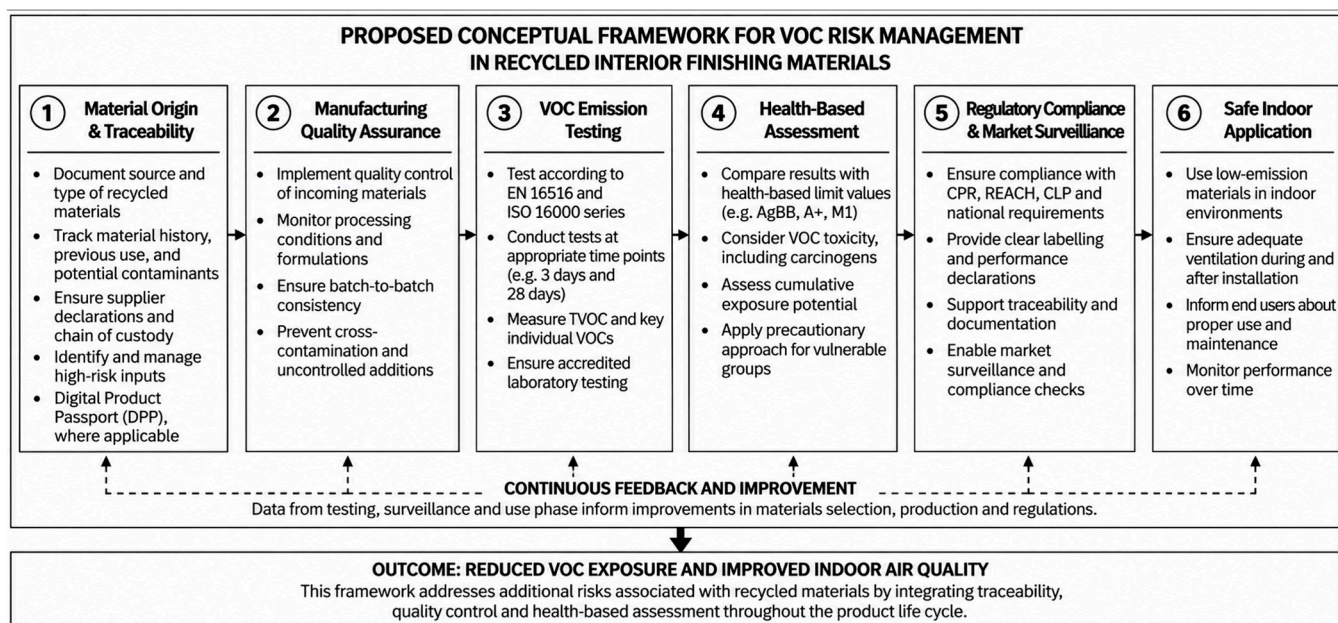


Figure 4. Proposed conceptual framework for VOC risk management in recycled interior finishing materials. The arrows indicate the progression between the framework stages and the continuous feedback process supporting improvements in VOC risk management.

The Digital Product Passport (DPP) framework introduced under Regulation (EU) 2024/3110 could provide a practical mechanism for improving material traceability, subject to the applicable implementation requirements. Where relevant information is available and incorporated into the passport, it could facilitate access to product identification, material composition, recycled content, and supporting technical documentation. However, the DPP should not be regarded as a substitute for chemical characterisation or VOC emission testing, particularly where the contamination history of secondary raw materials remains uncertain.

Stage 2. Manufacturing Quality Assurance

The second stage evaluates manufacturing processes, including sorting efficiency, contaminant removal, quality control procedures, and production consistency. Particular attention should be given to monitoring and controlling batch-to-batch variability in recycled feedstocks, particularly where changes in chemical composition or residual contamination may influence the emission performance of the finished product.

Stage 3. VOC Emission Testing

Finished construction products should be evaluated using harmonised European methodologies, including EN 16516 and the ISO 16000 series, to determine VOC emissions under standardised environmental chamber conditions. Testing should focus on measured emissions rather than solely on VOC content.

The practical implementation of VOC emission testing requires consideration of the financial and organisational capacities of manufacturers. While larger manufacturers may be able to integrate emission testing into established quality assurance procedures, small and medium-sized enterprises (SMEs) may face proportionally higher costs associated with laboratory testing, sampling, and technical documentation. A risk-based approach could help address these challenges by prioritising additional testing for materials with uncertain feedstock origins, variable chemical compositions, or potentially hazardous constituents. Shared testing facilities, cooperation with accredited laboratories, and sector-specific technical guidance could further improve accessibility for SMEs. Nevertheless, responsibility for demonstrating compliance with applicable product requirements

should remain with the relevant economic operators, in accordance with the applicable regulatory framework.

Stage 4. Health-Based Assessment

Measured emission results should be interpreted using health-based reference values, such as EU-LCI values, together with relevant toxicological classifications of emitted substances. This stage provides a health-based interpretation of product emission data and supports the identification of emissions that may require further evaluation or control.

Stage 5. Regulatory Compliance and Market Surveillance

Products demonstrating acceptable emission performance should comply with applicable European and national requirements and remain subject to appropriate market surveillance. Where justified by product characteristics, recycled feedstock variability, or other identified risk factors, targeted independent verification of emission performance could complement initial product assessment and provide additional confidence in continued compliance.

Stage 6. Safe Indoor Application

The final stage supports the specification and use of recycled interior finishing materials only where applicable emission, indoor environmental quality, and chemical safety requirements are satisfied. Within this framework, circular economy objectives are pursued within defined health and indoor environmental quality boundaries, ensuring that increased material circularity does not compromise the safety of indoor environments.

Building upon existing regulatory approaches that primarily assess the emission performance of finished construction products, the proposed framework places additional emphasis on material traceability and manufacturing consistency as complementary components of VOC risk management for recycled materials. The framework does not replace existing European legislation or harmonised testing standards; rather, it complements them by addressing aspects that become increasingly relevant as recycled construction materials are more widely introduced into indoor environments.

The proposed conceptual framework may also serve as a basis for future research aimed at developing risk-based assessment methodologies for recycled construction materials and for supporting the evolution of European regulatory policies towards more comprehensive chemical safety management within the circular economy.

Artificial intelligence (AI) and machine learning could provide additional opportunities for the future development of the proposed VOC risk management framework. Predictive models trained on validated emission measurements, recycled feedstock characteristics, manufacturing parameters, and environmental conditions could support the identification of emission patterns and potential risks associated with heterogeneous recycled materials. Such approaches may also assist manufacturers in detecting batch-to-batch variability, optimising quality assurance procedures, and developing more adaptive VOC monitoring strategies. However, their practical application would require sufficiently representative datasets, independent model validation, and transparent assessment of prediction uncertainty. AI-based tools should therefore be regarded as complementary decision-support instruments rather than substitutes for standardised emission testing and health-based assessment.

11. Recommendations

Based on the findings of this study, several measures could strengthen the management of VOC emissions from recycled interior finishing materials while supporting the continued implementation of circular economy principles within the European construction sector.

Firstly, greater emphasis should be placed on VOC emission performance rather than solely on VOC content when evaluating interior finishing materials. Because VOC content and VOC emissions represent different characteristics of a product, information on composition alone does not provide a direct measure of the substances released into indoor air under defined conditions. Wider use of emission-based assessment could therefore provide more relevant information for evaluating potential impacts on indoor environmental quality and for supporting material selection.

Secondly, greater attention should be given to the traceability of recycled raw materials used in construction products. Product documentation could be expanded to include information regarding the origin of recycled constituents, the proportion of recycled content, and the quality assurance procedures applied during material recovery and manufacturing. Improved traceability could reduce uncertainty regarding secondary raw material characteristics and provide a stronger information basis for assessing the chemical safety and emission performance of recycled construction products.

Thirdly, consideration should be given to strengthening quality assurance for construction products containing recycled materials. While emission testing evaluates the performance of finished products under defined conditions, additional quality management procedures could support the monitoring and control of batch-to-batch variability in recycled feedstocks and finished products. Such measures could help reduce uncertainty associated with heterogeneous secondary raw materials and improve confidence in the consistency of VOC emission performance over time.

Fourthly, greater harmonisation of low-emission product classification approaches across European Member States should be considered. Although several countries have established national VOC emission classification, labelling, or acceptance systems, substantial differences remain in how emission test results are classified, communicated, and applied in product selection. Greater harmonisation could facilitate cross-border product comparison, support more consistent specification of low-emitting materials, and improve transparency within the European construction market.

Fifthly, national authorities may consider strengthening the role of market surveillance and independent verification of VOC emission performance for construction products intended for indoor use. Rather than applying routine periodic testing to all products, targeted verification could be considered where product characteristics, recycled feedstock variability, changes in manufacturing processes, or other identified risk factors indicate a greater potential for variation in emission performance. Such a risk-based approach could complement initial product assessment while focusing regulatory resources on products for which additional verification may provide the greatest value.

For Latvia, the findings suggest that VOC emission management could be strengthened through clearer national guidance on low-emitting interior construction materials and more systematic use of established European emission assessment methodologies. Consideration could also be given to incorporating appropriate emission-based criteria into future public procurement specifications and sustainable building requirements where relevant. Such measures could support more consistent consideration of indoor environmental quality while remaining compatible with the broader European regulatory framework.

Future improvements in VOC risk management should combine advances in analytical technologies with a phased regulatory implementation strategy. Continuous indoor air monitoring, sensor networks, and automated data logging could complement standardised laboratory chamber testing by providing information on temporal emission variability under real operating conditions. However, sensor-based measurements would require calibration, quality assurance, and validation against established analytical methods. A

practical regulatory roadmap could begin with harmonised data collection and voluntary pilot programmes for recycled interior finishing materials, followed by the development of material-specific technical guidance and representative testing protocols. Subsequently, validated assessment approaches could inform relevant harmonised technical specifications under Regulation (EU) 2024/3110 and, where appropriate, national product requirements and market surveillance procedures. Such implementation should be proportionate to product risks and supported by clear responsibilities, transitional arrangements, and accessible testing infrastructure.

Finally, future research should focus on the development of risk-based assessment methodologies specifically addressing recycled construction materials. Particular attention should be given to the influence of recycled feedstock variability, contaminant history, long-term emission behaviour, and the relationship between laboratory emission testing and actual indoor exposure conditions. Improved scientific understanding in these areas would support both regulatory development and the safe expansion of circular construction practices.

Future research should also prioritise the assessment of long-term VOC exposure among potentially vulnerable population groups, particularly children and students in educational buildings. Longitudinal monitoring studies, advanced statistical analysis, and computational exposure modelling could help identify relationships between material emission profiles, indoor environmental conditions, exposure duration, and potential health outcomes. Such investigations should account for ventilation, occupancy patterns, multiple indoor pollution sources, and differences in individual susceptibility. The resulting evidence could support the identification of population-specific exposure profiles and inform more targeted preventive measures and material selection strategies.

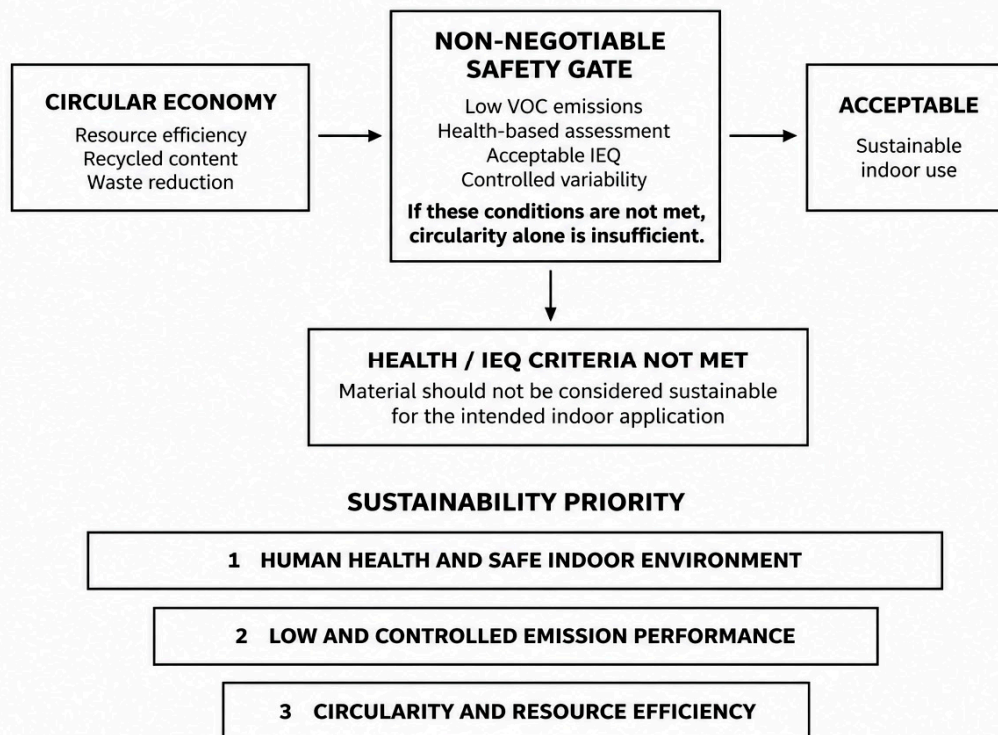
Higher education institutions could play an important role in strengthening awareness of VOC emissions and chemical safety in the transition towards circular construction. University curricula in civil engineering, architecture, construction management, and environmental sciences should integrate fundamental principles of indoor air quality, health-based material selection, VOC emission testing, and the specific uncertainties associated with recycled construction products. Case studies, laboratory demonstrations, interdisciplinary projects, and collaboration with construction product manufacturers could help students develop practical competencies in evaluating material sustainability alongside chemical safety. Such educational initiatives would support the preparation of future professionals capable of applying circular economy principles without compromising indoor environmental quality and occupant health.

Overall, the recommended measures are intended to build upon the existing European regulatory framework, harmonised testing standards, and established quality assurance principles rather than replace them. By addressing emerging challenges associated with recycled construction materials, these measures could support more comprehensive VOC risk management while contributing to circular economy objectives, indoor environmental quality, and the long-term protection of public health.

This relationship is summarised in Figure 5, emphasising that circular economy objectives should be pursued within health- and indoor environmental quality-based safety boundaries.

CIRCULARITY IS A MEANS — SAFE AND HEALTHY INDOOR ENVIRONMENTS ARE THE GOAL

Recycled content is sustainable only when material reuse does not compromise indoor environmental quality or health.



Circular economy objectives remain essential, but they should operate within health- and IEQ-based safety boundaries.

Figure 5. Health-first approach to integrating circular economy objectives with VOC emission control and indoor environmental quality.

12. Conclusions

The findings of this study support the following conclusions:

1. The increasing use of recycled interior finishing materials under circular economy policies highlights the need to ensure that improvements in resource efficiency are accompanied by an equivalent level of protection of indoor environmental quality and human health.
2. The European framework provides established methodologies for VOC emission assessment through standards such as EN 16516 and the ISO 16000 series, supported by complementary regulatory instruments including the CPR, REACH, and CLP.
3. Current VOC assessment approaches primarily evaluate the emission performance of finished construction products, while the specific uncertainties associated with recycled raw materials—including feedstock variability, material traceability, contamination history, and long-term emission consistency—are not explicitly addressed within the reviewed emission assessment frameworks.
4. Considerable differences remain between European Member States regarding VOC emission classification, product labelling, acceptance requirements, and market surveillance, resulting in heterogeneous regulatory implementation across the European construction market.
5. Latvia currently relies primarily on applicable European product requirements, project-specific specifications, procurement criteria, and voluntary certification schemes, while a dedicated national VOC emission classification or mandatory emission-labelling system comparable to those applied in several other European countries has not been established.

6. Future regulatory development should place greater emphasis on material traceability, quality assurance of recycled feedstocks, greater harmonisation of emission classification approaches, and risk-based market surveillance in order to support circular economy objectives while maintaining appropriate protection of indoor environmental quality and human health.

Author Contributions: Conceptualization, S.G. and R.B.; methodology, A.S., S.G. and R.B.; formal analysis, A.S., S.G. and R.B.; investigation, A.S.; writing—original draft preparation, A.S.; writing—review and editing, A.S., S.G. and R.B.; visualization, A.S.; project administration, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. European Commission. *A New Circular Economy Action Plan—For a Cleaner and More Competitive Europe*; European Commission: Brussels, Belgium, 2020.
2. Geissdoerfer, M.; Savaget, P.; Bocken, N.M.P.; Hultink, E.J. The Circular Economy—A new sustainability paradigm? *J. Clean. Prod.* **2017**, *143*, 757–768. [\[CrossRef\]](#)
3. Bray, F.; Laversanne, M.; Sung, H.; Ferlay, J.; Siegel, R.L.; Soerjomataram, I.; Jemal, A. Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA A Cancer J. Clin.* **2024**, *74*, 229–263. [\[CrossRef\]](#) [\[PubMed\]](#)
4. World Health Organization. *WHO Guidelines for Indoor Air Quality: Selected Pollutants*; WHO Regional Office for Europe: Copenhagen, Denmark, 2010.
5. Jones, A.P. Indoor air quality and health. *Atmos. Environ.* **1999**, *33*, 4535–4564. [\[CrossRef\]](#)
6. Salthammer, T.; Mentese, S.; Marutzky, R. Formaldehyde in the indoor environment. *Chem. Rev.* **2010**, *110*, 2536–2572. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Wolkoff, P. Indoor air pollutants in office environments. *Atmos. Environ.* **2013**, *69*, 371–383. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Mai, J.-L.; Yang, W.-W.; Zeng, Y.; Guan, Y.-F.; Chen, S.-J. Volatile organic compounds (VOCs) in residential indoor air during interior finish period: Sources, variations, and health risks. *Hyg. Environ. Health Adv.* **2024**, *9*, 100087. [\[CrossRef\]](#)
9. Cheng, Y.-H.; Lin, C.-C.; Lee, Y.-T.; Lin, Y.-C. The evaluation of BTEX and carbonyls emissions from recycled building materials. *Environ. Monit. Assess.* **2020**, *192*, 321. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Lin, C.-C.; Cheng, Y.-H.; Hsiao, C.-C. The study on material/air equilibrium partition coefficients and internal diffusion coefficients of volatile organic compounds within recycling green building materials. *Constr. Build. Mater.* **2025**, *490*, 142645. [\[CrossRef\]](#)
11. EN 16516:2017+A1:2020; Construction Products: Assessment of Release of Dangerous Substances—Determination of Emissions into Indoor Air. CEN: Brussels, Belgium, 2020.
12. ISO 16000-6:2021; Indoor Air—Part 6: Determination of Organic Compounds (VVOC, VOC, SVOC) in Indoor and Test Chamber Air by Active Sampling on Sorbent Tubes, Thermal Desorption and Gas Chromatography Using MS or MS FID. ISO: Geneva, Switzerland, 2021.
13. Domhagen, F.; Langer, S.; Sasic Kalagasidis, A. Theoretical Threshold for Estimating the Impact of Ventilation on Materials' Emissions. *Environ. Sci. Technol.* **2024**, *58*, 5058–5067. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Guo, H.; Murray, F.; Wilkinson, S. Evaluation of total volatile organic compound emissions from adhesives based on chamber tests. *J. Air Waste Manag. Assoc.* **2000**, *50*, 199–206. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Goodman, N.; Rajagopalan, P.; Francis, M.; Nematollahi, N.; Vardoulakis, S.; Steinemann, A. Indoor Volatile Organic Compounds in Prefabricated Timber Buildings—Challenges and Opportunities for Sustainability. *Buildings* **2024**, *14*, 3858. [\[CrossRef\]](#)
16. ISO 16000-3:2022; Indoor air—Part 3: Determination of Formaldehyde and Other Carbonyl Compounds in Indoor Air and Test Chamber Air—Active Sampling Method. ISO: Geneva, Switzerland, 2022.
17. Guo, S.; Liang, W. Volatile organic compounds and odor emissions characteristics of building materials and comparisons with the on-site measurements during interior construction stages. *Build. Environ.* **2024**, *252*, 111257. [\[CrossRef\]](#)

18. ISO 16000-9:2024; Indoor Air—Part 9: Determination of the Emission of Volatile Organic Compounds from Samples of Building products and furnishing—Emission Test Chamber Method. ISO: Geneva, Switzerland, 2024.
19. ISO 16000-11:2024; Indoor Air—Part 11: Determination of the Emission of Volatile Organic Compounds from Samples of Building Products and Furnishing—Sampling, Storage of Samples and Preparation of Test Specimens. ISO: Geneva, Switzerland, 2024.
20. Gorgolewski, M. *Resource Salvation: The Architecture of Reuse*; Wiley: Hoboken, NJ, USA, 2018.
21. Rose, C.M.; Stegemann, J.A. From Waste Management to Component Management in the Construction Industry. *Sustainability* **2018**, *10*, 229. [CrossRef]
22. Addis, B. *Building with Reclaimed Components and Materials: A Design Handbook for Reuse and Recycling*; Earthscan: London, UK, 2006.
23. Kommission Innenraumlufthygiene (IRK). *Recommendations for Good Indoor Air Quality in Timber Buildings*; Kommission Innenraumlufthygiene: Dessau-Roßlau, Germany, 2024.
24. Brown, S.K. Volatile organic pollutants in new and established buildings in Melbourne, Australia. *Indoor Air* **2002**, *12*, 55–63. [CrossRef] [PubMed]
25. Nakanishi, E.Y.; Poulin, P.; Blanchet, P.; Dubuis, M.-E.; Drouin, M.; Rhéaume, C.; Goupil-Sormany, I. A systematic review of the implications of construction materials on occupants' physical and psychological health. *Build. Environ.* **2024**, *257*, 111527. [CrossRef]
26. International Agency for Research on Cancer (IARC). Chemical Agents and Related Occupations. In *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*; IARC: Lyon, France, 2012; Volume 100F.
27. International Agency for Research on Cancer (IARC). Benzene. In *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*; IARC: Lyon, France, 2018; Volume 120.
28. Branco, P.T.B.S.; Sousa, S.I.V.; Dudzińska, M.R.; Ruzgar, D.G.; Mutlu, M.; Panaras, G.; Papadopoulos, G.; Saffell, J.; Scutaru, A.M.; Struck, C.; et al. A review of relevant parameters for assessing indoor air quality in educational facilities. *Environ. Res.* **2024**, *261*, 119713. [CrossRef] [PubMed]
29. European Commission. *Europe's Beating Cancer Plan*; COM(2021) 44 Final; European Commission: Brussels, Belgium, 2021.
30. Salthammer, T. Formaldehyde in indoor environments—40 years of research. *Indoor Air* **2022**, *32*, e13087.
31. OECD; European Commission. EU Country Cancer Profile: Latvia 2025. In *EU Country Cancer Profiles*; OECD Publishing: Paris, France, 2025. [CrossRef]
32. Regulation (EU) No 305/2011 of the European Parliament and of the Council Laying Down Harmonised Conditions for the Marketing of Construction Products (Construction Products Regulation); European Parliament and the Council of the European Union: Brussels, Belgium, 2011.
33. Regulation (EU) 2024/3110 of the European Parliament and of the Council of 27 November 2024 Laying Down Harmonised Rules for the Marketing of Construction Products and Repealing Regulation (EU) No 305/2011; European Parliament and the Council of the European Union: Brussels, Belgium, 2024.
34. Committee for Health-Related Evaluation of Building Products. Health-related evaluation of VOC, VVOC and SVOC emissions from construction products. *Bundesgesundheitsblatt* **2026**, in press.
35. Scutaru, A.M.; Witterseh, T. Risk mitigation for indoor air quality using the example of construction products—Efforts towards harmonization of the health-related evaluation in the EU. *Int. J. Hyg. Environ. Health* **2020**, *229*, 113588. [CrossRef] [PubMed]
36. European Commission; Joint Research Centre. *Harmonisation Framework for Health Based Evaluation of Indoor Emissions from Construction Products in the European Union Using the EU-LCI Concept*; Publications Office of the European Union: Luxembourg, 2013. [CrossRef] [PubMed]
37. Regulation (EC) No 1907/2006 of the European Parliament and of the Council (REACH); European Parliament and the Council of the European Union: Brussels, Belgium, 2007.
38. Regulation (EC) No 1272/2008 of the European Parliament and of the Council (CLP); European Parliament and the Council of the European Union: Brussels, Belgium, 2008.
39. AgBB. *Health-Related Evaluation of Emissions of Volatile Organic Compounds (VVOC, VOC and SVOC) from Building Products*; Committee for Health-related Evaluation of Building Products (AgBB): Berlin, Germany, 2026.
40. French Ministry for Ecological Transition. *Décret Relatif à L'étiquetage des Émissions de Polluants Volatils des Produits de Construction et de Décoration*; French Ministry for Ecological Transition: Paris, France, 2011.
41. Belgian Federal Public Service Health. *Royal Decree of 8 May 2014 Establishing Threshold Levels for Emissions into the Indoor Environment from Construction Products for Certain Intended Uses*; Belgian Federal Public Service Health: Brussels, Belgium, 2014.
42. RTS. *M1 Emission Classification of Building Materials*; RTS: Helsinki, Finland, 2023.
43. Government of Romania. Government Decision No. 699 of 12 June 2003 on Measures to Reduce Emissions of Volatile Organic Compounds Resulting from the Use of Organic Solvents in Certain Activities and Installations. Official Gazette of Romania, No. 489. 8 July 2003. Available online: <https://legis.medleg.ro/legislatie/2003-hg-699> (accessed on 13 October 2026).

44. Government of Romania. Government Decision No. 735 of 7 June 2006 on Limiting Emissions of Volatile Organic Compounds Due to the Use of Organic Solvents in Certain Paints, Varnishes and Vehicle Refinishing Products. Official Gazette of Romania, No. 521. 16 June 2006. Available online: <https://infodosar.ro/monitorul-oficial/guvernul/175205-hotarare-735-2006> (accessed on 13 October 2026).
45. Cabinet of Ministers of Latvia. *Regulation No. 353 "Requirements for Green Public Procurement and Procedures for the Application Thereof"*; As Amended; Cabinet of Ministers of Latvia: Riga, Latvia, 2017.
46. VARAM. *Green Public Procurement*; (Under the Responsibility of VARAM Until 9 June 2026); Ministry of Smart Administration and Regional Development of the Republic of Latvia: Riga, Latvia, 2026.
47. PTAC. *Information for Professionals: Construction Products*; Consumer Rights Protection Centre of Latvia: Riga, Latvia, 2026.
48. Cabinet of Ministers of Latvia. *Regulation No. 156 "Procedures for Market Surveillance of Construction Products"*; Cabinet of Ministers of Latvia: Riga, Latvia, 2014.
49. Cabinet of Ministers of Latvia. *Regulation No. 302 "Regulations Regarding Waste Classification and Properties Which Render Waste Hazardous"*; As Amended; Cabinet of Ministers of Latvia: Riga, Latvia, 2011.
50. *Waste Management Law. Waste Management Law of the Republic of Latvia*; As Amended; Saeima: Riga, Latvia, 2010.
51. Cabanes, A.; Valdés, F.J.; Fullana, A. A review on VOCs from recycled plastics. *Sustain. Mater. Technol.* **2020**, *25*, e00179. [[CrossRef](#)]
52. Wagner, S.; Schlummer, M. Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. *Resour. Conserv. Recycl.* **2020**, *158*, 104800. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.