



HAL
open science

Evaluation of the seasonal variation of VOC surface emissions and indoor air concentrations in a public building with bio-based insulation

Tamara Braish, Liselotte Tinel, Laurence Depelchin, Vincent Gaudion, Yves Andres, Cécile Caudron, Emmanuel Antczak, Franck Brachelet, Nadine Locoge

► To cite this version:

Tamara Braish, Liselotte Tinel, Laurence Depelchin, Vincent Gaudion, Yves Andres, et al.. Evaluation of the seasonal variation of VOC surface emissions and indoor air concentrations in a public building with bio-based insulation. *Building and Environment*, 2023, 238, pp.110312. 10.1016/j.buildenv.2023.110312. hal-04086653

HAL Id: hal-04086653

<https://hal.science/hal-04086653>

Submitted on 5 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Evaluation of the Seasonal Variation of VOC Surface Emissions and Indoor Air**
2 **Concentrations in a Public Building with Bio-Based Insulation**

3 Tamara Braish^a, Liselotte Tinel^{a,*}, Laurence Depelchin^a, Vincent Gaudion^a, Yves Andres^b,
4 Cécile Caudron^c, Emmanuel Antczak^d, Franck Brachelet^d, Nadine Locoge^a

5

6 ^aIMT Nord Europe, Institut Mines-Télécom, University of Lille, Centre for Energy and
7 Environment, F-59000, Lille, France

8 ^bIMT Atlantique, GEPEA UMR CNRS 6144, F-44307, Nantes, France

9 ^cCerema, F-59000, Lille, France

10 ^dUniversité d'Artois, IMT Nord Europe, Junia, University of Lille, ULR 4515, Laboratoire de
11 Génie Civil et géo-Environnement (LGCgE), F-62400, France

12

13 **Corresponding author: liselotte.tinel@imt-nord-europe.fr*

14

15 **Abstract**

16 The use of bio-based insulation materials is widely spreading in buildings. Due to their
17 organic load, they can be an important source of Volatile Organic Compounds (VOCs). This
18 study is among the first that evaluates the spatial and seasonal in-field VOC surface
19 emissions from bio-based and conventional building structures as a whole, in a French public
20 building insulated with wood wool. In addition to surface emissions, measurements of VOC
21 concentrations in indoor air were taken. Results showed that a spatial difference (up to 5
22 times) in VOC emissions was observed due to the inhomogeneity of the surface. Moreover,
23 the cardinal orientation of building structures with the same constitution induced a
24 difference (up to a factor 30) in emission rates due to the exposure to different
25 hygrothermal conditions. The variation in temperature and relative humidity between
26 seasons led to higher summer VOC emissions and indoor air concentrations. In addition,
27 indoor VOC concentrations were shown to be higher at night compared to daytime due to
28 the decreased ventilation rate. Furthermore, an interesting approach was developed in this
29 study to have a primary overview of the impact of surface emissions on indoor VOC levels.
30 Results confirmed that the three bio-based walls have no significant specific VOC emissions
31 at high rates compared to the floor and the ceiling. Bio-based insulations showed no impact
32 on microbial indoor air concentrations during the two seasons. Moreover, no detected VOCs
33 could be attributed to microbial development as they were also emitted from building
34 materials.

35 **Keywords**

36 Bio-based insulations, VOC, in-field emissions, indoor air, seasonal campaigns

37 **Highlights**

- 38 • Spatial, temporal, and seasonal variations affect in-field measured VOC emissions.
- 39 • VOC emissions rates from bio-based and conventional structures are comparable.
- 40 • No specific VOCs are exclusively emitted from bio-based surfaces.
- 41 • Emissions from building structures contribute moderately to VOC indoor air levels.
- 42 • No direct link between VOCs and microbial development could be evidenced.

43 **1. Introduction**

44 Indoor air pollution was traditionally overlooked compared to outdoor air pollution.
45 However, studies showed that the level of some organic pollutants is two to four times
46 higher indoors than outdoors [1]. Nowadays, indoor air quality (IAQ) receives large public
47 attention as people spend most of their times indoors, which has been exacerbated during
48 the COVID crisis [2]. During this time, they are exposed to indoor pollutants which can lead
49 to adverse health effects. Volatile organic compounds (VOC) are widely spread indoor
50 pollutants. These compounds can originate from anthropogenic activities, infiltration of
51 outdoor air, or indoor products emissions [3].

52 The indoor sources of VOC emissions can be mainly divided into two categories: short-term,
53 intensively emissive sources, such as cooking activities, air fresheners, and cleaning products
54 [4], and long-term emissive sources, like building materials and furniture [5], [6]. The latter
55 are considered an important source of VOCs. Molhave et al. found, in their Danish twin
56 apartment study, that the concentration of total VOCs (TVOC) in an unoccupied apartment
57 one year after construction was equal to 0.5 mg.m^{-3} , due to emissions from building
58 materials and furniture [7]. Several European regulations, labels, schemes, and directives
59 were established to classify building and construction materials based on their VOC
60 emissions in order to minimize human's indoor exposure to these compounds. Among them
61 is the French label issued in 2011 by the Ministry of Ecology [8], the German Committee for
62 Health-related Evaluation of Building Products (AgBB) [9], M1 Finnish label, Indoor Climate
63 Label (ICL), Natureplus, and the Blue Angel label [10]. Similarly, the European directive
64 2004/42/CE, was issued in 2004 to reduce air pollution by limiting the total VOC content in
65 certain paints and consumer products [11]. In 1988, the European directive 89/106/EEC was
66 founded with the aim of harmonizing the test methods, the declaration of performance
67 values, and the conformity assessment methods of construction products between member
68 states of the European Union [12]. Later on, this directive was replaced by the regulation
69 305/2011/EU in 2011 [13].

70 In France, approximately 20 million buildings were built before the introduction of the
71 thermal regulations in 1975, and these buildings account for more than 75% of energy
72 consumption in the housing sector [14]. However, environmental awareness and fights
73 against global warming led to the first thermal regulations in 1975, imposing thermal
74 insulation in walls and the regulation of heating systems with the aim of reducing energy
75 consumption. In this context, and as part of the Grenelle Environment agreements, a French
76 law was issued in 2009 stating that the primary energy consumption in buildings should be

77 reduced by 38% by the year 2020 [15]. It also engaged to renovating 400 thousand dwellings
78 per year starting from the year 2013.

79 The construction or demolition of buildings as well as the production and use of building
80 materials account for high carbon dioxide emissions. Therefore, the French Ministry of
81 Ecology has issued new environmental regulation to be applied from January 2022 aiming to
82 reduce the carbon footprint of new buildings over their estimated 50-year life cycle [16].
83 Hence, finding new building materials, especially insulation materials, which enable the
84 decrease of energy consumption and greenhouse gas emissions is necessary. The use of low
85 carbon materials and reuse of recycled materials are effective approaches to reduce carbon
86 dioxide emissions by up to 28% at the construction site [17]. The use of natural materials
87 and in particular bio-based materials, is also found to reduce the embodied energy and
88 carbon dioxide impact of construction [18], [19]. As a result, the use of bio-based insulation
89 materials has been spreading widely due to their lower production energy and enhanced
90 insulation properties [20]. In 2016, bio-based insulations represented already 60% of the
91 available bio-sourced products on the French market, illustrating the growth of this sector
92 [21]. However, taking into consideration the inherent carbon-based chemical structure of
93 these materials, bio-based insulations are a potential source of VOC emissions and could
94 potentially contribute to IAQ deterioration. Moreover, being composed of natural fibers,
95 bio-based insulation materials could serve as a substrate for the development of
96 microorganisms, such as fungi, under highly humid conditions [22]. Upon microbial
97 development, fungi could emit microbial VOCs (mVOCs) [23].

98 Several studies evaluate VOC emissions from bio-based insulations in test chambers. Their
99 results showed that mainly acetic acid, aldehydes, alcohols, and aliphatic hydrocarbons are
100 the main VOCs emitted from hemp, flax, cellulose, and wood wool insulation materials [5],
101 [18], [24]–[27]. When comparing VOC emissions between bio-based and conventional
102 building materials, bio-based materials are generally classed as low-emitting [18], [28].
103 However, in some other studies, wood insulations have shown to have the highest TVOC and
104 aldehydes emissions compared to other building materials [19], [26], [29].

105 However, most of the existing studies that characterize VOC emissions from bio-based
106 materials, particularly insulation, are based on laboratory tests employing test chambers or
107 emission cells to characterize VOC emissions from individual materials that are part of
108 different building structures (walls, ceiling, and floor). However, until today, and to our
109 knowledge, there are only a few studies that report the on-site emission of VOCs from a
110 building structure as a whole (wall or floor) [30], [31]. Therefore, the original objective of this
111 study is to characterize the in-situ surface emissions of the major VOCs emitted from the
112 building structures as an entity, especially those containing bio-based insulation, which could
113 help to have a better perspective on IAQ. Moreover, since emissions from building materials
114 and thus building structures can be greatly affected by the change in temperature and
115 relative humidity [32]–[35], it is interesting to evaluate the seasonal variation on VOC
116 emissions.

117 In this context, two seasonal, summer and winter, field campaigns took place at a public
118 building (town hall) in the North of France. The choice of the building was mainly based on

119 two factors. The first was that the selected building should contain bio-based insulation
120 materials to answer the implemented approach of the project in study. The second criterion
121 was that the targeted building should be publicly accessible, as these buildings are less
122 affected by occupant-specific activities (such as cooking and cleaning), and since a wider
123 public can be impacted by IAQ in these buildings.

124 This paper presents in its first part the spatial and seasonal variation of VOC surface
125 emissions from several building structures, in addition to the comparison of VOC emissions
126 from building structures including bio-based insulation to conventional ones. The second
127 part of this paper discusses the contribution of bio-based and conventional surface
128 emissions to indoor air concentrations in a real-world building, an understudied scale for
129 VOC measurements. This paper also includes indoor air microbial measurements in order to
130 estimate the potential contribution of microorganism to VOC emission, more specifically
131 mVOCs.

132

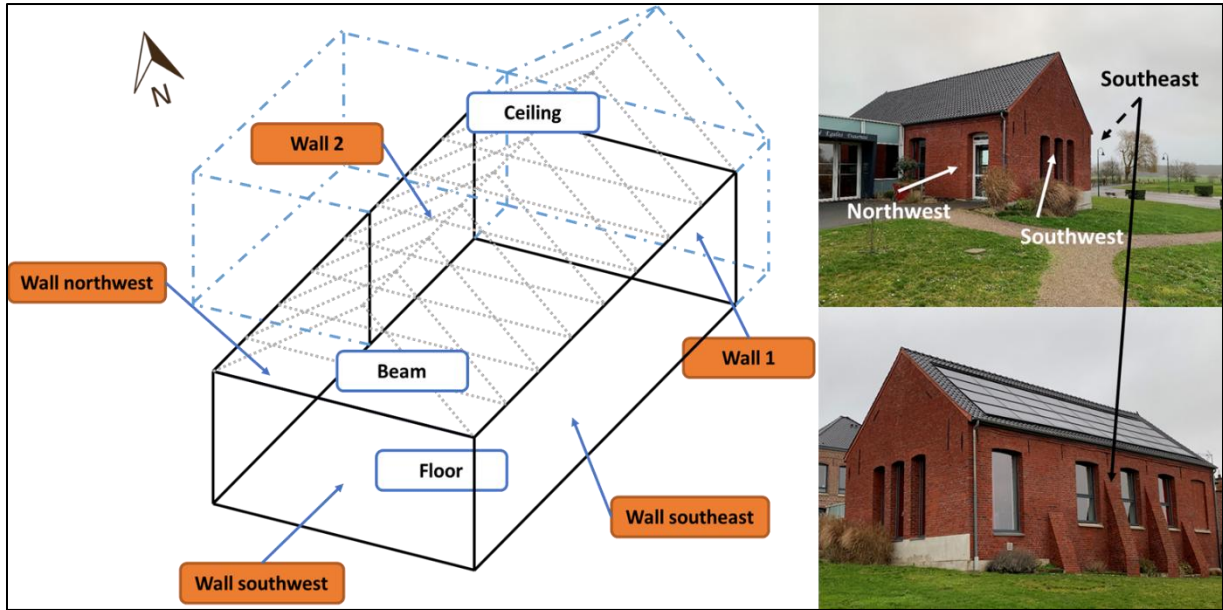
133 **2. Materials and Methods**

134 *2.1. Selection of the Building*

135 The town hall was renovated in 2014, with wood wool as the insulation material, which is
136 good for our study to prevent the overestimation of VOC emissions from new building
137 materials. The wedding hall, a semi-detached building, was selected to conduct this study.
138 The choice of the hall was based on the presence of the greatest number of surfaces
139 containing bio-based building materials compared to the other surfaces. Moreover, it was
140 also less often occupied, which made it more accessible for conducting the desired
141 experiments, and thus IAQ in this hall was less impacted by occupants' activities. The bio-
142 based structures of the hall consisted of the floor and three outer walls insulated with wood
143 wool, in addition to apparent wood structures (beam). The surface area of the floor was
144 about 85 m² for a room volume of 441 m³. Two seasonal field campaigns were carried out in
145 this building to evaluate VOC surface emissions and indoor air concentrations. The summer
146 campaign was conducted from 8 to 19 July 2019 while the winter campaign was carried out
147 from 28 January to 3 February 2020.

148 Figure 1 shows a schematic representation of this room. It included three walls exposed to
149 the exterior and constituted, from the exterior to the interior, of brick, followed by a layer of
150 120 mm thick wood wool, a vapor barrier, another 60 mm layer of wood wool, and two 18
151 mm plasterboards covered with a layer of painting, as shown in figure 2. These three walls
152 were oriented southeast (SE), southwest (SW), and northwest (NW). The northeast-oriented
153 wall (wall 1) in addition to half of the northwest-oriented wall (wall 2) were interior walls
154 with lighter insulation with rockwool of 45 mm thickness. The floor was made up of floating
155 parquet insulated by wood wool flakes (220 mm) in between. The ceiling was composed of
156 prefabricated sandwich panels insulated with 180 mm polyurethane foam and covered with
157 18 mm plasterboard. On the SE side, the roof was equipped with solar panels. The hall also
158 showed a number of wood beams from the roof structure. It also contained some tables, a
159 group of chairs, and some plants.

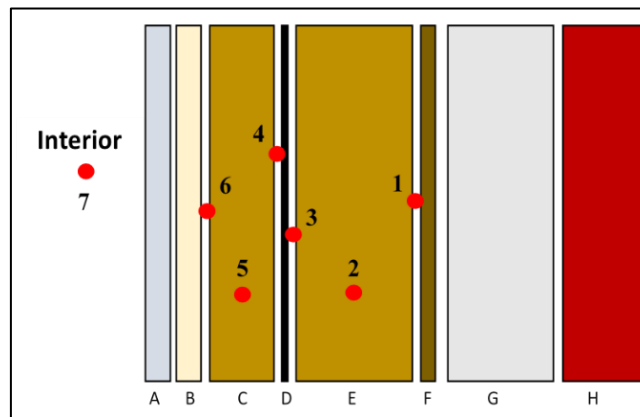
160 However, the three walls (SE, SW, and NW) containing wood wool will be considered the
 161 only bio-based surfaces in this study in order to facilitate the comparison of VOC emissions
 162 between similar building structures. In addition, the total surface area of the used bio-based
 163 insulation in the three walls is greater than that of the floor and the beam compared to the
 164 volume of the hall, and thus VOC emissions from bio-based materials are expected to be
 165 more remarkable from these walls rather than from the other bio-based surfaces.



166
 167 **Figure 1. A schematic representation of the marriage hall at the town hall**

168
 169 **2.2. Monitoring the Temperature and Relative Humidity in the Bio-based Walls**

170 Since surface emissions can be greatly affected by the change in temperature and relative
 171 humidity, 7 sensors (HMP 60 Vaisala) were installed for one year inside the SE wall to
 172 monitor the change in temperature (T) and relative humidity (RH) at different spots of the
 173 structure (sensors 1 to 6) and inside the wedding hall (sensor 7) (figure 2).



174
 175 **Figure 2. The installation of 7 T and RH sensors, indicated by numbers 1-7, inside the**
 176 **southeast wall. A and B: plasterboards, C: 60 mm wood wool, D: vapor barrier, E: 120 mm**
 177 **wood wool, F: air blade, G: concrete block, and H: brick**

178

179 2.3. VOC Surface Emissions

180 2.3.1. Instrumentation

181 Two FLECs (Field and Laboratory Emission Cells) were used to characterize VOC emissions
182 from the eight different surfaces as indicated in figure 1: the three exterior walls (SE, SW,
183 and the exterior part of the NW wall), two interior walls (wall 1 and part of the NW wall,
184 referred to as wall 2), the floor, the ceiling, and a beam. Once installed on a surface, the
185 FLECs were supplied with a flux of 500 mL min⁻¹ zero air provided by a zero-air generator
186 (Clained Brezza, Italy) at ambient temperature and 50% relative humidity (provided by a
187 system of bubblers).

188

189 2.3.2. Sampling

190 Two surfaces were characterized simultaneously per day. Active sampling occurred during
191 daytime (from approximately 9h-17h) 24 hours after the installation of the FLEC on the
192 surface, following the European standard ISO 16000-10 [36]. Sampling was done
193 simultaneously using 2,4-dinitrophenylhydrazine (DNPH) cartridges, for carbonyl
194 compounds, and Tenax TA tubes, for the other emitted VOCs. Before sampling, the Tenax TA
195 tubes were conditioned at 250 °C under a nitrogen flow for at least 8 hours. After sampling,
196 the Tenax TA tubes were tightly closed and kept at ambient temperature while the DNPH
197 cartridges were stored in the freezer (- 21 °C) until analysis, which was realized at the end of
198 each campaign. The sampling flow rate and time were adjusted to have a sampling volume
199 equal to 36 L. Potential breakthrough of VOCs on the adsorbents was considered by using
200 two adsorbent supports in series, for both DNPH and Tenax TA sampling. Table 1
201 summarizes the sampling from each surface with the number of collected samples as well as
202 the sampling dates and hours during both seasons.

203 Sampling of the five different walls took place at about 1.5 m height. However, as shown in
204 table 1, sampling of the SE wall occurred at two different heights (0.5 and 1.5 m) during the
205 summer campaign to evaluate the spatial effect on VOC emissions.

206

207 **Table 1. A summary of the number of samples collected from each surface and their**
208 **correspondent sampling dates and hours; n is the number of collected samples**

Surface	Summer			Winter		
	n	Date	Sampling time	n	Date	Sampling time
Beam	1	08/07/2019	14h – 17h	3	29/01/2020	15h – 00h
Floor	2	08/07/2019	11h – 17h	2	01/02/2020	09h – 15h
Wall 1	2	10/07/2019	11h – 17h	3	03/02/2020	09h – 17h
Wall 2	1	10/07/2019	14h – 17h	3	03/02/2020	08h – 17h
Wall SW	1	12/07/2019	14h – 17h	3	29/01/2020	15h – 00h (+1)
Wall SE-1.5 m	5	13-14/07/2019	04h - 00h (+1)	2	01/02/2020	09h – 15h

Wall SE-0.5 m	3	14/07/2019	22h - 07h (+1)	-	-	-
Wall NW	3	16/07/2019	02h - 14h	3	28/01/2020	08h – 17h
Ceiling	1	16/07/2019	14h – 17h	3	28/01/2020	08h – 17h

209

210 Moreover, in order to evaluate VOC concentration in indoor air and characterize the impact
 211 of surface emissions on indoor air VOC levels, a 24-hour sampling (corresponding to 8 x 3 h-
 212 samples) of indoor ambient air took place, during both seasons. A field blank was collected
 213 every sampling day by opening a DNPH cartridge or Tenax TA tube for few seconds and then
 214 tightly closing it.

215

216 2.3.3. Sample Analysis

217 DNPH cartridges were first eluted by 3 mL acetonitrile (velocity = 1.5 mL min⁻¹) and then
 218 analyzed using an HPLC-UV (High Performance Liquid Chromatography coupled to Ultra
 219 Violet Detector, Dionex Ultimate 3000, Thermo Scientific U.S.A.) equipped with an Acclaim
 220 RSLC Carbonyl column (2.2 μm, 2.1 x 150 mm, Thermo Scientific, U.S.A.). Tenax TA tubes
 221 were analyzed using a TD-GC-MS/FID system (Thermal Desorption Gas Chromatography,
 222 Clarus 680 - Mass Spectrometry and Flame Ionization Detection, Clarus SQ 8T, Perkin Elmer,
 223 U.S.A.) with a CP-Sil 5CB column (60 m x 0.25 mm x 1 μm, Agilent U.S.A.). A description of
 224 the used TD-GC-MS/FID and HPLC-UV methods is presented in tables S1 and S3, respectively,
 225 of the supporting information.

226 Calibrations were run before each HPLC and GC analysis. The 20 Carbonyls analyzed by HPLC
 227 were quantified using their individual calibration coefficients. These include formaldehyde,
 228 acetaldehyde, propanone, acrolein, propanal, butanal, crotonaldehyde, benzaldehyde,
 229 pentanal, isopentanal, tolualdehyde (o-, m-, and p-), methylpropenal, methyl vinyl ketone,
 230 methyl ethyl ketone, glyoxal, methylglyoxal, hexanal, and 2,5-dimethylbenzene. For the TD-
 231 GC-FID quantification a calibration was performed with authentic standards of benzene in
 232 addition to the eight VOCs (toluene, ethylbenzene, xylene, styrene, 2-butoxyethanol,
 233 tetrachloroethylene, 1,2,4-trimethylbenzene, and 1,4-dichlorobenzene) targeted by the
 234 French label [8]. Other detected VOCs in addition to TVOCs were quantified by FID as
 235 toluene equivalent. The emission of TVOCs from building materials is also standardized by
 236 the French label [37]. There exist several methods for calculating TVOCs [38]; however, in
 237 this study the ER of TVOCs was determined based on the method provided by the European
 238 Standard ISO 16000-6, where they are defined as the sum of VOCs ranging between C₆ and
 239 C₁₆ quantified by TD-GC-FID as toluene equivalent [39]. The limit of detection (LOD) of the
 240 different VOCs used for calibration in GC and HPLC methods are shown in tables S2 and S4,
 241 respectively.

242

243 2.4. Characterizing Micro-Organism Levels in Indoor Air

244 The microbial concentrations in indoor air were measured during winter and summer using a
 245 Microbial Air Monitoring System (MAS-100). Seven agar culture media were chosen to

246 represent the fungal and bacterial populations. Measurements were taken from spots next
247 to the walls with bio-based insulation: next to the NW wall in summer and from the same
248 spot and another one next to the SW wall in winter. Moreover, sampling occurred in the
249 morning and the afternoon during both seasons. The sampling flow rate of the MAS-100 was
250 set at 100 mL min⁻¹ and the sampling time at 5 min. Then, the petri dishes containing the
251 agar media were incubated for 4 to 5 days at 25 °C after sampling and before counting the
252 colony-forming units (CFU).

253

254 **3. Results and Discussion**

255 *3.1. VOC Surface Emissions*

256 VOC surface emission will be presented in terms of emission rate (ER, µg m⁻² h⁻¹), calculated
257 based on the following equation:

$$ER = \frac{C \times Q}{S} \quad (1)$$

258 where C is the determined VOC concentration measured in the sampling flow collected from
259 the FLEC placed on each surface (µg m⁻³), Q is the air flow rate into the FLEC and is equal to
260 0.03 m³ h⁻¹, and S is the tested surface area of the building structure, which is equal to the
261 surface area of the FLEC (0.0177 m²).

262 17 VOCs in addition to TVOCs were chosen to be presented in this study based on the
263 importance of their surface emission rate (ER ≥ 1 µg m⁻² h⁻¹ from at least one characterized
264 surface during summer or winter). However, since VOC emissions were weak in winter
265 compared to summer (discussed in parts 3.1.3 and 3.1.4), only summer emissions will be
266 discussed in the following two parts (3.1.1 and 3.1.2) due to the increased uncertainty in
267 quantifying compounds at low emission rates (close to the limit of quantification, LOQ).

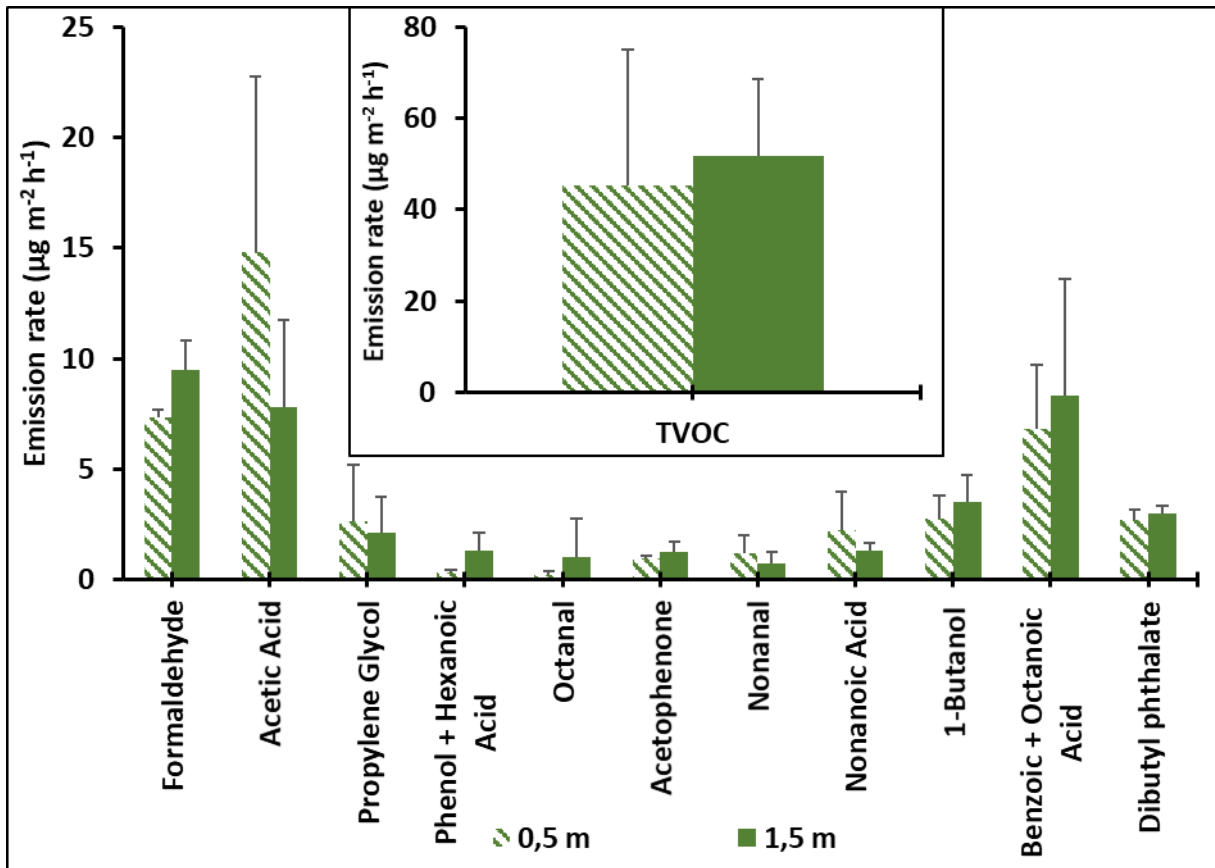
268

269 *3.1.1. Spatial Comparison of VOC Surface Emissions in Summer*

270 Figure 3 shows the summer surface emissions of the major VOCs from the SE wall at two
271 different heights (0.5 and 1.5 m) measured on two consecutive days (13 and 14/07/2019).
272 The ratio (R) of individual VOCs emission rates from the same building structure at two
273 different spots can be variable, ranging from 1 to 5. For most of the compounds, in addition
274 to TVOCs, emissions at 0.5 and 1.5 m were approximately equivalent (R ≈ 1). However, this
275 difference is higher (R up to 5 times) for the weakly emitted VOCs (ER < 1 µg m⁻² h⁻¹), such as
276 octanal and the coelution of phenol and hexanoic acid, since the uncertainty in quantifying
277 the detected compounds increases as we are close to LOQ, as previously mentioned. This
278 slight variation can be explained by the non-uniform variation of temperature and humidity
279 within the different layers of the wall structure or the inhomogeneity of the surface leading
280 to heterogeneity in VOC surface adsorption and desorption.

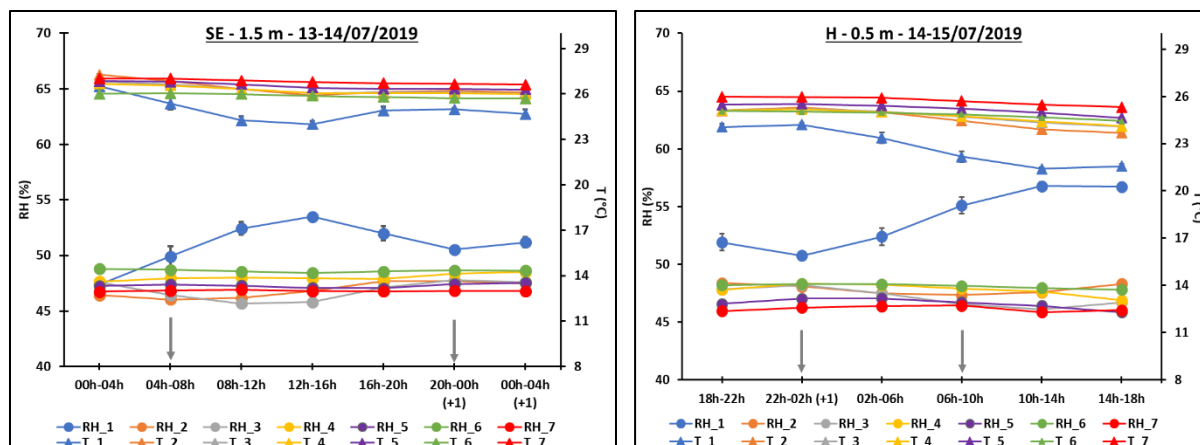
281 To eliminate the effect of the hygrothermal variation within the wall on VOC emissions at
282 different heights, the variations in T and RH were monitored within the SE wall (sensors 1 to
283 6 in figure 2) and in the room (sensor 7 in figure 2) during the sampling days at 0.5 and 1.5

284 m. As shown in figure 4, the T and RH were very similar between the two heights at each
 285 measurement point in the wall, and almost stable between the two sampling days, indicating
 286 that the variability in T and RH cannot explain the observed variation of VOC emissions from
 287 the same surface at two different heights. Another probable hypothesis is the
 288 inhomogeneity of the surface which might have an effect on the diffusivity of VOCs from the
 289 bulk of the material to the surface [40], and can therefore result in heterogenous VOC
 290 emissions from different parts of the same surface. Thus, the variation in VOC emissions
 291 should be considered when interpreting the obtained results.



292
 293 **Figure 3. VOC surface emissions from the southeast wall at two different heights: 0.5 and**
 294 **1.5 m; the error bars represent one standard deviation of 3 and 5 measurements at 0.5 m**
 295 **and 1.5 m, respectively**

296



297 **Figure 4. The change in temperature (▲, right axis) and relative humidity (●, left axis) within**
 298 **the wall-oriented Southeast (SE) during the sampling days: 13-14/07/2019 at 1.5 m and 14-**
 299 **15/07/2019 at 0.5 m. The sensors are placed within the wall in order from 1 (exterior) to 7**
 300 **(inside the wedding hall). Each presented value is the average of 24 measurements. The**
 301 **sampling period during these days is indicated by arrows on the graphs**

302

303 3.1.2. VOC Surface Emissions from the three Bio-based Walls in Summer

304 Surface emissions from the three bio-based walls in the wedding hall were compared to
 305 evaluate the effect of wall orientation, and thus different hygrothermal conditions, on VOC
 306 emissions. Table 2 shows the major VOC emissions from the three walls that contain wood
 307 wool as insulation material during summer.

308 In general, although emission rates vary largely during summer, the same emission profiles
 309 can be seen in the three walls, with a dominance of oxygenated VOCs. Overall, for the three
 310 walls, the largest emissions are measured for formaldehyde, acetic acid, the co-eluted
 311 benzoic and octanoic acids, and nonanoic acid. These compounds can be emitted by the
 312 wood wool insulation present in the walls [41]. In the study of Maskell et al., wood fiber
 313 emitted high concentrations of acetic acid [18]. This VOC may come from the cleavage of
 314 acetyl groups of the hemicellulose, while aldehydes mainly originate from the oxidative
 315 decay of cellulose and lignin present in the wood [42].

316 The difference in the emission of the most emitted VOCs and TVOCs varies from 1 to 5 times
 317 between the walls; however, this difference can increase up to 30 times for the minor VOCs
 318 ($ER < 1 \mu\text{g m}^{-2} \text{h}^{-1}$) due to the increased uncertainty associated to quantifying VOCs near
 319 LOQ. Moreover, the highest emissions for most of the quantified VOCs and TVOCs were
 320 observed for the SW wall, followed by the SE wall, and the NW wall. In the morning, the SE
 321 wall is exposed to the sun, but at the beginning of the afternoon and until the end of the
 322 day, the wall-oriented SW becomes fully exposed to the sun. The NW wall is located in the
 323 shade, with almost no sun exposure throughout the day. This difference in exposure may
 324 explain the higher emissions from the walls oriented SW and SE compared to the NW wall,
 325 as higher temperatures can induce higher emissions of VOCs [32]–[34]. The relatively high
 326 TVOC emission rate from the SW wall was driven by, in addition to the major emitted VOCs,
 327 species with $ER \leq 1 \mu\text{g m}^{-2} \text{h}^{-1}$ which are thus not shown in this list. This wall also shows high

328 formaldehyde emissions, which might point towards a local difference in this wall or
 329 anthropogenic contamination.

330
 331
 332
 333
 334
 335
 336
 337

338 **Table 2. VOC surface emission rates ($\mu\text{g m}^{-2} \text{h}^{-1}$) of the 8 surfaces at the wedding hall during**
 339 **summer**

VOC	SE	SW	NW	Wall 1	Wall 2	Floor	Beam	Ceiling
Formaldehyde	9.5	30.8	5.8	9.4	26.7	17.0	9.6	29.7
Propanal	<LOD	1.7	<LOD	<LOD	1.6	<LOD	0.5	1.8
Pentanal	<LOD	1.2	<LOD	<LOD	1.3	0.6	<LOD	1.7
Tolualdehyde	1.3	2.1	0.8	1.2	2.2	1.0	2.5	1.8
Furfural	0.2	1.3	0.2	0.1	0.6	0.4	<LOD	1.4
Octanal	1.0	1.7	0.1	0.1	0.4	0.7	0.4	2.4
Nonanal	0.8	2.8	0.6	0.6	0.8	2.4	0.3	3.4
Acetic Acid	7.8	3.7	7.7	1.8	2.6	29.0	0.3	0.9
Phenol + Hexanoic Acid	1.3	1.6	0.4	0.2	1.3	1.6	2.6	3.3
Benzoic + Octanoic Acids	10.4	5.9	5.0	14.5	1.3	8.5	0.3	15.6
Nonanoic Acid	1.3	4.0	1.2	2.4	1.5	1.1	4.1	14.1
1-Butanol	3.5	0.6	2.3	1.2	0.5	1.3	0.1	0.6
2-Ethyl-1-hexanol	0.7	2.9	0.4	0.7	0.9	1.0	0.3	9.7
Propylene Glycol	2.1	1.6	1.6	<LOD	1.5	1.0	0.2	1.3
Acetophenone	1.3	0.5	0.6	1.3	0.8	2.1	0.1	0.6
Dimethylglutarate	0.4	2.2	0.3	0.4	1.3	0.6	8.7	6.2
Dibutyl Phthalate	3.0	0.1	2.2	4.3	0.4	4.2	7.7	1.8
TVOC	51.7	73.1	37.2	61.4	25.2	101.0	41.3	130.8

340 <LOD: Analytical limit of detection (for carbonyls by HPLC-UV and for all the other VOCs by TD-GC-FID), TVOC:
 341 The sum of all VOCs quantified by GC-FID between C6 and C16 as equivalent toluene

342

343 3.1.3. VOC Emissions from the different Surfaces

344 Tables 2 and 3 sum up the VOC seasonal emissions from the 8 characterized surfaces in the
 345 wedding hall during summer and winter, respectively. Even if concentration in this part and
 346 the previous part (3.1.2.) are on the summer VOC emissions, it is worth mentioning that
 347 winter emissions were more homogeneous among the three walls compared to summer
 348 emissions. This can be related to the higher temperatures during summer, which may lead to

349 higher temperature variability within the different parts of the wall, and thus can increase
350 the inhomogeneity in VOC emissions.

351 For each of the VOCs, the highest emission rate from any of the characterized surfaces is
352 indicated in bold in both tables (tables 2 and 3). The highest emission rates of most of the
353 individual VOCs (10 out of 17), as well as for TVOCs, were from the ceiling during both
354 seasons. Wall 2 showed the lowest TVOC emissions in winter and summer (8.1 and 25.2 μg
355 $\text{m}^{-2} \text{h}^{-1}$, respectively). This might be explained here again by the exposure to the sun, where
356 the ceiling is the most exposed, and likely the surface undergoing the largest variations of
357 temperature during the day, while wall 2 is not directly exposed to the sun, as it is fully
358 interior to the building. The strongest emitted VOCs from all surfaces cumulated are
359 formaldehyde and acetic acid, in winter (23 and 17.9 $\mu\text{g} \text{m}^{-2} \text{h}^{-1}$, resp.) as well as in summer
360 (138.5 and 53.8 $\mu\text{g} \text{m}^{-2} \text{h}^{-1}$, resp.). The co-eluted benzoic and octanoic acids as well as the co-
361 elution of phenol and hexanoic acid also show high emission rates, but this needs to be
362 relativized as these represent the sum of two individual emission rates.

363 It is interesting to compare the VOC emissions from the three bio-based structures (SE, SW,
364 and NW walls) to emissions from the other structures (wall 1, wall 2, floor, beam, and
365 ceiling). When comparing the VOC emissions from the most emissive surface (ceiling) to
366 those from the bio-based walls in summer, we observe that emissions are generally lower, as
367 illustrated by the lower TVOC emission rates, despite the relatively high TVOC values for the
368 SW wall, as discussed in the previous section. Hence, for individual VOCs, emission rates are
369 comparable or lower for most compounds. However, emissions are higher from the bio-
370 based walls for some VOCs, notably propylene glycol and 1-butanol. These two compounds
371 are however also emitted by the other surfaces, and the difference in emission rate is
372 relatively small (max. 2.2 $\mu\text{g} \text{m}^{-2} \text{h}^{-1}$). It is hard to attribute specific VOCs, except acetic acid,
373 as emission fingerprints from wood wool insulation material during only 24-hour surface
374 measurement. This is due to multiple factors including the thickness of the building
375 structure, and thus the diffusion time needed by the VOC to arrive at the surface, and the
376 probable existing contamination (infiltration of outdoor air or anthropogenic activities), that
377 can result in the adsorption of VOCs on these surfaces and thus their detection upon
378 measurement.

379 VOC emissions from the different surfaces remain weak, even in summer, when compared
380 to the EU-LCI (European Lowest Concentration of Interest) guide on the emission of VOCs
381 from building materials [43]. For example, the highest emission of formaldehyde from the
382 SW wall (30.8 $\mu\text{g} \text{m}^{-2} \text{h}^{-1}$ equivalent to 17.9 $\mu\text{g} \text{m}^{-3}$) is less than the recommended LCI value
383 (100 $\mu\text{g} \text{m}^{-3}$). Similarly, the emission rate of acetic acid from the floor (29.0 $\mu\text{g} \text{m}^{-2} \text{h}^{-1}$
384 equivalent to 16.9 $\mu\text{g} \text{m}^{-3}$) is far below the guide value (1200 $\mu\text{g} \text{m}^{-3}$).

385 Therefore, we can conclude that the bio-based walls do not emit specific VOCs at high rates,
386 and that even if emissions from the floor and ceiling are higher than emissions from the
387 other surfaces, no alerting VOC surface emissions were observed in the selected building.

388

389 3.1.4. *VOC Surface Emissions: Summer versus Winter*

390 Significant seasonal difference was observed for almost all individual VOC and TVOC
391 emissions. In general, winter VOC emissions were relatively weak compared to summer
392 emissions. A ratio (R) of the VOC summer emission rate to winter emission rate is calculated
393 in table 3. Most emission rates from all surfaces were higher in summer than in winter. Only
394 three emission rates show a ratio < 1, and thus a decrease during summer. For each of them,
395 very low emission rates (close to LOQ) in summer lead to relatively large differences with
396 winter measurements; therefore, these ratios should thus be interpreted with care. For the
397 other VOCs, the ratio between summer and winter ranges from 1 and up to 87 times
398 between summer and winter. In this study, the placement of the FLEC at the same evaluated
399 position of each surface during both seasons remains approximate, and thus low variations,
400 ranging from 1 to 5 times between winter and summer, can be attributed to spatial
401 variations, as previously seen in part 3.1.1. On the other hand, the higher emission rates
402 observed in summer for the other VOCs (such as formaldehyde and nonanoic acid emitted
403 from the ceiling) can be explained by the change in meteorological conditions between
404 summer and winter. During the summer campaign, the average measured indoor
405 temperature and relative humidity in the wedding hall were 26 °C and 46%, respectively,
406 while they were equal to 22 °C and 45%, respectively, in winter. The relative humidity inside
407 the hall seems to be stable during winter and summer; however, this is not the case within
408 the different parts of the wall, where a higher variation in RH was observed during the
409 winter campaign compared to summer (Figures S1 and S2). Therefore, the change in the
410 temperature and relative humidity, especially higher temperatures, leads to higher VOC
411 emissions [32]–[34].

412 **Table 3. VOC surface emission rates ($\mu\text{g m}^{-2} \text{h}^{-1}$) of the 8 surfaces at the wedding hall during winter in addition to the ratio (R) of the summer**
 413 **to the winter emission rate**

VOC	Winter Surface Emissions								Ratio (R)							
	SE	SW	NW	Wall 1	Wall 2	Floor	Beam	Ceiling	SE	SW	NW	Wall 1	Wall 2	Floor	Beam	Ceiling
Formaldehyde	1.9	2.2	2.9	1.1	3.4	6.2	3.7	1.6	5	14	2	9	8	3	3	19
Propanal	<LOD	<LOD	<LOD	<LOD	<LOD	0.9	<LOD	0.5	-	-	-	-	-	-	-	3
Pentanal	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.7	-	-	-	-	-	-	-	2
Tolualdehyde	0.5	<LOD	<LOD	0.5	1.2	1.3	<LOD	<LOD	3	-	-	2	2	1	-	-
Furfural	<LOD	<LOD	<LOD	0.1	0.1	0.1	<LOD	<LOD	-	-	-	1	6	4	-	-
Octanal	<LOD	<LOD	0.1	0.2	0.1	<LOD	0.2	0.8	-	-	1	1	4	-	2	3
Nonanal	<LOD	0.1	0.2	0.5	0.3	<LOD	0.4	1.4	-	28	3	1	3	-	1	2
Acetic Acid	0.6	0.3	1.0	0.6	0.4	0.5	0.4	0.4	13	12	8	3	7	58	1	2
Phenol + Hexanoic Acid	1.0	0.5	1.1	0.9	0.5	1.7	1.8	4.6	1	3	0.4	0.2	3	1	1	1
Benzoic + Octanoic Acids	2.4	0.9	2.3	1.2	0.9	2.5	2.9	4.8	4	7	2	12	1	3	0.1	3
Nonanoic Acid	0.8	0.5	0.7	0.5	0.4	0.3	1.3	2.0	2	8	2	5	4	4	3	7
1-Butanol	0.1	0.1	0.3	0.3	0.2	0.1	0.1	0.1	35	6	8	4	3	13	1	6
2-Ethyl-1-hexanol	0.2	0.1	0.2	0.1	0.1	0.2	0.2	4.9	4	29	2	7	9	5	2	2
Propylene Glycol	0.7	<LOD	0.3	0.3	0.3	0.3	0.1	1.1	3	-	5	-	5	3	2	1
Acetophenone	0.1	0.2	0.2	0.3	0.3	0.1	0.1	0.3	13	3	3	4	3	21	1	2
Dimethylglutarate	0.1	<LOD	0.1	<LOD	<LOD	0.1	0.1	1.3	4	-	3	-	-	6	87	5
Dibutyl Phthalate	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	-	-	-	-	-	-	-	-
TVOC	16.8	12.1	14.5	12.2	8.1	14.2	20.9	51.7	3	6	3	5	3	7	2	3

414 <LOD: Analytical limit of detection (for carbonyls by HPLC-UV and for all the other VOCs by TD-GC-FID), TVOC: The sum of all VOCs quantified by GC-FID between C6 and C16
 415 as equivalent toluene

416 3.2. *Indoor Air Concentrations*

417 3.2.1. *Seasonal Variation*

418 27 VOCs, in addition to TVOCs, were found to have a concentration higher than $1 \mu\text{g m}^{-3}$ in
419 the indoor air of the wedding hall during summer and winter. The detected compounds
420 belonged to different chemical families including aromatic hydrocarbons, alcohols, terpenes,
421 and carboxylic acids, and a majority of ketones and aldehydes (54%). Table 4 shows the
422 average concentrations of the 8 measurements taken over 24h for both seasons. The
423 concentrations of TVOCs and almost all individual VOCs, except propanone, were two to six
424 times higher in summer than in winter. These findings are coherent with the study of
425 Mandin et al. [44], where they observed significantly higher concentrations of almost all
426 detected VOCs in indoor air in summer compared to winter.

427 The measured ventilation rate in the wedding hall during the summer and winter campaigns
428 was 217 and $173 \text{ m}^3 \text{ h}^{-1}$, respectively. Therefore, for equal source strength, lower
429 concentrations can be expected during the summer, due to the dilution from this increased
430 ventilation rate [45]. Propanone is the only compound showing an increase in winter
431 concentrations. This is in coherence with the study of Missia et al. [25], which showed that
432 the indoor air concentration of propanone is three times higher in winter than in summer.
433 This compound is usually widely emitted by household products [46]. Toluene and xylene
434 show insignificant seasonal variation compared to other VOCs. Even if in this study we did
435 not measure VOC concentrations in outdoor air, according to literature, these two
436 compounds mainly come from the infiltration of outdoor air [47]. On the other hand, for
437 aldehydes, the strongest increases in concentrations over the summer are seen for the
438 lighter aldehydes ($\leq \text{C}_6$). The observed higher concentrations can come from indoor source
439 emissions [48], which increase with increasing indoor temperatures. Moreover, due to
440 higher outdoor ozone concentrations in summer, the secondary formation of aldehydes
441 upon the reaction of ozone with indoor VOCs can also lead to an increase in the indoor
442 concentration of these compounds, and in particular formaldehyde [39]. Such increase has
443 been observed previously and was explained by the oxidation of terpenes by ozone [44],
444 [48]–[50]. In this case, the observed indoor concentration of terpenes might be expected to
445 be lower in summer than in winter. However, this is not the case here since the
446 concentration of α -pinene and 3-carene was three times higher in summer than in winter.
447 Thus, the indoor sources of terpenes in summer are stronger than their oxidation reaction
448 with ozone. Moreover, the source of the detected aldehydes indoors is probably dominated
449 by emissions from indoor building materials, especially wood wool, as illustrated previously
450 in this study, showing the domination of surface-emission sources compared to gas-phase
451 sources in indoor air [51]. Acetic acid shows the strongest increase over summer (seven
452 times higher), but overall its concentration remains relatively low.

453

454

455

456

457
458
459

Table 4. The average concentration ($\mu\text{g m}^{-3}$) of VOCs measured in the indoor air of the wedding hall during summer and winter. Standard deviations are calculated from 8 measurements taken during 24 hours

Family	VOC	Summer ($\mu\text{g m}^{-3}$)	Winter ($\mu\text{g m}^{-3}$)	Ratio of summer to winter
Aromatic Hydrocarbons	Toluene	1.3 ± 0.5	0.7 ± 0.2	2
	m+p-Xylene	1.1 ± 0.1	0.6 ± 0.04	2
Organic Acids	Acetic Acid	2.2 ± 1.2	0.3 ± 0.2	7
	Benzoic + Octanoic Acids	10.1 ± 1.1	4.0 ± 0.8	3
	Phenol + Hexanoic Acid	9.8 ± 2.6	3.7 ± 0.8	3
	Nonanoic Acid	5.5 ± 1.0	1.2 ± 0.2	5
Aldehydes	Formaldehyde	55.4 ± 10.4	15.3 ± 9.6	4
	Acetaldehyde	38.7 ± 8.5	15.4 ± 18.8	3
	Propanal	3.6 ± 0.7	0.6 ± 0.6	6
	Butanal	3.3 ± 0.4	0.6 ± 0.4	6
	Benzaldehyde	3.5 ± 0.6	0.8 ± 0.5	4
	Pentanal	5.8 ± 1.5	1.1 ± 0.7	5
	Furfural	2.8 ± 1.2	1.3 ± 0.4	2
	Methylglyoxal	4.8 ± 1.5	1.0 ± 0.6	5
	Hexanal	16.1 ± 3.5	2.6 ± 2.0	6
	Octanal	2.7 ± 0.8	1.9 ± 0.9	1
Alcohols	1-Butanol	2.1 ± 1.5	1.3 ± 0.6	2
	2-Ethyl-1-hexanol	5.1 ± 2.0	2.1 ± 0.6	2
Ketones	Propanone	26.7 ± 3.7	45.9 ± 43.2	0.6
	Methyl Vinyl Ketone	3.1 ± 0.9	0.7 ± 0.4	4
	Methyl Ethyl Ketone	2.8 ± 0.6	2.2 ± 1.1	1
Terpenes	3-Carene	3.2 ± 2.0	1.1 ± 0.8	3
	α -Pinene	4.7 ± 3.6	1.6 ± 1.1	3
Halogenated VOC	Tetrachloroethylene	13.1 ± 8.2	<LOD	-
TVOC		101.7 ± 20.4	52.2 ± 9.9	2

460

461 3.2.2. Temporal Variation

462 The variation of VOC concentrations was monitored during 24 hours in both summer and
463 winter. Figure 5 illustrates the 24-hour variation of the indoor air concentrations for TVOC
464 and selected VOCs during summer and winter campaigns. The hours are presented in the
465 figure according to the sampling order during both seasons.

466 The indoor air VOC concentrations were found to be higher during the night time for TVOC
467 and all the presented VOCs, except for the coeluted benzoic and octanoic acids and
468 nonanoic acid. Maximum VOC concentrations were measured between 21h30 - 3h30 in

469 summer and 1h30 - 7h30 in winter. During the day, the opening of doors to enter the hall
470 contributes to the increase in the air exchange rate, leading to further dilution of indoor air,
471 and thus a decrease in VOC indoor air concentrations [52]. On the contrary, the air exchange
472 rate inside the wedding hall is decreased during the nocturnal period, leading to higher
473 indoor air concentrations of the VOCs originating from indoor emissions.

474 On the other hand, the indoor air concentration of nonanoic acid was almost stable during
475 24 hours in both summer and winter. Similarly, the indoor air concentration of benzoic and
476 octanoic acids was almost stable in summer; however, it was found to decrease during the
477 night hours (19h30-7h30) in winter. As this is a coelution, it is impossible to evaluate the
478 individual contributions and therefore too uncertain to emit a hypothesis on drivers of this
479 changing temporal behavior between seasons.

480 In general, the indoor air concentrations of VOCs are higher at night compared to daytime;
481 however, it is still difficult to precisely predict the individual temporal behavior of each
482 detected VOC due to the multitude of influencing factors, including VOC sources,
483 hygrothermal variation, the change in ventilation rates, anthropogenic activities, etc.

484

485

486

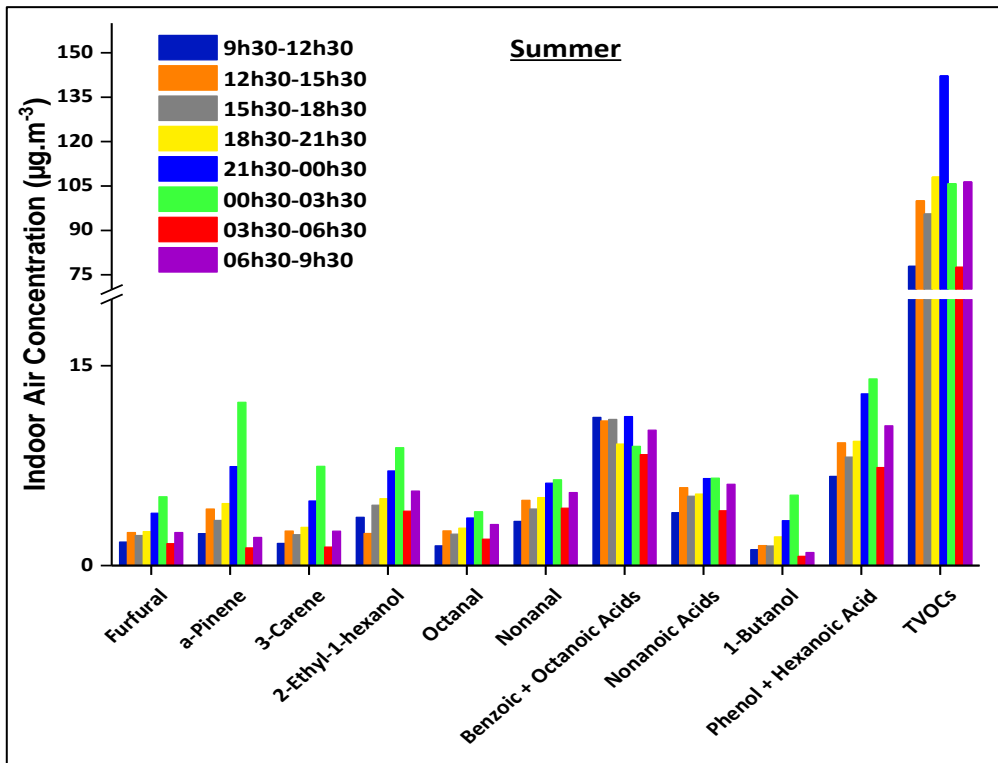
487

488

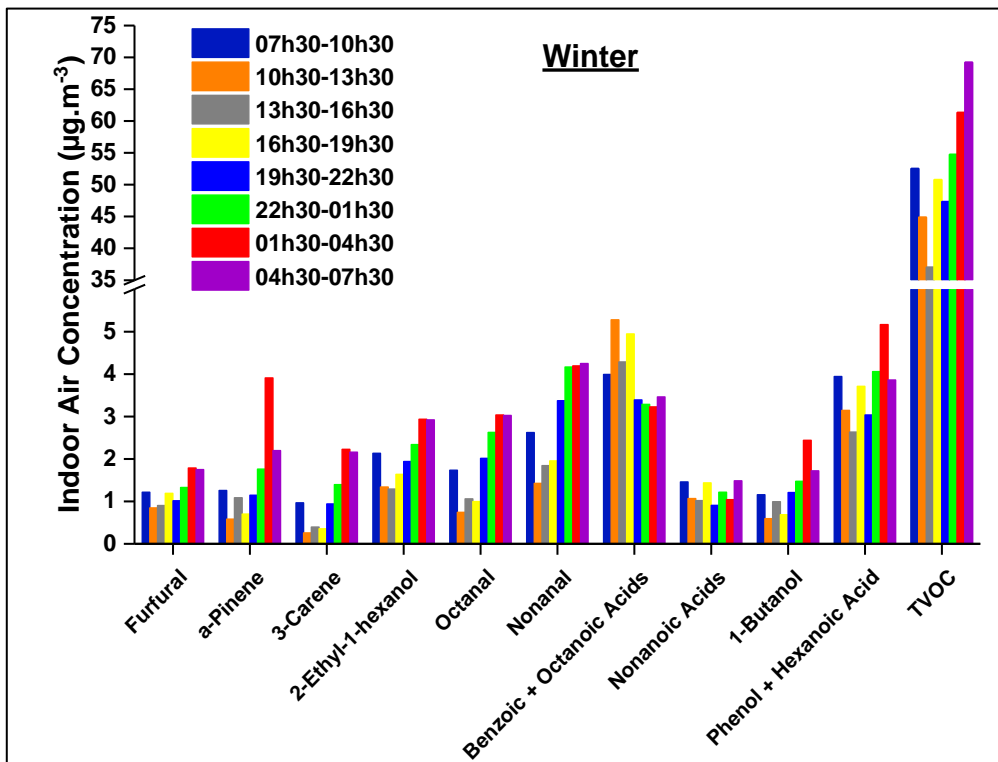
489

490

491



492



493

494 **Figure 5. The temporal variation during 24 hours in the VOC indoor air concentrations of**
 495 **the wedding hall of the town hall during the a) summer and b) winter campaigns**

496

497 **3.2.3. Contribution of Building Material Emissions to Indoor Air VOC Concentrations**

498 The indoor air concentration of each VOC emitted from the building structures of the
 499 wedding hall can be estimated by applying the following equation [25], [53]:

$$C_{e,i} = \frac{1}{Vn} A_i ER_i \quad (2)$$

500 Where $C_{e,i}$ ($\mu\text{g m}^{-3}$) is the estimated VOC indoor concentration contributed by the i^{th}
 501 material, V is the volume of the wedding hall which is equal to 441 m^3 , n (h^{-1}) is the air
 502 exchange rate, A_i (m^2) is the surface area of the i^{th} material (of only building structures
 503 evaluated in our study), and ER_i ($\mu\text{g m}^{-2} \text{ h}^{-1}$) is the VOC emission rate from the i^{th} material.
 504 The air exchange rate in the wedding hall was measured to be 0.4 and 0.5 h^{-1} in winter and
 505 summer, respectively. Based on the dimensions of the room, the surface area of each
 506 building structure was approximately calculated: 27.4 m^2 for wall 1 and the SW wall, 22.6 m^2
 507 for wall 2 and the NW wall, 45.2 m^2 for the SE wall, 85.7 m^2 for the floor, and 107.1 m^2 for
 508 the ceiling. The surface area of the beam was difficult to calculate due to the lack of
 509 dimensions; therefore, the contribution of this surface to VOC indoor air concentration will
 510 not be considered in this part. Then, the relative contribution of each material to the
 511 measured indoor air concentrations can be calculated by dividing $C_{e,i}$ by the measured
 512 indoor concentrations for each VOC (C_{in}).

513 Table 5 sums up the estimated contributions of each surface to the indoor air concentrations
 514 for each VOC detected both in ambient air and FLEC measurements (previously shown in
 515 tables 2 and 3). In addition, figure S4 of the SI shows the concentrations of the major VOCs
 516 quantified in indoor air and the corresponding surface emission rates from the eight
 517 characterized surfaces during both seasons.

518 Three trends can be observed when comparing the total estimated VOC indoor air
 519 concentration ($\sum C_{e,i}$) to the measured indoor air concentration (C_{in}): i) approximately equal,
 520 ii) higher C_{in} , or iii) lower C_{in} . For almost equal C_{in} and $\sum C_{e,i}$, such as for 2-ethyl-1-hexanol and
 521 1-butanol in summer, this can be since the emission of these compounds from the 7 building
 522 structures is probably the only source of these compounds indoors. Nevertheless, when C_{in} is
 523 higher than $\sum C_{e,i}$, sources other than emissions from the seven characterized building
 524 structures are expected to contribute to the indoor air concentration of some VOCs (like
 525 furfural, nonanal, phenol and hexanoic acid, and formaldehyde). Such sources may include
 526 emissions from furniture and consumer materials, secondary emissions due to indoor
 527 chemical reactions, infiltration of outdoor air, or even limitations related to emission
 528 measurements using the FLEC [54]. $\sum C_{e,i}$ was higher than C_{in} mainly for the quantified organic
 529 acids (acetic, benzoic coeluted with octanoic, and nonanoic acids). This can also be, as
 530 previously mentioned, due to indoor chemical reactions that may reduce these VOC indoor
 531 concentrations, in addition to the FLEC measurement limitations which may increase
 532 measurement uncertainties. Moreover, benzoic, octanoic, and nonanoic acids may be
 533 classified as semi-volatile compounds (SVOCs) since they have a low vapor pressure and high
 534 boiling temperature [55], [56]. Therefore, they can be adsorbed after emission on the
 535 different existing surfaces in the hall, and thus are less detected in indoor air.

536 When interpreting the estimated individual contribution of each surface to VOC indoor air
 537 concentrations, the calculations show that the ceiling, followed by the floor, are the main
 538 contributors to the indoor air VOC concentrations during summer and winter for almost all
 539 VOCs and TVOCs (marked in bold in tables 2 and 3), with contributions exceeding sometimes
 540 100%, as these surfaces have the highest surface area and have previously shown the

541 highest VOC surface emissions (tables 2 and 3). In general, the contributions of the five walls
542 to indoor air concentrations were relatively weak in winter and summer, except for acetic
543 acid. VOC emissions from the SE wall contribute relatively more, which can be explained by
544 its higher surface area. In winter, contributions from these surfaces were less than 20% for
545 TVOCs and all individual VOCs, except for the SE wall that showed a high contribution of
546 acetic acid (59%). Similarly, the summer contributions were also low ($\leq 20\%$), but once again
547 the SE wall showed a high contribution of acetic acid (74%) in addition to acetophenone
548 (34%) and 1-butanol (34%). Care should be taken however to not conclude from this first
549 comparison that bio-based walls contribute more to indoor VOC concentrations than the
550 other surfaces, as the conventional walls present smaller surface areas than the SE wall.
551 When comparing the contributions of building structures with bio-based insulation to
552 conventional structures of the same surface area, i.e. the SW wall to wall 1 and the NW wall
553 to wall 2, no significant difference ($\leq 10\%$) is observed during the two seasons, except for
554 acetic acid and acetophenone. These results support the previously made hypothesis that a
555 part of the acetic acid indoor air concentration comes from the wood wool used for
556 insulation in the three bio-based walls [42].

557 Although several studies have examined the levels of indoor air pollutants or have
558 characterized emission measurements in laboratories, in-situ studies linking the VOC
559 concentrations to their indoor sources are still rather limited [25], [30], [31]. This is mainly
560 due to the multiplicity of VOC indoor sources and the consequent time and cost difficulty
561 related to identifying and characterizing emissions from all these sources [54]. Despite all
562 limitations, this approach is interesting since it gives a primary overview of the impact of
563 VOC surface emissions from building structures, especially bio-based structures, on indoor
564 air concentrations. It allowed us to observe that no significant indoor air concentrations are
565 attributed to emissions from bio-based surfaces, except for acetic acid, which is considered a
566 fingerprint VOC for emissions from wood wool.

567

568

569

570

571

572

573

574

575

576
577

Table 5. The estimated indoor air concentrations ($\mu\text{g m}^{-3}$) and the respective contribution (%) of VOC emissions from the 7 building structures present in the wedding hall to VOC indoor air levels

VOC	Summer									Winter								
	C_{in} ($\mu\text{g m}^{-3}$)	$\sum_{i=1}^{n=7} C_{e,i}$ ($\mu\text{g m}^{-3}$)	Contribution (%)							C_{in} ($\mu\text{g m}^{-3}$)	$\sum_{i=1}^{n=7} C_{e,i}$ ($\mu\text{g m}^{-3}$)	Contribution (%)						
			Wall 1	Wall 2	SE	SW	NW	Floor	Ceiling			Wall 1	Wall 2	SE	SW	NW	Floor	Ceiling
Acetic Acid	2.2	15.0	10	12	74	21	36	518	20	0.3	1.0	36	20	59	18	49	94	94
Phenol + Hexanoic Acid	9.8	2.9	0	1	3	2	0	6	16	3.7	2.6	4	2	7	2	4	22	76
Benzoic + Octanoic Acids	10.1	16.2	18	1	21	7	5	33	75	4.0	4.3	5	3	15	4	7	30	73
Nonanoic Acid	5.5	8.6	5	3	5	9	2	8	125	1.2	1.4	6	4	17	6	7	12	101
Formaldehyde	55.4	31.3	2	5	4	7	1	12	26	15.3	7.1	1	3	3	2	2	20	6
Propanal	3.6	1.3	0	5	0	6	0	0	25	0.6	0.7	10	4	8	0	6	71	50
Furfural	2.8	1.1	0	2	1	6	1	6	24	1.3	0.1	1	1	0	0	0	4	0
Octanal	2.7	1.9	1	1	7	8	0	10	43	1.9	0.2	2	1	0	0	1	0	26
Nonanal	5.0	3.3	1	2	3	7	1	19	33	3.0	0.4	3	1	0	1	1	0	29
Acetophenone	0.8	1.7	20	10	34	8	8	103	37	0.2	0.3	19	16	10	13	10	20	74
2-Ethyl-1-hexanol	5.1	5.8	2	2	3	7	1	8	91	2.1	0.3	1	1	2	1	1	5	144
1-Butanol	2.1	2.0	7	2	34	4	11	24	14	1.3	0.3	4	2	2	1	3	4	5
TVOC	101.7	136.4	7	3	10	9	4	39	62	52.2	30.5	4	2	8	4	4	13	60

578 C_{in} is the measured indoor air concentration by active sampling in the wedding hall.

579 $\sum_{i=1}^n C_{e,i}$ is the sum of the estimated indoor concentrations contributed from surface emissions from the different building structures ($C_{e,i}$)

580 3.3. *Micro-organisms and Microbial VOC (mVOC) Concentrations in Indoor Air*

581 The results from the microbial analysis obtained during the two measurement campaigns
 582 are grouped in table 6. The concentration values show that the concentrations of microbial
 583 aerosols in the air of the wedding hall are below the guide values presented by Brauner et al.
 584 [57], who stipulates that the concentration of viable molds and bacteria in the indoor air of
 585 non-industrial indoor locations in the European Union should be less than 2000 CFU m⁻³. The
 586 measured indoor microbial concentrations from the same spot were up to 5 times higher in
 587 summer compared to winter which is coherent with other studies reported in literature [58].
 588 Winter microbial aerosol concentrations measured in the morning, next to the NW wall,
 589 were approximately equal to concentrations taken at the same time near the SW wall,
 590 indicating that the indoor air of the wedding hall is quite homogeneous or mixed in the case
 591 of xerophilic fungi (measured with Dichloran-Glycerol (DG18) Agar).

592 Many of the detected VOCs in indoor air (table 4), such as acetic acid, octanal, nonanal, 2-
 593 ethyl-1-hexanol, and 1-butanol, are classified as mVOCs based on the mVOC database [59].
 594 However, these compounds were also emitted from the building structures (tables 2 and 3).
 595 Therefore, it is impossible to attribute these compounds solely to microbial development.

596

597 **Table 6. The concentrations of microbial aerosols (CFU m⁻³) measured during the summer**
 598 **and winter campaigns in the indoor air of the wedding hall of the town hall.**
 599 **Measurements were done next to the northwest (NW) and southwest (SW) walls**

Media	Summer		Winter		
	NW-Morning	NW-Afternoon	NW-Morning	NW-Afternoon	SW-Morning
Ordinary Agar	340	200	102-116	42-68	122
R2A Agar	148	78	90-110	68-98	98
Chapman Agar	50	44	8-16	8-10	18
MEA Agar	ND*	ND	70-72	56-106	68
Czapek Agar	322	184	52-88	32	50
DRBC Agar	42	28	4-46	12-22	12
DG18 Agar	366	188	100-106	16-34	52

600 *ND: Non-determined; R2A: Reasoner's 2A; MEA: Melt-Extract Agra; DRBC: Dichloran Rose-
 601 Bengal Chloramphenicol; DG18: Dichloran-Glycerol

602

603 **4. Conclusion**

604 This study characterizes the seasonal in-field VOC emissions from building structures as a
 605 whole in public buildings. The measurements undertaken in two different seasons, winter
 606 and summer, allowed us to evaluate the changes in VOC emissions from structures
 607 containing bio-based insulation materials (wood wool) in contrasted conditions, and to
 608 compare VOC emissions from bio-based and conventional building structures. Observed
 609 emission rates from the different construction surfaces were then compared with VOC levels
 610 measured in indoor air. Potential microbial development on bio-based surfaces was
 611 explored.

612 A comparison of VOC emissions between samples taken at different locations of the same
613 surface showed a pronounced heterogeneity with emission rates changing up to a factor of
614 5. Moreover, a difference in VOC emissions ranging between 1 to 30 times was observed
615 among the three bio-based walls with a similar building structure. This difference was
616 explained by the exposure of the walls to different hygrothermal conditions. Part of this
617 variation could be related to spatial heterogeneity. Acetic acid emitted from these bio-based
618 surfaces seems to be the only quantified compound to consider as a fingerprint VOC for
619 emissions from wood wool. In the future, this compound should receive particular attention
620 if wood wool was intensively used.

621 In addition, VOC emissions from the eight different characterized surfaces (bio-based and
622 conventional) were also compared. Results showed that the two conventional surfaces,
623 ceiling and floor, were the most emissive surfaces. However, in general, emissions from the
624 different building structures, especially the three bio-based walls, remained well below
625 sanitary recommendations. VOC levels varied largely between summer and winter, with
626 summer emissions being 1 to 87 times higher than those in winter due to the difference in
627 hygrothermal conditions between the two seasons.

628 Indoor air concentrations followed a similar seasonal trend, and were 1 to 6 times higher in
629 summer compared to winter, with part of these levels driven by the increase in surface
630 emissions in summer. The calculated contributions of the emissions of the different surfaces
631 to ambient VOC concentrations showed that:

- 632 - Conventional surfaces with the highest VOC emissions and surface area (floor and
633 ceiling) showed the highest contribution to indoor VOC concentrations.
- 634 - Bio-based surfaces showed a relatively small contribution to indoor air levels (< 20%
635 for most VOCs) compared to the floor and ceiling.

636 This comparison gives a first estimation of the relative contributions of surface emissions,
637 especially bio-based ones, to indoor air concentrations.

638 No VOC emissions could be attributed specifically to microbial development since the
639 detected mVOCs were also emitted by the characterized building structures.

640 In light of the results obtained in this study, comparison of in-field VOC emission rates with
641 emissions rates from laboratory-tested materials is not always straightforward. Our
642 understanding of the underlying mechanisms explaining these differences is fundamental,
643 especially to be integrated in modeling experiments. As an ongoing part of this project, a
644 comparison of the in-field results to laboratory VOC emissions from the individual materials
645 constituting each building structure is planned.

646

647 **Acknowledgment**

648 This work was supported financially by the French Agency for Ecological Transition (ADEME).

649 **References**

- 650 [1] A. C. Heeley-Hill *et al.*, “Frequency of use of household products containing VOCs and
651 indoor atmospheric concentrations in homes,” *Environ Sci Process Impacts*, vol. 23,
652 no. 5, pp. 699–713, May 2021, doi: 10.1039/d0em00504e.
- 653 [2] N. E. Klepeis *et al.*, “The National Human Activity Pattern Survey (NHAPS): A resource
654 for assessing exposure to environmental pollutants,” *J Expo Anal Environ Epidemiol*,
655 vol. 11, no. 3, pp. 231–252, 2001, doi: 10.1038/sj.jea.7500165.
- 656 [3] P. Wolkoff, “VOC - Sources, measurements, emissions, and the impact on indoor air
657 quality,” University of Copenhagen, 1995.
- 658 [4] A. Steinemann, “Volatile emissions from common consumer products,” *Air Qual
659 Atmos Health*, vol. 8, no. 3, pp. 273–281, Jun. 2015, doi: 10.1007/s11869-015-0327-6.
- 660 [5] S. Kim, H. J. Kim, and S. J. Moon, “Evaluation of VOC emissions from building finishing
661 materials using a small chamber and VOC analyser,” *Indoor and Built Environment*, vol.
662 15, no. 6, pp. 511–523, 2006, doi: 10.1177/1420326X06072040.
- 663 [6] A. Gross *et al.*, “Assessment of VOCs material/air exchanges of building products using
664 the DOSEC®-SPME method,” in *Energy Procedia*, 2017, vol. 122, pp. 367–372. doi:
665 10.1016/j.egypro.2017.07.318.
- 666 [7] L. Mølhave, L. E. Sparks, P. Wolkoff, P. A. Clausen, P. A. Nielsen, and N. C. Bergso, “The
667 Danish Twin Apartment Study - Part II: Mathematical modeling of the relative strength
668 of sources of indoor air pollution,” *Indoor Air*, vol. 6, no. 1, pp. 18–30, 1996, doi:
669 10.1111/j.1600-0668.1996.t01-3-00003.x.
- 670 [8] Official Journal of the French Republic, “Decree no. 2011-321 of 23 March 2011 on the
671 labeling of construction and wall or floor coating products and paints and varnishes on
672 their emissions of volatile pollutant,” 2011. [Online]. Available:
673 <https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000023759679/>
- 674 [9] Committee for Health-related Evaluation of Building Products, “Requirements for the
675 indoor air quality in buildings: Health-related Evaluation procedure for emissions of
676 volatile organic compounds (VVOC, VOC, and SVOC) from building products,” 2018.
- 677 [10] European Commission, “Harmonisation of indoor material emissions labelling systems
678 in the EU,” 2005.
- 679 [11] Official Journal of the European Union, *Directive 2004/42/CE of the European
680 Parliament and of the Council of 21 April 2004 on the limitation of emissions of volatile
681 organic compounds due to the use of organic solvents in certain paints and varnishes
682 and vehicle refinishing products and amending Directive 1999/13/EC*. 2004. [Online].
683 Available: [http://eur-
684 lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32004L0042:EN:NOT](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32004L0042:EN:NOT)
- 685 [12] Official Journal of the European Communities, *Council Directive of 21 December 1988
686 on the approximation of laws, regulations and administrative provisions of the
687 Member States relating to construction products (89/106/EEC)*. 1989.

- 688 [13] Official Journal of the European Union, *Regulation (EU) No 305/2011 of the European*
689 *Parliament and of the Council of 9 March 2011 laying down harmonised conditions for*
690 *the marketing of construction products and repealing council directive 89/106/EEC.*
691 2011.
- 692 [14] ADEME, “French know-how in the field of energy efficiency in buildings,” 2010.
- 693 [15] Republique Française, *LOI n° 2009-967 du 3 août 2009 de programmation relative à la*
694 *mise en œuvre du Grenelle de l’environnement (1) - Légifrance.*
- 695 [16] Official Journal of the French Republic, *Law no 2018-1021 of November 23, 2018 on*
696 *the development of housing, development and digital technology (1).* 2018. Accessed:
697 Jan. 10, 2023. [Online]. Available:
698 <https://www.legifrance.gouv.fr/loda/id/JORFTEXT000037639478>
- 699 [17] A. K. Shuvo and S. Sharmin, “Carbon emission scenario of conventional buildings,”
700 *Journal of Construction Engineering, Management & Innovation*, vol. 4, no. 3, pp. 134–
701 150, Sep. 2021, doi: 10.31462/jcemi.2021.03134150.
- 702 [18] D. Maskell *et al.*, “Properties of bio-based insulation materials and their potential
703 impact on indoor air quality,” *Academic Journal of Civil Engineering*, vol. 33, no. 2, pp.
704 156–163, 2015, doi: <https://doi.org/10.26168/icbbm2015.24>.
- 705 [19] C. F. F. P. da Silva, C. Rana, D. Maskell, A. Dengel, M. P. Ansel, and R. J. Ball, “Influence
706 of eco-materials on indoor air quality,” *Green Mater*, vol. 4, no. 2, pp. 72–80, 2016.
- 707 [20] L. C. Silva, L. R. Caldas, R. L. M. Paiva, and R. D. T. Filho., “Role of bio-based building
708 materials in climate change mitigation: Special report of the Brazilian Panel on climate
709 change,” 2018. [Online]. Available:
710 [http://pbmc.coppe.ufrj.br/index.php/pt/publicacoes/relatorios-especiais-](http://pbmc.coppe.ufrj.br/index.php/pt/publicacoes/relatorios-especiais-pbmc/item/role-of-bio-based-building-materials-in-climate-change-mitigation)
711 [pbmc/item/role-of-bio-based-building-materials-in-climate-change-mitigation](http://pbmc.coppe.ufrj.br/index.php/pt/publicacoes/relatorios-especiais-pbmc/item/role-of-bio-based-building-materials-in-climate-change-mitigation)
- 712 [21] ADEME, “Recensement des produits biosourcés disponibles sur le marché et
713 identification des marchés publics cibles,” 2015.
- 714 [22] A. M. Tobon, Y. Andres, and N. Locoge, “Impacts of test methods on the assessment of
715 insulation materials’ resistance against moulds,” *Build Environ*, vol. 179, Jul. 2020, doi:
716 10.1016/j.buildenv.2020.106963.
- 717 [23] A. Korpi, J. Järnberg, and A. L. Pasanen, “Microbial volatile organic compounds,”
718 *Critical Reviews in Toxicology*, vol. 39. pp. 139–193, Feb. 2009. doi:
719 10.1080/10408440802291497.
- 720 [24] M. Richter, W. Horn, E. Juritsch, A. Klinge, L. Radeljic, and O. Jann, “Natural building
721 materials for interior fitting and refurbishment—What about indoor emissions?,”
722 *Materials*, vol. 14, no. 1, 2021, doi: 10.3390/ma14010234.
- 723 [25] D. A. Missia, E. Demetriou, N. Michael, E. I. Tolis, and J. G. Bartzis, “Indoor exposure
724 from building materials: A field study,” *Atmos Environ*, vol. 44, no. 35, pp. 4388–4395,
725 2010, doi: 10.1016/j.atmosenv.2010.07.049.

- 726 [26] M. Koivula *et al.*, “Emissions from thermal insulations - Part 2: Evaluation of emissions
727 from organic and inorganic insulations,” *Build Environ*, vol. 40, no. 6, pp. 803–814,
728 2005, doi: 10.1016/j.buildenv.2004.08.008.
- 729 [27] P. Pandit, G. T. Nadathur, S. Maiti, and B. Regubalan, “Functionality and properties of
730 bio-based materials,” in Ahmed, S. (eds) *Bio-based Materials for Food Packaging*,
731 Singapore: Springer, 2018, pp. 81–103. doi: [https://doi.org/10.1007/978-981-13-
732 1909-9_481](https://doi.org/10.1007/978-981-13-1909-9_481).
- 733 [28] Y. H. Cheng, C. C. Lin, and S. C. Hsu, “Comparison of conventional and green building
734 materials in respect of VOC emissions and ozone impact on secondary carbonyl
735 emissions,” *Build Environ*, vol. 87, pp. 274–282, May 2015, doi:
736 10.1016/j.buildenv.2014.12.025.
- 737 [29] M. G. D. Baumann, L. F. Lorenz, S. A. Batterman, and G.-Z. Zhang, “Aldehyde Emissions
738 from particleboard and medium density fiberboard products,” *For Prod J*, vol. 50, no.
739 9, pp. 75–82, 2000.
- 740 [30] H. Järnström, K. Saarela, P. Kalliokoski, and A. L. Pasanen, “Reference values for
741 structure emissions measured on site in new residential buildings in Finland,” *Atmos
742 Environ*, vol. 41, no. 11, pp. 2290–2302, Apr. 2007, doi:
743 10.1016/j.atmosenv.2006.11.033.
- 744 [31] V. Desauziers, D. Bourdin, P. Mocho, and H. Plaisance, “Innovative tools and modeling
745 methodology for impact prediction and assessment of the contribution of materials
746 on indoor air quality,” *Herit Sci*, vol. 3, no. 1, p. 28, 2015, doi: 10.1186/s40494-015-
747 0057-y.
- 748 [32] S. Kim and H. J. Kim, “Comparison of formaldehyde emission from building finishing
749 materials at various temperatures in under heating system; ONDOL,” *Indoor Air*, vol.
750 15, no. 5, pp. 317–325, Oct. 2005, doi: 10.1111/j.1600-0668.2005.00368.x.
- 751 [33] S. Zhou, H. Liu, Y. Ding, and Y. Wu, “The effects of temperature and humidity on the
752 VOC emission rate from dry building materials,” in *IOP Conference Series: Materials
753 Science and Engineering*, Oct. 2019, vol. 609, no. 4. doi: 10.1088/1757-
754 899X/609/4/042001.
- 755 [34] Y. K. Lee and H. J. Kim, “The effect of temperature on VOCs and carbonyl compounds
756 emission from wooden flooring by thermal extractor test method,” *Build Environ*, vol.
757 53, pp. 95–99, 2012, doi: 10.1016/j.buildenv.2011.10.016.
- 758 [35] H. Wang, J. Xiong, and W. Wei, “Measurement methods and impact factors for the key
759 parameters of VOC/SVOC emissions from materials in indoor and vehicular
760 environments: A review,” *Environ Int*, vol. 168, no. 107451, Oct. 2022, doi:
761 10.1016/j.envint.2022.107451.
- 762 [36] ISO 16000-10, *Indoor air — Part 10: Determination of the emission of volatile organic
763 compounds from building products and furnishing — Emission test cell method*. 2006.
- 764 [37] Official Journal of the French Republic, *Decree no. 2011-321 of 23 March 2011 on the
765 labeling of construction products or wall or floor coating and paints and varnishes on*

- 766 *their emissions of volatile pollutants*. 2011. Accessed: Jan. 17, 2019. [Online].
767 Available:
768 <https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000023759679&dateTexte&categorieLien=id>
769
- 770 [38] T. Salthammer, "TVOC - Revisited," *Environ Int*, vol. 167, Sep. 2022, doi:
771 10.1016/j.envint.2022.107440.
- 772 [39] ISO 16000-6, *Indoor air — Part 6: Determination of volatile organic compounds in*
773 *indoor and test chamber air by active sampling on Tenax TA sorbent, thermal*
774 *desorption and gas chromatography using MS or MS-FID*. 2011.
- 775 [40] C. Yu and D. Crump, "A review of the emission of VOCs from polymeric materials used
776 in buildings," *Build Environ*, vol. 33, no. 6, pp. 357–374, 1998, doi: 10.1016/S0360-
777 1323(97)00055-3.
- 778 [41] J. Pohleven, M. D. Burnard, and A. Kutnar, "Volatile organic compounds emitted from
779 untreated and thermally modified wood - A review," *Wood and Fiber Science*, vol. 51,
780 no. 3, pp. 231–254, 2019, doi: 10.22382/wfs-2019-023.
- 781 [42] M. Sassoli *et al.*, "Characterization of VOC emission profile of different wood species
782 during moisture cycles," *IForest*, vol. 10, no. 3, pp. 576–584, 2017, doi:
783 10.3832/ifor2259-010.
- 784 [43] Joint Research Center of the European Commission, "Report no 29: Harmonisation
785 framework for health based evaluation of indoor emissions from construction
786 products in the European Union using the EU-LCI concept," 2013. doi: 10.2788/26234.
- 787 [44] C. Mandin *et al.*, "Assessment of indoor air quality in office buildings across Europe –
788 The OFFICAIR study," *Science of the Total Environment*, vol. 579, pp. 169–178, 2017,
789 doi: 10.1016/j.scitotenv.2016.10.238.
- 790 [45] R. D. Edwards, J. Jurvelin, K. Saarela, and M. Jantunen, "VOC concentrations measured
791 in personal samples and residential indoor, outdoor and workplace
792 microenvironments in EXPOLIS-Helsinki, Finland," *Atmos Environ*, vol. 35, no. 28, pp.
793 4829–4841, 2001, doi: 10.1016/S1352-2310(01)00271-0.
- 794 [46] G. Vincent, P. M. Marquaire, and O. Zahraa, "Abatement of volatile organic
795 compounds using an annular photocatalytic reactor: Study of gaseous acetone," *J*
796 *Photochem Photobiol A Chem*, vol. 197, no. 2–3, pp. 177–189, 2008, doi:
797 10.1016/j.jphotochem.2007.12.021.
- 798 [47] O. Geiss, G. Giannopoulos, S. Tirendi, J. Barrero-Moreno, B. R. Larsen, and D. Kotzias,
799 "The AIRMEX study - VOC measurements in public buildings and
800 schools/kindergartens in eleven European cities: Statistical analysis of the data,"
801 *Atmos Environ*, vol. 45, no. 22, pp. 3676–3684, 2011, doi:
802 10.1016/j.atmosenv.2011.04.037.
- 803 [48] D. Campagnolo *et al.*, "VOCs and aldehydes source identification in European office
804 buildings - The OFFICAIR study," *Build Environ*, vol. 115, pp. 18–24, 2017, doi:
805 10.1016/j.buildenv.2017.01.009.

- 806 [49] D. Kotzias *et al.*, "Exposure to multiple air contaminants in public buildings, schools
807 and kindergartens-the European indoor air monitoring and exposure assessment
808 (airmex) study," *Fresenius Environ Bull*, vol. 18, no. 5 A, pp. 670–681, 2009.
- 809 [50] J. Xu *et al.*, "Heterogeneous chemistry of ozone with floor cleaning agent: Implications
810 of secondary VOCs in the indoor environment," *Science of the Total Environment*, vol.
811 862, no. 160867, Mar. 2023, doi: 10.1016/j.scitotenv.2022.160867.
- 812 [51] C. Wang *et al.*, "Surface reservoirs dominate dynamic gas-surface partitioning of many
813 indoor air constituents," *Sci Adv*, vol. 6, no. 8, 2020, doi: 10.1126/sciadv.aay8973.
- 814 [52] V. Sahu and B. R. Gurjar, "Spatio-temporal variations of indoor air quality in a
815 university library," *Int J Environ Health Res*, vol. 31, no. 5, pp. 475–490, 2021, doi:
816 10.1080/09603123.2019.1668916.
- 817 [53] D. H. Kang, D. H. Choi, D. Won, W. Yang, H. Schleichinger, and J. David, "Household
818 materials as emission sources of naphthalene in Canadian homes and their
819 contribution to indoor air," *Atmos Environ*, vol. 50, pp. 79–87, Apr. 2012, doi:
820 10.1016/j.atmosenv.2011.12.060.
- 821 [54] W. Liang and X. Yang, "Indoor formaldehyde in real buildings: Emission source
822 identification, overall emission rate estimation, concentration increase and decay
823 patterns," *Build Environ*, vol. 69, pp. 114–120, Nov. 2013, doi:
824 10.1016/j.buildenv.2013.08.009.
- 825 [55] ISO 16000-25, "Determination of the emission of semi-volatile organic compounds by
826 building products - micro-chamber method," 2011.
- 827 [56] C. J. Weschler and W. W. Nazaroff, "Semivolatile organic compounds in indoor
828 environments," *Atmos Environ*, vol. 42, no. 40, pp. 9018–9040, 2008, doi:
829 10.1016/j.atmosenv.2008.09.052.
- 830 [57] E. V. Bräuner, M. Frederiksen, B. Kolarik, and L. Gunnarsen, "Typical benign indoor
831 aerosol concentrations in public spaces and designing biosensors for pathogen
832 detection: A review," *Build Environ*, vol. 82, pp. 190–202, 2014, doi:
833 10.1016/j.buildenv.2014.08.020.
- 834 [58] D. Haas *et al.*, "Comparison of background levels of culturable fungal spore
835 concentrations in indoor and outdoor air in southeastern Austria," *Atmos Environ*, vol.
836 98, pp. 640–647, 2014, doi: 10.1016/j.atmosenv.2014.09.039.
- 837 [59] "Microbial Volatile Organic Compounds Database."
838 <https://bioinformatics.charite.de/mvoc/index.php?site=home> (accessed Aug. 26,
839 2022).
- 840