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1 **A review of environmental odor quantification and** 2 **qualification methods: the question of objectivity in** 3 **sensory analysis**

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10 **Abstract**

11 For several years, various issues have up surged linked to odor nuisances with impacts on
12 health and economic concerns. As awareness grew, recent development in instrumental
13 techniques and sensorial analysis have emerged offering efficient and complementary
14 approaches regarding environmental odor monitoring and control. While chemical analysis
15 faces several obstacles, the sensory approach can help overcome them. Therefore, this latter
16 may be considered as subjective, putting the reliability of the studies at risk. This paper is a
17 review of the most commonly sensory methodology used for quantitative and qualitative
18 environmental assessment of odor intensity (OI), odor concentration (OC), odor nature (ON)
19 and hedonic tone (HT). For each of these odor dimensions, the assessment techniques are
20 presented and compared: panel characteristics are discussed; laboratory and field studies are
21 considered and the objectivity of the results is debated. For odor quantification, the use of a

22 reference scale for OI assessment offers less subjectivity than other techniques but at the
23 expense of ease-of-use. For OC assessment, the use of dynamic olfactometry was shown to be
24 the least biased. For odor qualification, the ON description was less subjective when a
25 reference-based lexicon was used but at the expense of simplicity, cost, and lesser panel-
26 training requirements. Only when assessing HT was subjectivity an accepted feature because
27 it reflects the impacted communities' acceptance of odorous emissions. For all discussed
28 dimensions, field studies were shown to be the least biased due to the absence of air sampling,
29 except for OC, where the dispersion modeling approach also showed great potential. In
30 conclusion, this paper offers the reader a guide for environmental odor sensory analysis with
31 the capacity to choose among different methods depending on the study nature, expectations,
32 and capacities.

33 **Keywords:** outdoor odor monitoring, odor intensity, odor concentration, odor nature, hedonic
34 tone, sensory analysis

35 **1. Introduction**

36 Odor nuisance constitutes the major subject of complaint regarding air pollution in Europe
37 and the United States (Leonardos, 1995). This nuisance brings about many negative effects on
38 human life, such as health risks. Health concerns may be physiological, such as headache,
39 nausea, drowsiness, and irritation (Schiffman et al., 2000, 1995; Schiffman and Williams,
40 2005), or psychological, such as stress and alterations in mood (Oiamo et al., 2015).
41 According to Schiffman and Williams, these health effects may be explained by either (i)
42 exposure to odorants, which are chemical compounds that trigger odor perception, (ii)
43 copollutants, or (iii) innate (genetically coded) and learned aversion (Schiffman and Williams,
44 2005). Odor nuisance implicates not only health risks but also economic difficulties. Real
45 estate prices are affected by nearby odor emissions (Li and Li, 2018). Sometimes, residents

46 consider even moving, which can lead to grief that increases with attachment to their current
47 residence (Wojnarowska et al., 2020). Moreover, degradation of the quality of life has been
48 observed (Călămar et al., 2018; Heisterberg et al., 2014), as well as negative effects on the
49 subjective well-being of residents (Eltarkawe and Miller, 2018).

50 Odor nuisance cases refer to situations where residents declare mismatches between the
51 perceived odors and expected odors (Pourtier, 2013). Jaubert described odor nuisance as a
52 combination of four main components: (i) psychosociocultural factors such as social opinions,
53 personal experiences, and memories; (ii) circumstantial factors including the spatiotemporal
54 context where the odor was smelled, frequency and persistence of odor perception
55 (Schlegelmilch et al., 2005), meteorological effects, etc.; (iii) the characteristics of the
56 affected population, its average age, etc.; and (iv) the psychophysical properties of the odor,
57 such as odor concentration (OC), odor intensity (OI) and odor nature (ON) (Jaubert, 2010).

58 Odor perception begins when odorous substances reach the nasal cavity, by respiration or by
59 sniffing, and activate olfactory receptor cells (Forest et al., 2017; Rodríguez et al., 2011). An
60 olfactory receptor may be activated by different odorants, and on the other hand, each odorant
61 may activate different olfactory receptors. Once activated, an electric message is triggered
62 from the olfactory receptor and carried through the olfactory bulb to the brain to be analyzed,
63 associating these stimuli with memories and experiences. Various odorant substances are
64 recognized and distinguished by activating different olfactory receptor combinations, i.e., a
65 specific pattern corresponds to each odorant (Firestein, 2001). The perceived odor is the result
66 of complex mixtures of odorants, usually volatile organic compounds (VOCs) (Blanes-Vidal
67 et al., 2009). Its intensity is mainly related to the concentration of odorant substances (Wu et
68 al., 2016) whereas the odor nature is mainly related to their chemical structure (Bushdid et al.,
69 2016).

70 Odor emissions may be assessed using two approaches: chemical analysis and sensory
71 analysis. Chemical analysis is widely used to determine the molecules present in the air and
72 their chemical concentrations (Davoli et al., 2003; Kim et al., 2007; Zhang et al., 2010). This
73 approach for environmental assessment has already been discussed (Conti et al., 2020) and it
74 is considered as a powerful and relevant methodology. However, chemical analysis faces
75 several obstacles when applied to monitor odors in ambient air. First, chemical analysis does
76 not provide data on the sensory properties of the analyzed molecules. Second, the
77 concentration levels at which some odorants are smelled may be less than the instrumental
78 detection limits (Rappert and Müller, 2005). Third, mixture effects on odor intensity and odor
79 nature (Ferreira, 2012a, 2012b; Yan et al., 2014) are not considered by chemical analysis
80 (Capelli et al., 2008; Kim and Park, 2008). Last, odors in the environment are emitted in puffs
81 (Zannetti, 1981), which can be a challenge to analyze consistently.

82 Hence, sensory analysis is used as a complementary tool. This approach depends on human
83 assessors, called a panel, who smell and analyze the odor. Sensory analysis offers many
84 advantages, such as providing organoleptic data and allowing the quantification and
85 qualification of the odor. It has been applied in many environmental domains, offering a less
86 expensive analytical technique relative to chemical analysis (Lewkowska et al., 2015) and is
87 easier to deploy in large areas. Sensory analysis has become very reliable, especially after
88 introducing several standards regarding odor assessment in the environment, such as OC
89 determination, intensity, hedonic tone assessment, odor frequency, and dispersion (EN13725,
90 2003; Guillot et al., 2012; van Harreveld et al., 1999; VDI 3882, part 1, 1992), ensuring more
91 reproducible and repeatable results.

92 However, sensory analysis is disputed related to the subjectivity of the human panel and
93 psychological factors that could affect the analysis (Conti et al., 2020). Thus, objectivity in
94 sensory analysis is a requirement for monitoring odors over large periods, comparing data

95 from different panels, and ideally establishing a relationship between sensory and chemical
96 data, especially when a quantitative approach is considered. This, alongside the absence of a
97 complete understanding of the effect of odor mixtures, constitutes the main obstacle when
98 assessing odors in the environment. This might be a source of biases that could lead to
99 ineffective measurements. Several attempts to “objectify” sensory analysis and to limit the
100 biases have been made. Unfortunately, little work has been done to compare the different
101 sensory analytical methods and to discuss their degree of objectivity.

102 In this review, we will focus on the psychophysical properties of odor nuisance. Therefore,
103 we will discuss the most commonly used sensory methods to assess the psychophysical
104 properties of odors. The two main aspects of sensory analysis in environmental studies, the
105 quantification and qualification of odors, will be discussed in detail. For each dimension, we
106 will cover and discuss the sensory techniques used to evaluate the odor, the assessment
107 strategy, whether it is in a laboratory or in the field, and the panel characteristics. Based on
108 studies performed in the environment, this review offers a guideline for sensory analytical
109 campaigns or laboratory assessments, allowing the reader to choose the appropriate approach
110 based on his/her needs and constraints.

111 **2. Air sampling**

112 As will be presented later, odorous air can be analyzed in the laboratory and in the field.
113 Analysis in the laboratory offers the complete anonymity of the sample, thus lowering the risk
114 of prejudgments. For this approach, odorous air needs to be sampled. Samples may be
115 gathered using various containers. Tedlar® (PVF), Nalophan® (PET), or Teflon (FEP) bags
116 (Muñoz et al., 2010) are widely used, even if the use of glass vials has also been described in
117 the literature (Agus et al., 2012; NFX 43-103, 1996). Air sampling is recommended to be
118 done with the least contact possible with the pump and sampling material to reduce any

119 contamination (EN13725, 2003) for that, “lung sampler” is favored (a sampling technic based
120 on creating a depression in a solid container with a bag inside so that the air is introduced to
121 the bag by the difference in pressures between ambient air and the solid container). Odors
122 may be smelled directly from sampling bags (bags may be equipped with a mouthpiece) or
123 connected to olfactometers, as is discussed in part 3.2.

124 The use of sampling bags presents two obstacles. First, odorant compounds may be released
125 by the bag material, especially phenol-like odors (Keener et al., 2002; Trabue et al., 2006).
126 Abraham et al. studied the effect of odor treatment from wastewater treatment plants by using
127 seashell biofilters. They used Tedlar[®] bags to sample odorous air. The results showed that the
128 presence of phenol/medicinal-like odors emitted from the bag itself interfered with their
129 results (Abraham et al., 2015).

130 The second problem is sample losses that may occur in sampling bags (Kasper et al., 2018;
131 Koziel et al., 2005; Mochalski et al., 2009; Zhou et al., 2016). For example, Koziel et al.
132 found that losses in concentrations of p-cresol were approximately 95% in commercial
133 Tedlar[®] half an hour after sampling and 99.1% after 24 hours (Koziel et al., 2005). Losses in
134 odor concentration were also reported after 12 h in Nalophan[®] bags (from 11227 ou_E/m³ at 5.1
135 hours to 4789 ou_E/m³ at 31.5 hours) (van Harreveld, 2003). Sample losses may imply the
136 modification of sensory interactions between the odorants that may occur, affecting the
137 overall odor quantity and quality of the sampled odorous air.

138 In addition, sampling canisters have been used in several studies to sample odorous air.
139 However, sampling canisters show to be, in some examples, less efficient than bags. Koziel et
140 al. showed that the mean recovery percentages for 11 odorants (found in odorous emissions
141 from livestock) were 4.2% et 0.5 % for 0.5- and 24-hours storage time respectively. On the
142 other hand, the lowest mean recovery found in bags was 47.3% and 37.4 % for 0.5 and 24

143 hours respectively (Koziel et al., 2005). In another study, Trabue et al. found losses of up to
144 40% of hydrogen sulfide, methanethiol, and dimethyl disulfide in field samples from animal
145 feeding operation after passing through calcium chloride drying tube (Trabue et al., 2008).

146 **3. Odor quantification**

147 Odor quantification is widely used to assess odor nuisance impacts in addition to frequency,
148 location, duration, and hedonic tone (Nicell, 2009). When studying environmental odors and
149 quantifying the odorous compounds responsible for the nuisance, the first obstacle to
150 overcome is the gap between odor perception limits and the detection limits of the instruments
151 used for chemical analyses (Rappert and Müller, 2005). Hence, the need to quantify an odor
152 may be assured by sensory analyses. Odor intensity and odor concentration are used for odor
153 quantification using a human panel. Indeed, the electronic nose (a sensor array that mimics
154 the human olfactory epithelium) can distinguish odor fingerprints, and recent advancements
155 in the field have given electronic noses the ability to assess the intensity of the signals (Yan et
156 al., 2017). However, electronic noses are not within the scope of this review and have been
157 discussed in other works (Karakaya et al., 2020; Röck et al., 2008; Szulczyński et al., 2017).

158 On the one hand, OI quantifies the odor based on the strength of the stimuli created by the
159 odor when smelled by the assessor. On the other hand, OC quantifies the odor based on the
160 number of dilutions needed until it becomes imperceptible. OI and OC are related to the
161 chemical concentrations of the odorants by using two relations: Stevens law (eq 1) and
162 Weber-Fechner law (eq 2).

163 $OI = C^n$ (eq 1) where C is the concentration, generally in g/L, and n is the Stevens
164 coefficient,

165 $OI_i = K_i \log\left(\frac{C_i}{C_{OT,i}}\right) + 0.5 = K_i \log(OC_i) + 0.5$ (eq 2) where K_i is the Weber-Fechner
166 coefficient, C_i is the chemical concentration of i , $C_{OT,i}$ is the detection threshold of i and OC_i
167 is the odor concentration of i .

168 The two laws were developed by psychophysicists to relate a perceived intensity to its stimuli
169 for any sense: taste, odor, brightness, etc. For some authors, Stevens law is more descriptive
170 of stimulus-perceived intensity than Weber-Fechner law (Nutter Jr, 2010).

171 **3.1. Odor intensity assessment**

172 Intensity assessment is performed under various conditions described by three parameters: (i)
173 the scaling techniques that are used to “express” the strength of the odor intensity, (ii) the type
174 of study, whether under laboratory conditions or in the field, and (iii) the panel performing the
175 assessment. To address this point, Table 1 summarizes 22 studies performed between 1994
176 and 2018 mostly in Europe, East Asia, and the United States; it presents several examples of
177 environmental odor assessments from various application domains, such as industrial plants,
178 waste treatment, and animal production.

179 For each point addressed within this part, different approaches will be presented along with
180 their concepts. Afterward, examples of applications will be discussed, and their advantages
181 and disadvantages will be described. In the next sections of this review, the same structure
182 will be followed for each odor parameter.

183 **3.1.1. Scaling techniques**

184 When assessing odor intensity, the panel needs to use a communication technique to express
185 the strength of the stimulus. For this, assessors may scale the magnitude of the stimuli using
186 description-based numbers or other methods. The three main scaling techniques used in

187 environmental studies are category scale, odor intensity reference scale, and cross-modality
188 matching (Table 1).

189 3.1.1.1 Category scale

190 For category scale, odor intensity is scaled using numbers. The widely used scale is a seven-
191 point scale where 0 is the absence of perception and 6 is an extremely strong perception (Kim,
192 2011, 2010; Sucker et al., 2008; Wu et al., 2016). The German Standard VDI 3881 also
193 recommends a seven-point scale: extremely strong (6), very strong (5), strong (4), distinct (3),
194 weak (2), very weak (1), and not perceptible (0) (VDI 3882, part 1, 1992). This scale allows
195 the application of mathematical operations, e.g., developing equations to relate OI to chemical
196 concentration (Kim, 2011, 2010; Wu et al., 2017, 2016). It should be mentioned that if the
197 odor intensity of odorant A is equal to 1 and the OI of B = 5, this does not indicate that
198 $OI_B=5 \times OI_A$ (Gostelow et al., 2001).

199 The category scale is easy to use and does not require much training. When Sucker et al.
200 assessed the intensity, hedonic tone, and frequency of odors emanating from six different
201 industries, they gathered data from 10 to 16 selected assessors per site in addition to the data
202 gathered from 1456 residents (approximately 200 per site). The results of the OI assessment
203 from assessors and residents are shown in Figure 1. The averaged results show close OIs
204 between panelists and residents for rusk, cast iron, and seed oil industries but a difference of
205 approximately one magnitude for sweets, textile, and fat industries. Sucker et al. argued that
206 the differences between the results of the residents and those of the assessors may be a result
207 of the residents using memory-based ratings while the assessors relied solely on the stimuli
208 (Sucker et al., 2008).

209

210 The use of these category scales to assess stimuli is highly subjective. Actually, (i) the
211 sensitivity towards an odor may differ from one person to another for many reasons, e.g.,
212 hormonal, gender, physiology, etc. (Doty and Cameron, 2009; Jaeger et al., 2013) and (ii) the
213 strength of perception relative to a specific scale level from an assessor may be distinct from
214 another. Sucker et al. proposed more training to improve panelist assessment (Sucker et al.,
215 2008). Furthermore, if training is a promising solution, it may be an obstacle when a large
216 number of evaluators is needed, such as for odor dispersion studies in very large cities where
217 many residents are involved covering a large geographic area (Lee et al., 2013; Tran et al.,
218 2019).

219 The use of category scales can also be biased by adaptive phenomena relative to the area
220 context. Indeed, as 15°C can be considered a mild temperature in the cold season but a cold
221 temperature in the hot season, a “weak” odor coming from a certain industry may not
222 correspond to the same intensity coming from another. Therefore, the category scale is similar
223 to a rubber ruler that contracts or stretches to fit the domain of applications (Bartoshuk et al.,
224 2004; Lawless, 2000).

225 Defining each level of magnitude may be a solution to overcome this difficulty. In the work
226 of Qamaruz-Zaman and Milke on odors as an indicator of decomposition of wasted food, they
227 asked two assessors to describe the intensity of the odor released by decomposing food using
228 a category scale (Qamaruz-Zaman and Milke, 2012). Each magnitude (number) was affiliated
229 with a well-defined OI category (1 for weak, etc.) (Table 2).

230 While this approach may remove ambiguity when using the category scale by defining each
231 magnitude, thus offering a simple and reliable OI scale, Qamaruz-Zaman and Milke used only
232 two assessors, and no difference between the results of the panelists was visualized to
233 compare the efficiency when using a category scale with or without defining each magnitude.

234 Atanasova et al. mentioned that the category scale poses a question since assessors have to
235 affiliate a number to a sensation without a point of reference (Atanasova et al., 2004). The
236 Odor Intensity Reference Scale (OIRS) and the cross-modality may solve this problem by
237 comparing the scented odor's intensity to the intensity of another reference.

238 3.1.1.2. Odor Intensity Reference Scale (OIRS)

239 The concept of the OIRS is to compare the intensity of the odor of interest to the intensity of a
240 referent odor. The reference odorant is prepared at different concentrations, thus resulting in a
241 scale of different magnitudes of OIs (Yu et al., 2010). Several standards recommend using the
242 OIRS, such as the American ASTM Standard E-544 (ASTM.E544-75, 1999) and the French
243 Experimental Norm NFX 43-103 (NFX 43-103, 1996). The most commonly used referent is
244 n-butanol (Table 1), as it is readily available in high purity, relatively nontoxic, stable, and
245 has a reasonably pleasant odor that is unrelated to most other odors of interest (Mackie et al.,
246 1998). The samples are sniffed, and their intensities are compared with the intensity of a
247 solution of n-butanol (Deshmukh et al., 2014). Other referents have also been used, such as
248 pyridine (CAS: 110-86-1), orycton (CAS: 32210-23-4), and ethyl butanoate (CAS: 105-54-4)
249 (Devos et al., 2002; Quéré et al., 1994). The OIRS can be divided into five (Guo et al., 2005),
250 eight (Zhang et al., 2005), or 12 levels (Kośmider and Krajewska, 2007). The concentration of
251 n-butanol generally increases following a geometric progression of 2; however, there are
252 scales in which a geometric progression of 1.5 or 3 is used (Kośmider and Krajewska, 2007).
253 The number of levels and the increasing factors depend on the study.

254 Huang and Guo studied odorous emissions from poultry and dairy barns to determine the
255 relationship between several odor properties, including OI, OC, and hedonic tone. The
256 assessment of OI was performed using a six-point n-butanol OIRS (0 to 5). Figure 2 shows
257 the results obtained when determining OC, OI, and hedonic tone from various barns over

258 several months (Huang and Guo, 2018a). The results show the relationship between OC and
259 OI and a decreased hedonic tone (HT) when the OC increases.

260 Atanasova et al. analyzed the OI of various concentrations of two odorants (ethyl butyrate and
261 guaiacol) using a six-point n-butanol OIRS with a panel consisting of 16 assessors. The
262 results showed a small within-subject deviation in comparison to other methods (a residual
263 standard error between 0.39 and 0.47 arbitrary units) (Atanasova et al., 2004).

264 The OIRS is considered an objective approach (Deshmukh et al., 2014). Training is less
265 important because referent solutions may be available to the assessors when determining the
266 OI of an odor of interest. However, when the study is conducted with residents, the use of
267 many referents becomes more complex in regard to distributing referent samples. Therefore,
268 smaller scales were developed to economize time and to simplify the analysis for assessors,
269 such as the three-point scale adapted by Guo et al. (Guo et al., 2001), making the use of the
270 OIRS in the field easier. Nevertheless, when managing several panelists, the use of the OIRS
271 demands more preparation and consumes more time than the category scale. Moreover, the
272 use of n-butanol, which can be distinct from the odor of interest, may lead to confusion and
273 hence difficulties when assessing the OI of the sample. In addition, different sensitivities of
274 assessors towards butanol may lead to a decrease in panel homogeneity (Atanasova et al.,
275 2004).

276 3.1.1.3. Cross modality matching

277 Cross modality matching is based on matching the intensity of an odor to another different
278 sensorial modality, e.g., matching the intensity of an odor with the length of a line. In
279 environmental use, one of the most commonly used cross-modality matchings is the flavor
280 profile method (FPA) (Table 1). Initially used for flavors and odors in drinking water, the
281 FPA method uses a seven-point intensity scale (scale values of 1, 2, 4, 6, 8, 10, and 12) to

282 measure the intensity of an odor in comparison with a taste intensity (APHA, 2012). Three of
283 the intensity points are anchored to standards of sugar concentrations in water: point 4
284 corresponds to the tasting intensity of 5% sugar in water, point 8 to 10%, and point 12 to
285 15%. This method was based on the cross-modal assertion that our senses are linked;
286 therefore, taste can be used to inform the sense of smell (Spence, 2016).

287 In a study related to odor nuisance from a trash-transfer station, Curren et al. determined the
288 OI at different locations around the station using the FPA method (Curren et al., 2016). The
289 results presented in Figure 3 exhibit an important standard deviation wherever the site,
290 regardless of the odor quality, and whenever the assessment was performed. This deviation
291 may have been the result of panel sensitivity discrepancies (panel selection is discussed in
292 part 3.1.3), or this may have been due to the FPA method itself.

293 Curren et al. compared the two scales (the n-butanol OIRS and FPA) when assessing the OI
294 of dimethyl sulfide and butyric acid at different concentrations with a panel of eight assessors.
295 The variance of results between panelists and between sessions was determined. The results
296 showed that the OIRS appeared to show less variance between panelists and that the FPA
297 appeared to show less variance between sessions (Curren et al., 2014).

298 Cross modality matching is not only based on comparing the OI to taste intensity. Indeed,
299 Jiang et al. used a scale with matching temperatures (Table 3) in a study on the relation
300 between the odor concentration and the odor intensity when analyzing odors issued from
301 alumina refineries (Jiang et al., 2006).

302 3.1.1.4. Choosing the appropriate scale

303 Choosing the right method depends on several factors, e.g., the intended study, the aims,
304 logistics, etc. In this part, the scales described earlier are compared. Table 4 summarizes the
305 different methods presenting their advantages and disadvantages.

306 In 2002, Devos et al. performed a comparative study of Stevens' coefficients obtained by
307 different psychophysical methods. Devos et al. analyzed sensory data of 249 odorants from 87
308 papers (21663 potential data) in which odor intensity was assessed using different odor
309 intensity scales. After data analysis and selection, Devos et al. showed that data from the
310 category scale and the n-butanol OIRS were more in accordance than data from cross-
311 modality matching (Devos et al., 2002).

312 However, it is important to keep in mind that whatever scale is chosen, fatigue will always be
313 an issue for its consequence on decreasing the reliability and a limiting factor to the number
314 of possible measurements per assessor e.g. Agus et al. limited each assessor to a maximum of
315 two samples per day, separated by at least 4 h between runs to avoid fatigue (Agus et al.,
316 2012).

317 **3.1.2. Assessment Strategy**

318 Two main assessment strategies widely used (Table 1) are: laboratory assessment and field
319 assessment. In laboratory assessments, samples are collected from the source or impacted
320 area, and later, the odor characteristics are analyzed. The field assessment consists of a direct
321 on-site analysis of ambient odor quality. The choice of strategy depends on the objectives of
322 the study.

323 3.1.2.1. Laboratory analysis

324 Sampling odorous air and assessing the OI have been reported in several studies (Huang and
325 Guo, 2018b; Junior et al., 2010; Lim et al., 2001; Truppel et al., 2005). Nevertheless, as OI is
326 proportional to the chemical concentration, OI results may be biased due to sampling
327 complications explained by air sampling (part 1). Therefore, field studies are sometimes
328 encouraged.

329 3.1.2.2. Field study

330 In environmental odor pollution cases, direct assessments on-site may be performed to assess
331 odor intensity (Curren et al., 2016; Guo et al., 2001; Hile et al., 2015). Field studies may be
332 performed by using the following strategies: the grid method, the plume method, and
333 community assessment. Essentially, the grid method was standardized to determine the
334 distribution of the odor-hour frequency, while the plume method was developed to determine
335 the dispersion of odors from a specific source, without the mention of OI, OC, and odor
336 quality assessment (EN 16841-1, 2016; EN 16841-2, 2016; Guillot et al., 2012). However,
337 several field studies were based on the measurement and deployment strategy offered by both
338 approaches, as presented later.

339 **Grid measurement methodology** is a technique in which the assessors register odor data
340 following measuring grids within the area under study for a fixed period of time (NF EN
341 16841-1, 2016; Sówka, 2010; Guillot et al., 2012) (Figure 4). A large period is considered (6
342 months to one year), as well as subsequently a multiplicity of meteorological conditions. In
343 addition, the method allows us to cover a large impacted area and to assess areas that are not
344 exposed or are low exposed, as well as highly exposed areas (Sucker et al., 2008). The grid
345 edges are recommended to be 250 m, but they can be adjusted to 50, 125, or even 500 m
346 depending on the conditions and needs (Yusoff and Zaman, 2017).

347 Sówka et al. studied odors coming from numerous industries in an urban area located in the
348 southern part of Poland. Nine assessors selected according to their sensitivity towards n-
349 butanol (EN13725, 2003) assessed the odors at each grid point and noted the intensity and
350 character of the smelled odors. This allowed them to identify the odor sources in the region
351 along with the extent of these odors (Sówka et al., 2018).

352 **The plume method** allows the definition of the dispersion area of the odor. Based on the
353 wind direction and source localization, the dispersion direction is supposed, and the jury can
354 experimentally define the plume delineation (EN 16841-2, 2016). The plume method is
355 efficient when assessing the dispersion of an isolated odor source (Yusoff and Zaman, 2017).
356 The panel walks in a crisscross itinerary along with the wind direction starting from the
357 source, as shown in Figure 5. In this way, the panel can detect the expansion of the odor
358 plume. This is called a dynamic plume method. The static-dynamic plume method is where
359 the jury walks perpendicularly to the wind direction, walking in and out of the plume (Guillot
360 et al., 2012). Other itineraries included simply traveling downwind from the odor source and
361 assessing all directions (Stowell et al., 2007).

362 However, as a relatively fast method (in comparison with the grid method), yearlong
363 meteorological factors, in addition to wind direction and actual weather, may not be well
364 understood (Guillot et al., 2012). This limits the approach to rapid assessments instead of a
365 well-understood odor impact.

366 **Community assessment** is when residents may be involved to report the odors impacting
367 their community. Residents usually answer a questionnaire where they describe the odor:
368 intensity, offensiveness, frequency, etc. (Gallego et al., 2008; Lee et al., 2013; Sucker et al.,
369 2008). Some questionnaires may include health data of the residents (Aatamila et al., 2010)
370 and/or sociodemographic data, e.g., job, smoking habits, hours spent in residence, etc.
371 (Avishan et al., 2012) to better contextualize the impact. On the one hand, community
372 assessment is considered an effective method to acquire an odor impact (Hayes et al., 2014).
373 This may be due to the great number of participants. On the other hand, the results from
374 exposed residents may be biased due to their more subjective judgment (Lee et al., 2013;
375 Nicolas et al., 2010) and the deficiency of training (Gallego et al., 2008). For further readings

376 considering questionnaires and community involvement, one may read the review by Hayes et
377 al. (Hayes et al., 2014).

378 To conclude, field assessments offer many advantages over laboratory analyses because (i)
379 when studying odors directly in the field, one can easily skip sampling, thus economizing
380 time; (ii) because no sampling container was used, there was no sample alteration, thus
381 eliminating the bias related to odorant stability in the sampling container (Hayes et al., 2014);
382 and (iii) field assessment is relatively less expensive than laboratory assessment in regard to
383 the long-term follow-up of complex odor emission areas. Furthermore, if well trained, local
384 communities may be an efficient network of panelists to assess odors in the long term in a
385 large geographic area. However, one must consider that when assessing odors in the field, the
386 panel may have assumptions about the odors due to their presence near the sources, unlike
387 laboratory assessment, where the analysis is done in complete anonymity.

388 **3.1.3. Panel Characteristics**

389 A panel consists of at least four to ten assessors depending on the purpose of the study and the
390 level of expertise of the assessors. They are usually trained to use the intended scaling method
391 and notified that eating, drinking, or smoking may influence their analysis (Junior et al.,
392 2010). Training the panel is a real added value, as Sucker et al. has highlighted. The
393 disparities between assessors and residents has been explained as a result of the absence of
394 training for the residents (Sucker et al., 2008). When the assessment is performed with the
395 community, the number of participating residents varies from 44 to 1456 participants, usually
396 volunteers. Thus, training is not conceivable. They do not need to be experts to study the
397 impact on their communities and nuisance level, rather than determining the OI objectively.
398 However, residents living near emission sources are sometimes avoided because they tend to
399 assess odor more subjectively than others (Lee et al., 2013; Nicolas et al., 2010).

400 Panel selection is a factor that may affect the entire assessment. Smokers and assessors in
401 poor health or old may have a decreased sensitiveness (Gostelow et al., 2001). In addition,
402 assessors who are used to the odor may also have a decrease in sensitiveness due to olfactory
403 fatigue (Dravnieks and Jarke, 1980; Gostelow et al., 2001).

404 To limit these biases, screening tests are performed to select panelists with homogeneous
405 olfactory capabilities. The French standard NFX43-103 proposes selecting panelists according
406 to their capability to rearrange odorant solutions (basically n-butanol or pyridine) by order,
407 according to their odor intensity (NFX43-103, 1996). Spearman's rank correlation coefficient
408 was calculated between the panelist ranking and the expected ranking. Usually, a coefficient
409 greater than 0.8 or 0.9 is considered a good indicator, and the panelist is chosen. However,
410 Issanchou et al. applied the ranking test with growing concentrations of 1-octen-3-ol on a
411 panel of 103 to 118 assessors. Their results showed that 56% of the panelists found the right
412 ranking, and 81% had a correlation score >0.9 (Issanchou et al., 1995). They argued that the
413 test is easy, which is why it may not be very effective.

414 Curren et al. selected panelists using the University of Pennsylvania Smell Identification Test
415 (UPSIT) (Curren et al., 2016). The concept is to identify odors from a collection of 40
416 odorants. Panelists are classified into five categories: normosmia, mild hyposmia, severe
417 hyposmia, moderate hyposmia, and anosmia. If 34 odorants or more are identified, the
418 panelist is considered to have "normosmia" or normal olfaction (Frank et al., 2006).
419 Nevertheless, it is important to mention that this approach does not check the ability of the
420 panelist to properly assess the OI.

421 Laor et al. developed a screening method for field assessments. Their test comprises three
422 parts: odor identification using forced-choice, intensity assessment, hedonic tone, and quality
423 assessment. The intensity assessment was divided into two parts: (i) based on the OI, placing

424 a solution of n-butanol in its place in a series of n-butanol solutions with increasing
425 concentrations and (ii) describing the OI of the previously assessed n-butanol solutions using
426 a category scale. Each panelist results are graded based on (i) the positioning of the unknown
427 solution and (ii) on the difference between the OI attributed by the panelist and the mean of
428 all participants (Laor et al., 2008). It has been shown that this test was useful in selecting
429 panelists with good smelling capability. The test also covers many odor properties, such as
430 odor nature and hedonic tone. Furthermore, intensity-based screening tests evaluate the ability
431 of a panelist to correctly determine an unknown odor intensity.

432 To conclude, tests that focus on intensity only are not that common. Usually, selection
433 procedures for other assessments are used, e.g., panel selection tests for odor concentration
434 determination or tests that require identifying odorants. A screening procedure that considers
435 multiple odor properties may be efficient when selecting assessors such as the one devised by
436 Laor et al. (Laor et al., 2008).

437 **3.2. Odor concentration**

438 Odor concentration (OC) offers a direct quantification not based on scales but on a dilution
439 factor. OC is the number of dilutions needed for the odorous sample to become inodorous,
440 i.e., reaching the detection threshold. Its unit is ou_E/m^3 , European odor unit per cubic meter.
441 The European Norm EN 13725 defines the OC of an odor at $1 \text{ ou}_E/\text{m}^3$ as having the same
442 stimulus as one European reference odor mass (EROM) (n-butanol), equivalent to $123 \mu\text{g}$,
443 evaporated in 1 m^3 (EN13725, 2003). Table 5 presents twenty studies, performed mostly in
444 Europe, from 2008 to 2018, focusing on environmental odor assessments where the OC
445 determination approach was used. Table 5 shows the OC determination method used, whether
446 by dynamic or static olfactometry or calculated using chemical concentrations; the assessment
447 strategy used, whether analyses were performed in a laboratory using sampling from the

448 exposed area, field assessments or using the dispersion method; and the panel characteristics.
449 Analysis performed in a laboratory with sampling from exposed areas enables the
450 determination of the OC of air samples collected directly in the field. Dispersion modeling
451 allows the prediction of odor impacts in a certain area and enables real-time surveillance
452 without the use of a human panel by determining the OC in the laboratory using samples
453 collected directly from the source. Finally, field olfactometry allows the determination of the
454 OC directly in the field in exposed areas without the need for sampling.

455 **3.2.1. Determining odor concentration**

456 In the literature, three methods are mentioned to determine the OC: the dynamic olfactometry
457 method, static olfactometry method, and OC determination method using chemical
458 concentrations (Table 5). The first two methods rely only on sensory analysis, while the third
459 method depends mainly on chemical analysis and detection thresholds.

460 3.2.1.1. The Dynamic olfactometry method

461 The use of a dynamic olfactometer is the most commonly used method. Most international
462 odor policies are based on a required compliance odor frequency with maximum allowable
463 odor concentrations. Thus, OC measurements by using the dynamic olfactometry method
464 have indisputably become the most commonly employed sensorial technique (Muñoz et al.,
465 2010), especially because the use of dynamic olfactometers, as shown later, offers less bias. It
466 is a device that allows automatic dilution of a gaseous odorous sample with neutral gas
467 (nitrogen or clean air). The sampling bag in “air sampling” (part 1) is attached directly to the
468 olfactometer, which in turn dilutes the odor and transfers it to panelists at increasing
469 concentrations (Muñoz et al., 2010). The odor concentration is determined when the diluted
470 odor sample reaches the olfactory detection threshold for 50% of the panel.

471 This approach is widely used in many environmental domains, e.g., landfills, industrial zones,
472 wastewater treatment, etc. (Table 5) (Capelli et al., 2012, 2011; Sironi et al., 2010; Toledo et
473 al., 2018; Wu et al., 2015). For example, Vieira et al. determined the odor concentration
474 coming from a rendering plant using a dynamic olfactometer. This enabled them to calculate
475 the odor emission rate and compare it to the Brazilian Standard for compliance (Vieira et al.,
476 2016).

477 In regard to the detection of the perception threshold by the panel using olfactometers, two
478 methods exist: the Yes/No method and the forced-choice method. In the Yes/No method, the
479 panelists smell various concentrations, one at a time; at each olfaction, they answer by “yes”
480 if they smell something or “no” if they do not. The forced choice consists of obliging the
481 panel to select between two (or more) samples, one containing the odor sample and the
482 other(s) containing neutral gas, which is odorous (EN13725, 2003). The forced-choice
483 method is generally preferred over the Yes/No method (Dravnieks and Jarke, 1980; van
484 Harreveld et al., 1999), which may be because the forced-choice method yields a higher OC
485 than the Yes/No method (Ueno et al., 2009).

486 3.2.1.2. The Static olfactometry method

487 In the case of the static olfactometry method, dilution is performed manually using sampling
488 bags until the detection threshold is reached (Li et al., 2019; Wenjing et al., 2015). This
489 method does not require complex instrumentation and hence is easier and less expensive than
490 dynamic olfactometry.

491 Nevertheless, as it is a manual dilution, errors related to the manipulator may increase, and
492 using several sampling bags may introduce additional biases. Moreover, biases may be due to
493 the use of multiple sampling bags.

494 Ueno et al. compared the triangle odor bag method (a forced-choice using three bags, one
495 odorous and two neutral, in static olfactometry) with dynamic olfactometry using the Yes/No
496 and forced-choice methods. The results showed that the triangle odor bag method yielded a
497 higher OC than dynamic olfactometry using the forced choice method but yielded the same
498 OC levels using dynamic olfactometry as the Yes/No method. According to Ueno et al., the
499 difference between static and dynamic olfactometry may be decreased if the same panel
500 screening method is used (Ueno et al., 2009).

501 3.2.1.3. Determination using chemical analyses

502 The determination of the OC can also be calculated from the chemical concentration
503 determined by chemical analyses using the following equation:

504 $OC = \sum_{i=0}^n \frac{C_i}{C_{OT,i}}$ (eq 3), where C_i is the chemical concentration of odorant i and $C_{OT,i}$ is the
505 olfactory detection threshold of i (Cariou et al., 2016).

506 This approach is also known as the odor activity value (OAV) (Kim and Park, 2008; Parker et
507 al., 2012, 2010):

$$508 \quad OC = \sum OAV_i = \sum_{i=0}^n \frac{C_i}{C_{OT,i}} \quad (\text{eq 3'})$$

509 The OAV does not require the intervention of a human panel. The detection threshold can be
510 obtained from the literature.

511 However, Capelli et al. studied odors coming from a landfill and compared the determination
512 of the OC using dynamic olfactometry and using the OAV. Air samples were analyzed by gas
513 chromatography-mass spectrometry to identify and quantify the different VOCs
514 (hydrocarbons, oxygenated, sulfured, halogenated, and nitrogenous compounds). They
515 showed that the measured odor concentration with dynamic olfactometry did not correlate
516 with the calculated odor concentration. Capelli et al. argued that the difference may have been

517 due to two factors: (i) the detection thresholds taken from the literature and used to calculate
518 the OAV were not accurate and (ii) the model proposed, which was a simple summation (eq
519 3), did not match the potential interaction, synergy, and masking effects (Capelli et al., 2008).
520 Additionally, chemical and sensory analyses were compared for different odor sources,
521 including the steel industry, different chemical industries, and wastewater treatment plants
522 (Capelli et al., 2012). Figure 6 shows the relation between the OAV calculated from chemical
523 analysis and the OC (C_{OD}) determined by dynamic olfactometry. The OAV was more than
524 two to three orders of magnitude lower than the corresponding measured OC.

525 To investigate the effect of imprecision on the detection thresholds taken from the literature,
526 Cariou et al. studied the prediction of the odor concentration by using gas chromatography on
527 a mixture of six odorants. The OC calculated from the sum of the OAV of each odorant based
528 on perception thresholds from the literature was approximately 5000 dilution-fold, while
529 based on detection thresholds measured in the laboratory, it was around 18400 dilution-fold
530 (Cariou et al., 2016). They showed that the perception threshold determined in the laboratory
531 yielded better results than those gathered from the literature. The OC of the mixture of
532 odorants determined by dynamic olfactometry was approximately 12000 dilution-fold. Thus,
533 the need to determine the studying panel perception thresholds and not to use ones from the
534 literature is a must when using the OAV method (Cariou et al., 2016). These values illustrate
535 the crucial role of taking into consideration the sensory interactions when determining the OC
536 of a mixture of odorants.

537 Hence, Wu et al. introduced a factor called the OAV coefficient, γ , which is a coefficient that
538 evaluates the interactions between two odorants. Odorants were identified by chemical
539 analysis from samples collected at waste disposal plants. γ is calculated from the ratio
540 between the OAV of a single odorant yielding a certain OI_{target} , determined with sensory
541 approaches, and the OAV of a mixture of the odorant and a referent odorant at the same

542 OI_{target} , determined using the concentration-to-perception threshold ratio. As mentioned, γ
543 reflects the binary interactions in an odorous mixture e.g, the γ phenol decreased from 0.56 to
544 0.15 as OI_{target} increased from 2 to 4.5 indicating that more phenol is needed in a mixture with
545 H_2S to maintain the same OI_{target} as in its pure form, thus indicating an antagonistic effect. On
546 the contrary, γ values of trimethylamine increased from 5.57 to 17.64 as OI_{target} rose from 2 to
547 4.5 indicating a synergetic interaction where less trimethylamine is needed to maintain an
548 OI_{target} of a mixture with H_2S . Then, γ is multiplied by the OAV of a mixture composed of the
549 previously identified odorants. This yields an odor activity factor (OAF). The OAF showed a
550 good correlation with the OC determined by dynamic olfactometry (Wu et al., 2015). This
551 study confirms the important role of sensory interactions among odorants in field studies.
552 However, as OAF requires many experiments, including olfactometric experiments, static and
553 dynamic olfactometry methods are still preferred.

554 **3.2.2. Assessment Strategy**

555 Assessment strategies are grouped into three categories as presented in Table 5: (i) laboratory
556 assessment with sampling from the exposed area, where ambient air is sampled from exposed
557 areas and OC is assessed in a laboratory; (ii) odor dispersion modeling, where air samples are
558 collected from odor emission sources, OC is assessed in a laboratory using an air dispersion
559 model, and OC in exposed areas is modeled; and (iii) field olfactometry, where the OC in the
560 ambient air in exposed areas is assessed directly in the field using a field olfactometer. As the
561 most commonly used methods are dispersion models and field olfactometry, more details will
562 be given mostly on these two methods.

563 **3.2.2.1. Laboratory assessment-sampling from exposed areas**

564 In this approach, ambient air samples are collected from exposed areas, usually in bags, and
565 their OC is determined using olfactometry or by calculating it using the OAV (Palmiotto et
566 al., 2014; Wu et al., 2018). This allows the detection of OC in exposed areas using

567 olfactometry. Laboratory analyses are necessary in some cases because, unlike OI, it needs an
568 instrument that cannot be easily deployed in the field. However, when studying the odor
569 impact on communities, dynamic olfactometry, performed using on-site collected samples, is
570 unsuitable due to the lack of precision when OC levels are low: some laboratory olfactometers
571 have method detection minimal limits of 5–10 dilutions (McGinley and McGinley, 2004).
572 Therefore, laboratory assessment of OC by direct sampling from the exposed area is not often
573 used and is substituted by odor dispersion modeling or field olfactometry.

574 3.2.2.2. Laboratory assessment-sampling from the source and dispersion modeling

575 Dispersion models use odor concentration emission rates from odorous sources combined
576 with topological and meteorological data to model the concentrations and frequency of odors
577 from specific sources, i.e., the impacted zone and odor concentrations during a definite
578 percentage of time (Figure 7). At the source, odorous air is sampled in bags over a definite
579 period. Afterward, the samples are analyzed in a laboratory to determine the odor
580 concentration emitted during the sampling time to calculate the odor concentration emission
581 rate (OU_E/s) (Capelli et al., 2013a).

582 Odor concentrations at the source are high; hence, the use of laboratory-based olfactometry is
583 pertinent and not limited by the factors mentioned for laboratory assessment. Then, the most
584 common approach is using a dispersion model that considers the odor concentration emission
585 rate along with meteorological and topological data such as elevation, wind speed, wind
586 direction, etc. Different models have been used, such as analytical stationary plume models,
587 puff models, Lagrangian models, etc., or hybrids of different models (Capelli et al., 2013b).
588 For example, this method has been used in many environmental studies pertaining to
589 industrial plants (Capelli et al., 2011; Sironi et al., 2010), landfills (Naddeo et al., 2016), or
590 waste treatment plants (Doğruparmak et al., 2018; Gutiérrez et al., 2015; Toledo et al., 2018).

591 3.2.2.3. Field olfactometry

592 Field studies can be used to determine OC in specific areas surrounding an odor source (Bax
593 et al., 2020; Capelli et al., 2013b; Hayes et al., 2014). This approach allows studying odors at
594 the receptor, i.e., directly in exposed residential areas. Studies can follow both grid and plume
595 measure and deployment strategies. While the grid offers a long time period, the plume offers
596 a relatively fast approach but under specific meteorological conditions (Capelli et al., 2013b).

597 To determine the OC on-site, portable or field olfactometers have been developed. In 2000,
598 McGinley and McGinley used a Nasal Ranger[®] developed by St Croix Sensory, Inc., Lake
599 Elmo, MN, USA. It is a portable device that dilutes the odor using carbon-filtered air from the
600 atmosphere at different ratios: from a dilution factor of 2 to 500 (Figure 8) (McGinley and
601 McGinley, 2004).

602 In 2014, Szydlowski used another field olfactometer, the Scentroid SM100 (IDES Canada,
603 Inc.) which uses compressed neutral air to dilute the odor (Szydlowski, 2014). For example,
604 field olfactometers have been used to quantify odors from different sources: municipal
605 landfills (Gębicki et al., 2017), water treatment plants (Barczak and Kulig, 2017), land
606 manure (Brandt et al., 2008), agriculture (Nicolas et al., 2013), and livestock (Pan et al.,
607 2007).

608 This can be illustrated by the study done by Kitson et al., where odor emissions from different
609 industries in an urban area in Camden, NJ, USA, were determined. They used the Nasal
610 Ranger[®] field olfactometer coupled with odor description using five descriptors: food,
611 emission/fuel, waste, natural, and smoke. The study combined sensory analysis with
612 cartography to geolocate the odor data (Kitson et al., 2019). Figure 9 shows the map where
613 OC (referred to as smell intensity with dilution to the threshold D/T as a unit) and the odor
614 character are represented at each analysis point (randomly selected).

615 Field olfactometry seems to have many advantages over laboratory analyses: (i) there is no
616 need to sample ambient air, and thus, there are no sample losses related to the use of sampling
617 recipients and conditions, (ii) field olfactometry is more cost-effective, and (iii) this approach
618 allows real-time analysis and odor quantification at receptor locations (Figure 9).

619 However, in an analysis of 3096 individual OCs collected from observations at livestock
620 facilities, Brandt et al. utilized the field olfactometry approach using Nasal Ranger[®] and
621 found that the method was repeatable between assessors but not reproducible from one
622 olfactory session to another. The results showed the influence of odor source distance, wind
623 direction, barometric pressure, and wind velocity (Brandt et al., 2011). The same
624 reproducibility results were found by McGinley and McGinley when determining the OC of
625 hydrogen sulfide at different concentrations in a controlled chamber using Nasal Ranger[®]
626 (McGinley and McGinley, 2004).

627 Moreover, several factors may bias the results, such as fatigue, anxiety, prejudgments of
628 odors, and distractions, as well as not mentioning background odors, that may occur in the
629 field, which may be more easily managed in laboratory analyses (Brandt et al., 2011). Some
630 studies on the Nasal Ranger[®] even showed the absence of correlation between this field
631 olfactometer and a laboratory olfactometer (Bokowa, 2013, 2008). They also found that small
632 charcoal filters can sometimes not be able to completely filter the air used to dilute odorous
633 air when odors are at a high OC (Bokowa, 2008). The Scentroid SM100, on the other hand,
634 correlated well with laboratory results (Damuchali and Guo, 2019) with some deviations from
635 the manufacturer specifications (Maurer et al., 2018). Furthermore, in a study by Vieira et al.,
636 the two instruments were shown to be unsuitable for assessing OC within odor plumes,
637 especially on the boundaries of the plume and at further distances from the plume due to nose
638 fatigue (in the case of Nasal Ranger[®]) and high dilution gas consumption (in the case of
639 Scentroid SM100), but showed that field olfactometry is a reliable method to validate odor

640 dispersion modeling (Vieira et al., 2018). For all of these discrepancies, the use of portable or
641 field olfactometers are not recommended any more in the last revised version of the EN
642 13725 standard (van Harreveld et al., 2020).

643 Few data exist on the direct comparison between field olfactometry and odor dispersion
644 modeling. One study performed on odors coming from a palm oil mill realized by Yaacof et
645 al. compared the use of field olfactometry (with Scentroid SM100) with the dispersion model,
646 CALPUFF (a Lagrangian puff model created by Earth Tech, Inc. for the California Air
647 Resources Board (CARB) and the U.S. Environmental Protection Agency (US EPA)). Their
648 study showed that there was no good correlation between the two approaches regarding odor
649 quantification. However, on a macro level, when the model predicted an increase in OC, the
650 results of the field olfactometry showed a similar increase (Yaacof et al., 2017). This might
651 have been due to many factors, including the sample losses in the sampling Nalophan bag,
652 which decreased the OC, thus biasing the odor emission rate and consequently the results of
653 the model.

654 **3.2.3. Panel characteristics**

655 Generally, the panel (four to eight assessors) passes a screening test to narrow the sensitivity
656 disparity, and then the assessors are trained to use the olfactometer (Table 5). The most
657 commonly used screening test is the one proposed by the European norm EN13725
658 (“EN13725,” 2003). This is achieved by determining the individual threshold estimate (ITE),
659 which is the individual perception limit of n-butanol, of each panelist using dynamic
660 olfactometry. The ITE is determined ten times during three sessions with a minimum pause of
661 one day between each session. Then, two criteria must be respected to choose a panelist: (i)
662 the antilog of the standard deviation calculated from the logarithms of the individual ITEs
663 needs to be below 2.3; and (ii) the geometric mean of the ITEs should be between 60 and 250
664 $\mu\text{g}/\text{m}^3$.

665 As Capelli et al. argued, laboratories tend to use the same initial n-butanol concentration
666 (approximately 182 mg/m³) and the same dilution factors between the ten ITE determination
667 sessions. This induces memory effects among the assessors. They proposed changing the
668 initial butanol solution concentration and that the olfactometer operator does not know it to
669 avoid this bias (double-blind methodology). The application of these modifications showed a
670 drop in panel selection from 60% to 33% (Capelli et al., 2010).

671 However, the use of n-butanol as a reference certainly helps to select a panel with sensitivity
672 within a defined bandwidth (EN13725, 2003) but does not guarantee the same sensitivity
673 towards other odorous compounds because each individual has a unique set of genetic
674 variations that lead to variation in olfactory perception (Mainland et al., 2014).

675 Some methods also require panel selection to be based on the identification of components of
676 a mixture at defined concentrations, such as the procedure established by the Korean Ministry
677 of the Environment, where panelists are chosen if they manage to identify the components of
678 a mixture containing 1% acetic acid, 0.1% trimethylamine, 3.2% methylcyclopentolonone,
679 and 1% β -phenyl ethyl alcohol (Kim, 2011, 2010).

680 **3.3. Comparison of odor intensity and odor concentration assessment**

681 In regard to quantifying environmental odors, a choice has to be made between assessing the
682 OI or the OC. Both methods offer a quantifiable dimension, but each one has different
683 advantages and disadvantages.

684 In a field inspection studying five odor sources in Idaho, Sheffield et al. compared the use of
685 laboratory dynamic olfactometry using forced-choice (LDOFC), field olfactometers, the field
686 OIRS, and the laboratory OIRS. They found that the LDOFC and the Nasal Ranger[®] showed
687 lower variability in their results. Furthermore, differences with poor correlation

688 between laboratory results and field results were noticeable (Sheffield et al., 2004). In another
689 study performed on manure odor in a controlled atmosphere, Henry et al. quantified the odor
690 using LDOFC, two field olfactometers, and the field OIRS. They showed a good correlation
691 between the results of the field olfactometers and the results using the OIRS. However, the
692 correlation was poor between field methods and the LDOFC. They proposed that the absence
693 of correlation may be due to the interference from the background odors present in the Tedlar
694 bags[®] used to sample the air from the control room to perform olfactometry (Henry et al.,
695 2011).

696 To compare the different approaches, Table 6 presents the major advantages and
697 disadvantages of the most commonly used methods in environmental studies: field OI
698 assessment, field olfactometry, and odor dispersion modeling. While these methods have
699 different pros and cons, the choice of the method remains a question of the available resources
700 (budget, personnel, etc.) and exigency.

701 **4. Odor qualification**

702 In environmental studies, odor profile qualification is frequently used in connection with the
703 evaluation of the impact of odor nuisance on the population. Odor quality aggregates two
704 dimensions: the odor nature (ON) and the hedonic tone (HT), also known as offensiveness.
705 The ON, which is what the odor smells like, is often used to identify odor sources (Muñoz et
706 al., 2010). HT is how pleasant or unpleasant an odor is to assessors and is often used when
707 assessing odor nuisance impacts in exposed areas (Nicell, 2009). Hence, odor quality is a
708 predictor of odor annoyance (Weitensfelder et al., 2019).

709 **4.1. Odor nature**

710 Odor nature, as mentioned before, is used mainly to identify the source(s) of odors or to
711 characterize the profile of odorous emissions. This helps in identifying the main cause
712 (geographical emission source and/or odorants potentially responsible for the odor) of odor
713 nuisances in the exposed areas. In Table 7, ten studies from 2009 to 2019 where ON was
714 assessed are presented along with the assessment strategy and the panel characteristics.

715 **4.1.1. Description method**

716 Three main methods used to describe the odor nature in the environment are evocations, the
717 odor profile method, and odor nature reference description (Table 7).

718 4.1.1.1. Evocations

719 When describing the nature of any sensation, one may tend to describe it by analogy to a
720 known source. When smelling an odor, we tend to use evocation-related sources to describe
721 it; e.g., limonene is ascribed to the odor of orange, pinene to pine, etc.; to use evocation-
722 related adjectives such as fruity, musky, woody, etc.; or sensation-like adjectives such as
723 sharp, pungent, etc. (Auffarth, 2013; Trabue et al., 2011).

724 Zarra et al. evaluated odor nuisance in an industrial area to optimize field inspection methods
725 for odor impact assessment. They described the odor nature using four descriptors: sewage,
726 waste, smog, and others. The first three descriptors were sufficient to describe the majority of
727 the encountered odors (Zarra et al., 2010). As illustrated in the study by Zarra et al. (2010),
728 the use of descriptors is simple because it refers to “labels” for everyday items that everybody
729 knows very well.

730 However, odor description language was not constructed via discussions of a shared meaning
731 during verbal communication (Dubois and Rouby, 1997), which indicates that odor
732 descriptions (including intensity and nature) are not common to all humanity. The olfactive

733 stimuli are complex and make common education difficult, contrary to learning colors that
734 include clear and common references. Odor naming and memory storing are influenced by the
735 social, cultural, and historical context and can differ among populations (Baccino et al.,
736 2010). Thus, the interference of a person's experiences, memories, and acquisitions (such as
737 education) may lead to the subjectivity of odor perception (Jaubert, 1990).

738 Some researchers believe that training improves odor assessment. The greater the panel is
739 trained, the more efficiently they use the descriptors. An untrained assessor may, for example,
740 use "Grandma's linen cupboard" as an accurate descriptor, whereas a trained assessor would
741 describe it as woody (the cupboard), musky (the linen), and camphoraceous (the mothballs)
742 (Turin and Yoshii, 2003). However, this does not remove the ambiguity of an odor
743 description; e.g., geosmin and 2-methyl isoborneol are considered earthy odors, but each
744 molecule produces a different perception.

745 Thus, the use of evocations is ill fated with the subjectivity that biases the results. Even if
746 training improves the assessment conditions, the use of descriptors based on evocations still
747 poses some questions. It is worth mentioning in the literature that odor nature is described
748 using a well-defined vocabulary (Brancher et al., 2017; Verrielle et al., 2012), e.g., odor
749 wheels (Figure 10), which are a method to classify odor nature descriptors or characters that
750 are usually developed for each domain based on odors and/or odorants frequented during
751 sensory analysis (Suffet and Rosenfeld, 2007).

752 4.1.1.2. Odor Profiling Method (OPM)

753 The OPM is one of the most commonly used methods worldwide to describe odor nature in
754 the environment (Table 7). The odor profiling method is an odor evaluation approach based
755 on attributing an intensity to different odor descriptors. The intensity scale used is usually the

756 FPA (cross-modality) described in 2.1.1 (Burlingame, 1999). However, due to the subjectivity
757 of odor descriptors based on evocations, lists of descriptors were developed as the odor wheel.
758 Burlingame et al. evaluated the odors coming from different processes for treating wastewater
759 to identify the source of the odors. Therefore, they developed a specific odor wheel for the
760 wastewater treatment plants shown in Figure 10. Odor wheels have been developed for many
761 domains, such as for drinking water (Suffet et al., 1999), compost (Rosenfeld et al., 2004a),
762 urban odors (Rosenfeld et al., 2004b), and even wines (Noble et al., 1987). As seen in Figure
763 10, the odor wheel proposed by Burlingame et al. (2004) is divided into three degrees of
764 precision. The inner circle represents the primary category, such as the primary colors of the
765 rainbow. The outer circle gives some precision to the primary category, e.g., in the
766 fragrant/fruity primary category, there are several subcategories: soapy/detergenty, fruity,
767 citrusy, and green. Chemical substances that may be responsible for the odor character are
768 suggested, e.g., the citrusy character may be caused by d-limonene (Suffet and Rosenfeld,
769 2007).

770 Odor wheels aim to create a unified lexicon to describe the odor nature in a targeted domain
771 “to standardize the basis on which to classify, communicate and identify odor qualities”
772 (Muñoz et al., 2010). Information present in odor wheels may be presented at different levels
773 of detail and may be adapted to communities to create simpler information that residents
774 without experience or training can use (Hayes et al., 2017).

775 Often, the results linked to the OPM are useful in guiding the type of chemical analyses
776 required to identify compounds (Abraham, 2014).

777 Furthermore, odor wheels have been used to assess odor annoyance by attributing an
778 annoyance level to each odor character. The results helped create a framework used to assess
779 odor nuisance at the fence line of the plant (Burlingame, 2009).

780 Nevertheless, despite the progress that the OPM presents to create a standardized vocabulary,
781 odor wheels still rely on evocative descriptors, which is still a subjective method. Muñoz et al.
782 argued that due to the subjectivity of the method, comparison and interoperation of data
783 collected by different laboratories (or even between different analysts) can be difficult
784 (Muñoz et al., 2010). Moreover, the lack of diversity of molecules responsible for the odor
785 character may be a source of imprecision. Furthermore, the same odor may be caused by
786 different odorants with different chemical structures, e.g., methyl methacrylate (CAS: 80-62-
787 6) is described as having a solvent odor (Figure 10), but in another study, methyl methacrylate
788 was shown to have a sulfurous odor (Hawko et al., 2021). Hence, in this case, choosing a
789 specific sulfur detector will not be successful in detecting this molecule.

790 4.1.1.3. Odor nature reference description

791 To describe colors, one can refer to an evocation, e.g., red is the color of strawberries.
792 However, to create a unified lexicon that will not change from one person to another, color
793 references are used, such as Pantone® numbers or the RGB system. The same logic may be
794 applied to odors. Odor Nature Reference Description (ONRD) uses odor references as
795 descriptors instead of evocations. “Field of odors®” and “Langage des Nez®” (LdN) methods
796 are known to use referents as odor nature descriptors.

797 The field of odors is an organized collection of 45 odor referents (Jaubert et al., 1995). LdN is
798 a collection of 26 referents (chemical substances) distributed in seven poles based on their
799 odorous similarities (Figure 11). The seven poles are terpenic, alkyl, ester, amine,
800 phenol/pyrogenic, sulfurous, and aromatic; they are not defined following evocations but
801 rather in reference to chemical substances. These poles are built around a nucleus, constituted
802 by one to three referent(s) (represented on the first concentric circle) and gather one to three
803 satellite referents (represented on the second and third concentric circles), as seen in Figure
804 11. For example, the alkyl pole is defined by the two referents, diacetyl and nonanal (number

805 7 and number 6 in the figure), at the center of the pole. Additionally, three referents are
806 associated with this pole, butyric acid, cis-hexenol, and acetic acid, which share an alkyl-like
807 odor but tend to reach other poles, such as acetic acid, which presents an ester-like facet.

808 ONRD requires a specially trained panel that must memorize the odor of each referent. When
809 characterizing an “unknown” odor, the panel describes the scented odor by comparing it with
810 the less different referents.

811 In an effort to survey the ambient air odor quality in Normandy, France, Atmo Normandie,
812 the air pollution monitoring network in the region, trained hundreds of volunteer residents to
813 use ONRD. Thus, they deployed a network of assessors in a vast area (approximately 300
814 km²) that assessed the nature of air odors, helping to collect information about the perceived
815 daily odors (Leger, 2008). Moreover, there are trained assessors in industrial enterprises that
816 help to create an odor profile and to keep track of the odors emitted from their industrial
817 plants (Capo and Leger, 2017).

818 For example, in 2012, Atmo Normandie held a yearlong campaign in the city of Le Havre,
819 France. Thirty-three local assessors were asked to sniff the air two times per day and to
820 describe the odor nature using odor referents. The results of their observations created a
821 description of the odor of the city (Figure 12), where dimethyl disulfide (DMDS), phenol,
822 acetyl pyrazine, and furfuryl mercaptan-like odors were the most frequent (Atmo Normandie,
823 2015). When compared with odor descriptions of the different industries in the region, this
824 approach allowed the identification of odor sources in the city (Leger, 2016).

825 The use of odor referents provides objective and repeatable results over time and between
826 assessors, as shown with the odor nature description of 44 compounds potentially released in
827 the industrial zone of Le Havre (Hawko et al., 2021). Descriptions refer to the odor of a
828 chemical substance that assessors have memorized and not to evocations that could differ

829 from one person to another (Jaubert et al., 1995). Thus, it creates a unified lexicon to describe
830 odors objectively by linking the description to the odor sensation directly (Verriele et al.,
831 2012). Furthermore, depending on the study, referents may be added to the basic collection to
832 more precisely describe the perceived odor. As an example, in Figure 12, furfuryl mercaptan
833 was added as a referent to the odors emitted by the coffee roasting industry in the city.
834 Likewise, Verriele et al. adapted the referent list to describe the odor in a new car cabin
835 (Verriele et al., 2012).

836 However, this method requires a long training (Leger, 2017) in addition to the extensive
837 memorization of the many referents to have an efficient panel, and therefore, upkeeping with
838 the jury is a must (Verriele et al., 2012). Unfortunately, there are few published works using
839 ONRD to discuss and compare methods.

840 4.1.1.4. Method comparison

841 As mentioned before, choosing a method depends on the study, its requirements, and its
842 logistic capacities. To compare them, Table 8 presents the advantages and disadvantages of
843 each method.

844 Thus, using any description method cited in Table 8 is a matter of trading the subjectivity
845 with more training and upkeeping.

846 **4.1.2. Assessment strategies**

847 As with other odor dimensions, ON can be assessed in a laboratory or in the field (Table 7).

848 As discussed before, laboratory assessment may implicate many biases; thus, field studies are
849 encouraged.

850 Field studies may also be performed according to a grid (Zarra et al., 2010) or by analyzing
851 the plumes (Burlingame, 2009). These studies were performed with trained assessors.
852 Therefore, community assessments are not so frequent. However, even if full of constraints,

853 resident and industrial employee training to assess ambient odor quality may be done (Capo
854 and Leger, 2017; Leger, 2016), offering a network of assessors that may be an efficient and
855 less costly alternative to air surveyance instruments. Moreover, as mentioned before, the
856 human nose can smell odors at very low concentrations, sometimes lower than instruments,
857 and it can provide sensory data on the odor. Nevertheless, with all the advantages, one must
858 consider the important time and logistic engagement to train the residents and their upkeep,
859 especially if ONRD is used.

860 Nevertheless, in an attempt to facilitate community assessment, methodologies can be adapted
861 or developed. As an example, an application called ODO was developed to allow residents to
862 signal any odor nuisance using a restricted list of odor evocations (“ODO - Grand Public,”
863 2020).

864 **4.1.3. Jury characteristics**

865 When assessing odor nature, the number of assessors may be between three and ten. OPM
866 usually recommends three to four well-trained assessors (Burlingame, 2009). There is no
867 general screening test used to select the panel even if Curren et al. used the UPSIT (see 2.1.3),
868 which relies on the capacity to identify odorants (Curren et al., 2016; Frank et al., 2006).
869 ONRD does not require screening tests.

870 On the other hand, training is needed for OPM and ONRD. Burlingame et al. mentioned a
871 training method based on smelling odorants that are recurring in the environment
872 (Burlingame, 2009). ONRD training is a must. Training consists of memorizing the referents
873 and describing known and unknown odors in mixtures.

874 **4.2. Hedonic tone**

875 HT is used to assess the pleasantness of an odor and to reflect the odor impact on
876 communities alongside frequency, odor intensity (OI)/odor concentration (OC), duration, and
877 location. Recently, Invernizzi et al. developed an odor nuisance index (ONI) based on the HT,
878 OC, frequency, duration, and location to determine the annoyance levels in exposed areas
879 (Invernizzi et al., 2017). Having a different point of view, the HT will be discussed differently
880 than the other parameters.

881 The HT of an odor is assessed using a negative to positive offensiveness scale (Nicell, 2009).
882 The German standard VDI 1994, part 2, recommends using a 9-point scale from -4 to +4,
883 where -4 is extremely unpleasant, 0 is neutral and +4 extremely pleasant (VDI 3882, part 2,
884 1992). Other studies reported using a 21-point scale: from -10 to +10 where -10 is extremely
885 unpleasant and + 10 is extremely pleasant (McGinley and McGinley, 2002).

886 HT was used to assess odor impact on communities from many sources, such as animal
887 production (Nimmermark, 2011; Stowell et al., 2007), industries (Both et al., 2004; Sucker et
888 al., 2008), waste transfer stations (Qamaruz Zaman et al., 2017), etc. Pérez et al. studied odor
889 nuisances from sewer networks focalizing on various geographic points to identify the most
890 critical ones. They used a nine-point scale to assess the HT of the odor of samples collected
891 using sampling bags. The analysis was performed using a panel of sixteen assessors who also
892 analyzed the OC and OI. The results obtained showed a decrease in HT when the OC was
893 high (Pérez et al., 2013).

894 However, the HT faces the problem of subjectivity. Sucker et al. studied the relationship
895 between odor frequency, OI, and HT of emissions coming from six industries: two generally
896 considered pleasant (rusk and sweets industries), two generally considered neutral (seed oil
897 and textile industries) and two generally considered unpleasant (cast iron and fat industries)

898 using a -4 to +4 scale for HT and a category scale for OI. The study was conducted in the
899 field following the grid method plus a community assessment. In Figure 13, the results of the
900 assessment of HT and OI both by residents and assessors are presented as a relation between
901 HT as a function of OI. Sucker et al. justified the differences between results from the
902 residents and results from the assessors as a consequence of memory-based responses from
903 the residents, while trained assessors analyzed the odor based solely on the stimuli (Sucker et
904 al., 2008).

905 As seen in the figure, the standard deviations are sometimes large, showing a discord among
906 residents and assessors, notably when assessing “strong to extremely strong” odors. Even the
907 general correlation between the OI and HT in pleasant industries changed between residents
908 and assessors: a negative correlation when the assessment was performed by residents and a
909 positive correlation when it was performed by assessors. Hence, as a resident or an assessor,
910 evaluating HT remains subjective due to the influence of memories and past experiences.

911 HT may be related to the spatiotemporal context, memories, experiences, and social
912 background of the assessor analyzing the odor (Jaubert, 2010). The spatiotemporal situation
913 may be explained by the example of the odor of fries: if smelled in the morning, it may not be
914 appreciated in the same way as smelled around lunchtime. In another comparison, the same
915 odor of fries may not be appreciated the same way it is smelled in the bedroom or the kitchen.
916 Moreover, previous experiences and the social background of the individual may affect
917 his/her appreciation of the odor (Candau, 2001). For example, a person who lived in an
918 agricultural society may not be offended by odorous emissions from agricultural domains
919 (livestock or natural fertilizers) as a person living in modern metropolises.

920 Hence, the HT is by essence subjective. Therefore, if needed to be assessed, HT may be used
921 to study the impact of olfactory annoyance on a population. Community assessment

922 (Brancher and Lisboa, 2014; Sucker et al., 2008) in this case seems to be a more suitable
923 strategy. Residents are reliable specialists to evaluate odor annoyance due to their exposure
924 history. Indeed, the laboratory assessment of OC alone is not sufficient because data on the
925 perception of the odor by the community are missing (Drew et al., 2007). During odor
926 annoyance studies, the community assessment of HT offers results that reflect the reality more
927 due to the social and spatiotemporal background they share: residents smell the odors at the
928 same time, in their homes and they share the same social background (agricultural
929 communities, urban residents, etc.), which assessors (used during a field study or laboratory
930 assessment) do not experience. In this case, the panel of residents needs to be as
931 representative of the studied area as possible (60 naïve assessors according to AFNOR (NF
932 XP V 09-500, 2000)) and should be chosen among the targeted population of the area.
933 Community assessment should need neither preselection nor intensive training. Residents are
934 randomly selected (Blanes-Vidal et al., 2012).

935 However, HT assessed in a laboratory has always been done (Le et al., 2009; Lim et al., 2003,
936 2003; Nimmermark, 2006; Parker et al., 2005). Field studies performed by trained assessors
937 have also been reported following a plume methodology (Lin et al., 2007, 2006; Stowell et al.,
938 2007) or a grid methodology (Both et al., 2004; Sucker et al., 2008). Both strategies depend
939 on trained assessors. It is a panel comprising a minimum of four assessors who are trained to
940 use the scale and are selected using tests adapted for OC or OI. For example, the jury may be
941 chosen following EN 13725 if there is an OC assessment (Lin et al., 2007).

942 **5. Conclusion**

943 Olfactory analysis is essential when assessing odor nuisance in the environment. However,
944 authors may face many difficulties, especially because it relies on human perception instead

945 of instrumentation. As seen in this review, the authors developed several methods to quantify
946 and qualify environmental odors using sensory approaches.

947 To quantify, the authors used the odor intensity, the strength of the stimulus, and/or the odor
948 concentration, i.e., the dilution factor needed for an odor to become imperceptible. While both
949 methods were used in the field and in the laboratory, authors favor in-field studies due to the
950 difficulties faced when sampling odorant air. Moreover, delicate panel selection and training
951 are needed.

952 To qualify the odor, the authors considered two different factors, the odor nature, i.e., what
953 does the odor smells like, and the hedonic tone, i.e., the pleasantness of an odor. On the one
954 hand, odor nature determination was used to identify the emission sources. On the other hand,
955 the hedonic tone was used to study odor annoyance in the exposed population because it
956 reflects the level of pleasantness of the ambient odor in addition to not requiring any
957 expertise. However, odor nature determination requires very well-trained assessors, which is
958 time-consuming. For odor quantification, authors prefer in-field studies due to sampling
959 issues.

960 When quantifying odors, odor intensity assessment may be objectified by using intensity
961 references. Nevertheless, when authors gained objectivity, studies became more complex and
962 difficult to use in field studies. Moreover, odor concentration offers a standardized approach
963 with the ability to be easily applied in the field but requires the use of olfactometers.

964 For odor qualification, similar to the OI, the description of odor nature was assessed
965 objectively by authors by using odor references as descriptors, yielding better repeatability
966 than the use of evocation-based descriptors. However, similar to OI, studies became more
967 complex and time-consuming, not to mention the need to train the panel and maintain upkeep.

968 The hedonic tone is the most subjective dimension of an odor. When studied, authors tend to

969 assess the hedonic tone by the exposed community to obtain results that reflect its sensation
970 or by a trained panel.

971 After reviewing the existing methods, for odor quantification and qualification, subjectivity in
972 the olfactory analysis may be restrained but at the expense of simplicity, thus leading to more
973 panel training and screening. Moreover, the biases may also be moderated by limiting
974 sampling as much as possible.

975 This review revisited the most commonly used sensory analytical techniques for
976 environmental odors with their advantages and disadvantages. Assessment strategies and
977 panel characteristics were also discussed. Thus, the review presents a guide to the reader on
978 sensory analyses performed to assess environmental odors.

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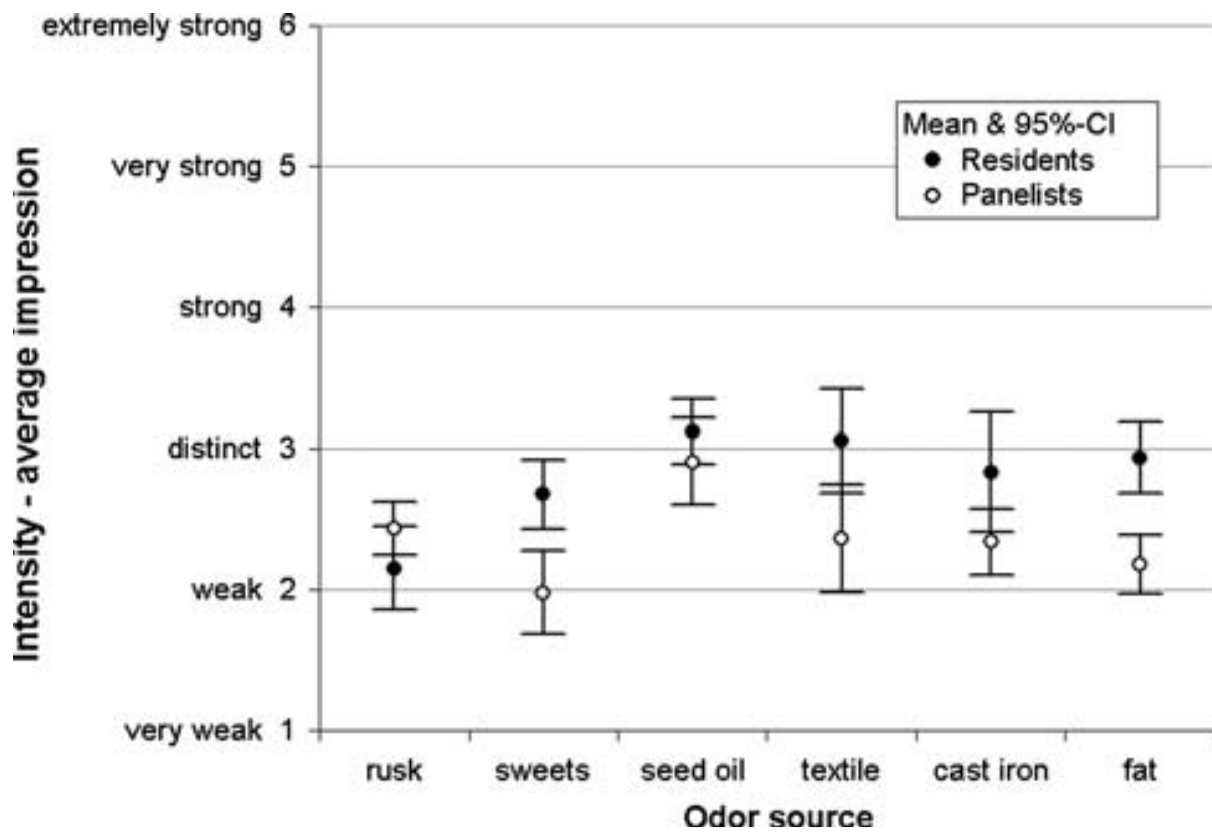


Figure 1: Comparison of mean rating values and their 95% confidence intervals for the average intensity rating by panelists and residents for odors from six different industries (rusk, sweets, seed oil, textile, cast iron, and fat industries) (Sucker et al., 2008b).

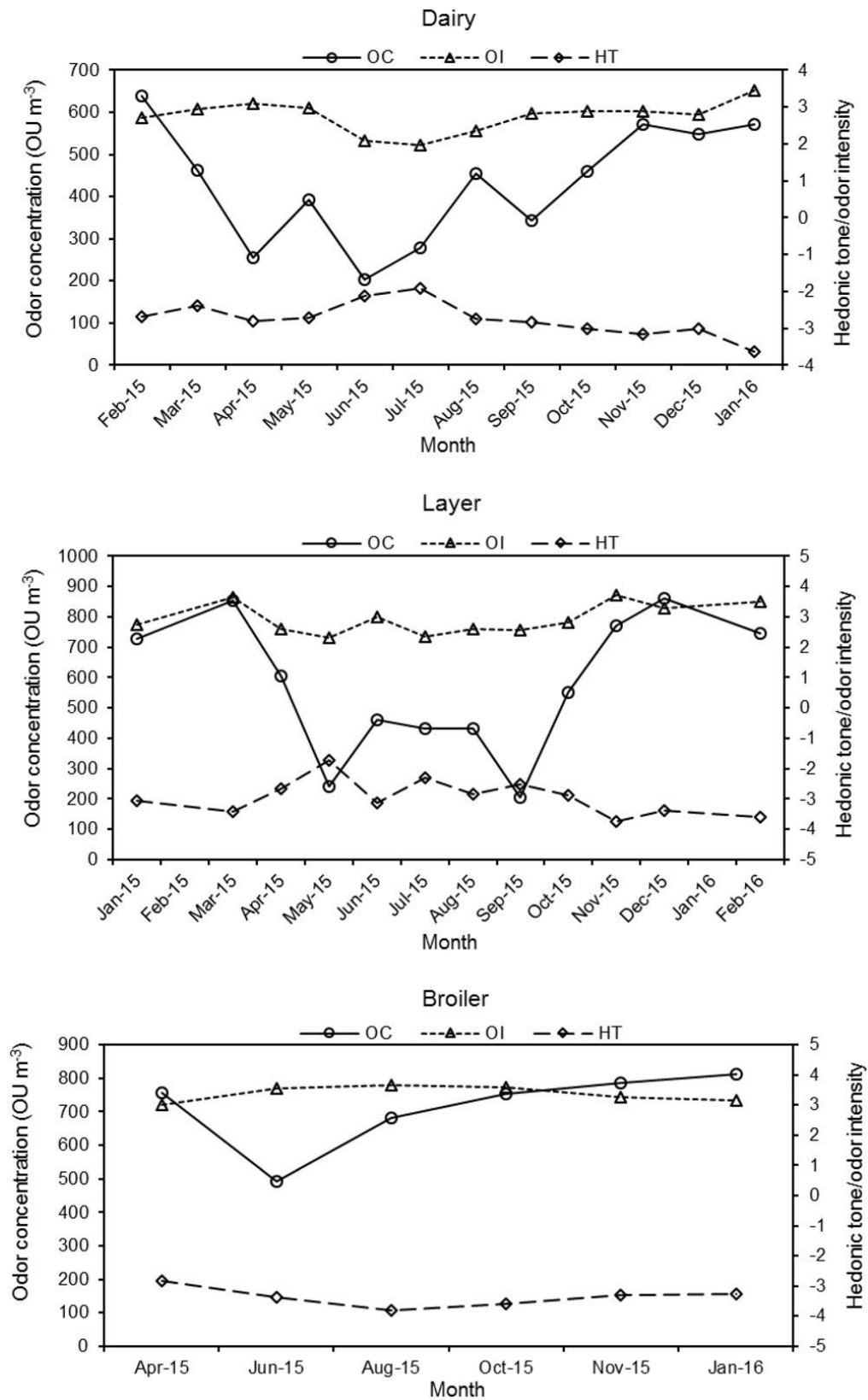


Figure 2: OC, OI, and hedonic tone variations among seasons for odors coming from dairy, layer, and broiler barns (Huang and Guo, 2018).

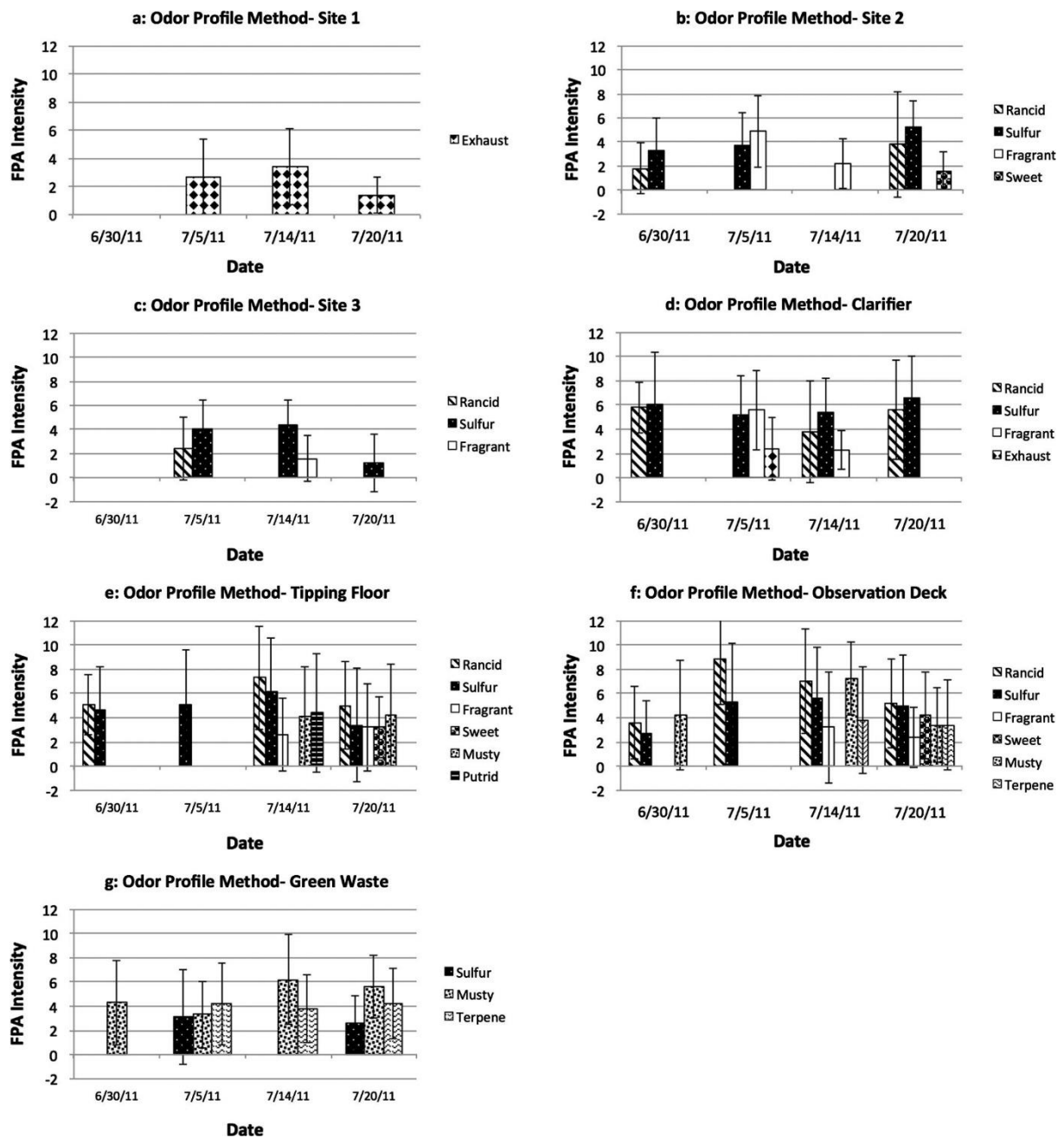


Figure 3: OI, with error bars, of various odors coming from different analysis sites in a trash-transfer station. The OI was determined using the FPA method (Curren et al., 2016).

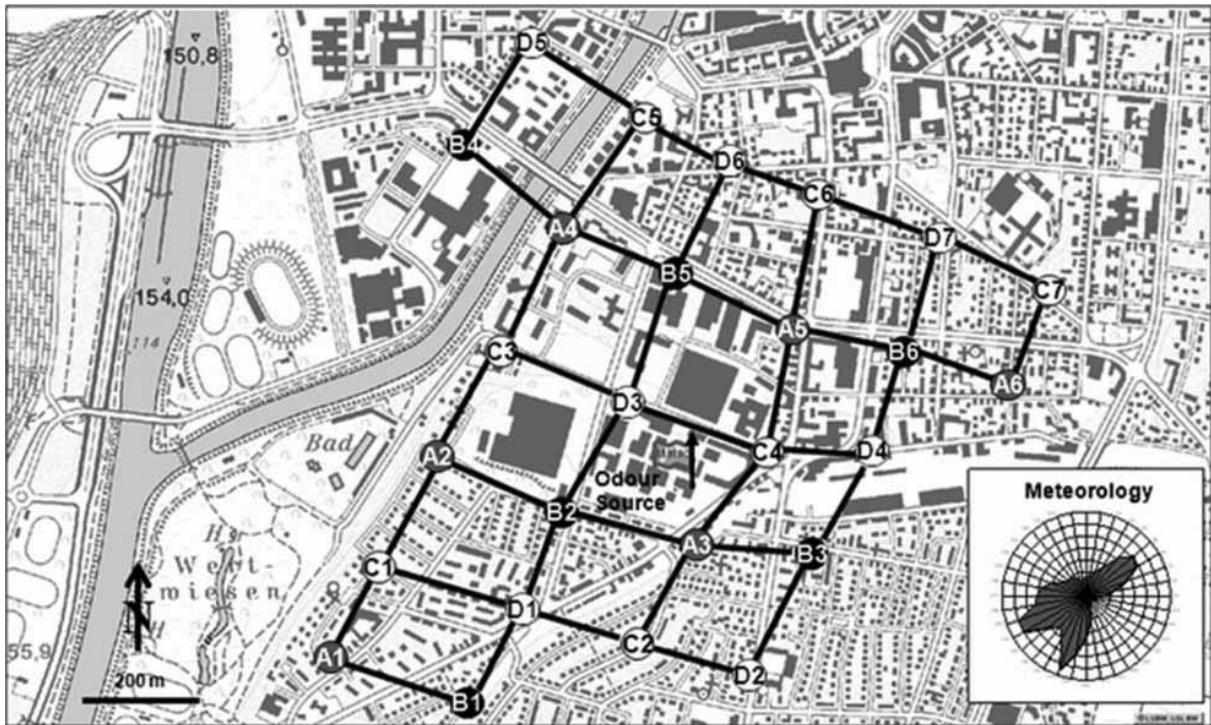


Figure 4: The grid method. The measurement points are represented by dots. Measurement round A consists of six measurement points: A1, A2, A3, A4, A5, and A6; measurement round B consists of six measurement points: B1, B2, B3, B4, B5, and B6; measurement round C consists of seven measurement points: C1, C2, C3, C4, C5, C6, and C7; and measurement round D consists of seven measurement points: D1, D2, D3, D4, D5, D6, and D7 (Guillot et al., 2012).

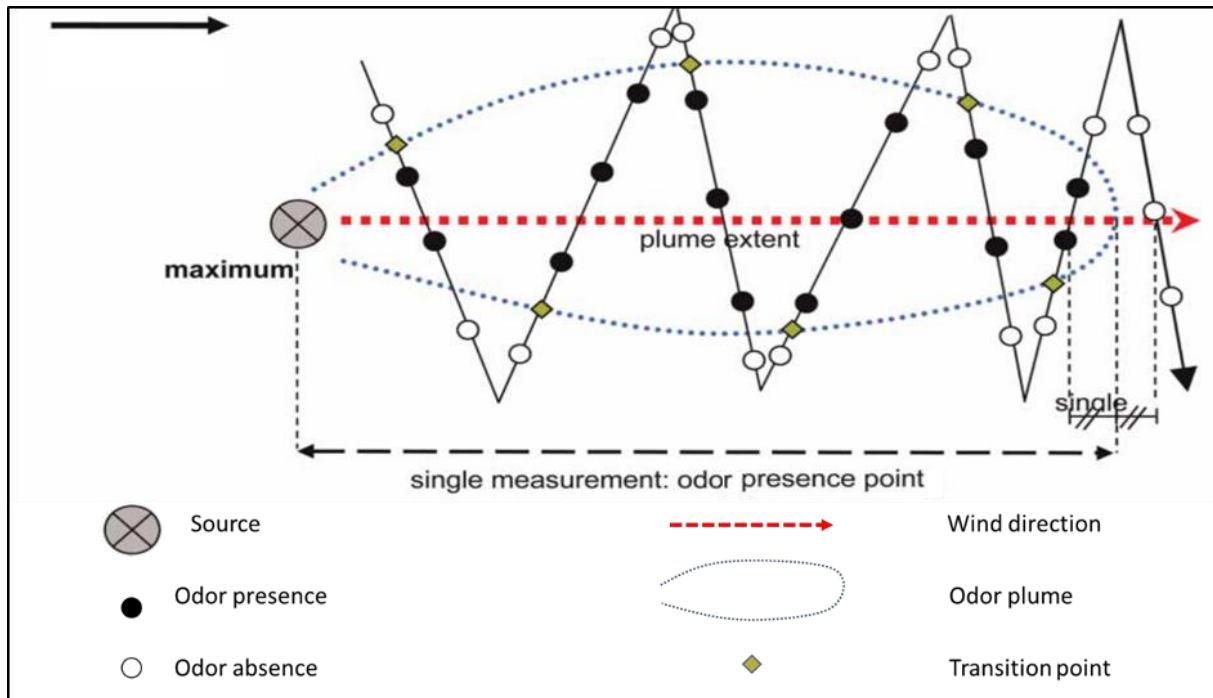


Figure 5: Dynamic plume method: Jury's itinerary performed to determine the area affected by the odor plume (adapted from Guillot et al., 2012).

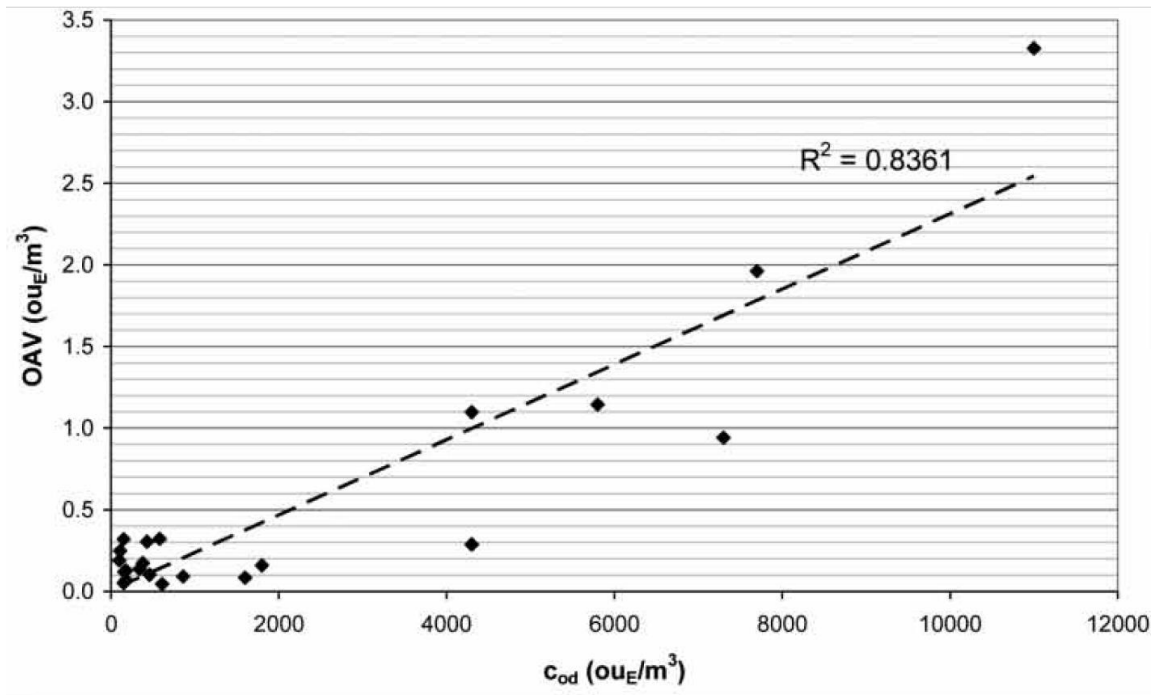


Figure 6: Relation between the calculated OAV and determined OC (C_{OD}) from different industries (Capelli et al., 2012).

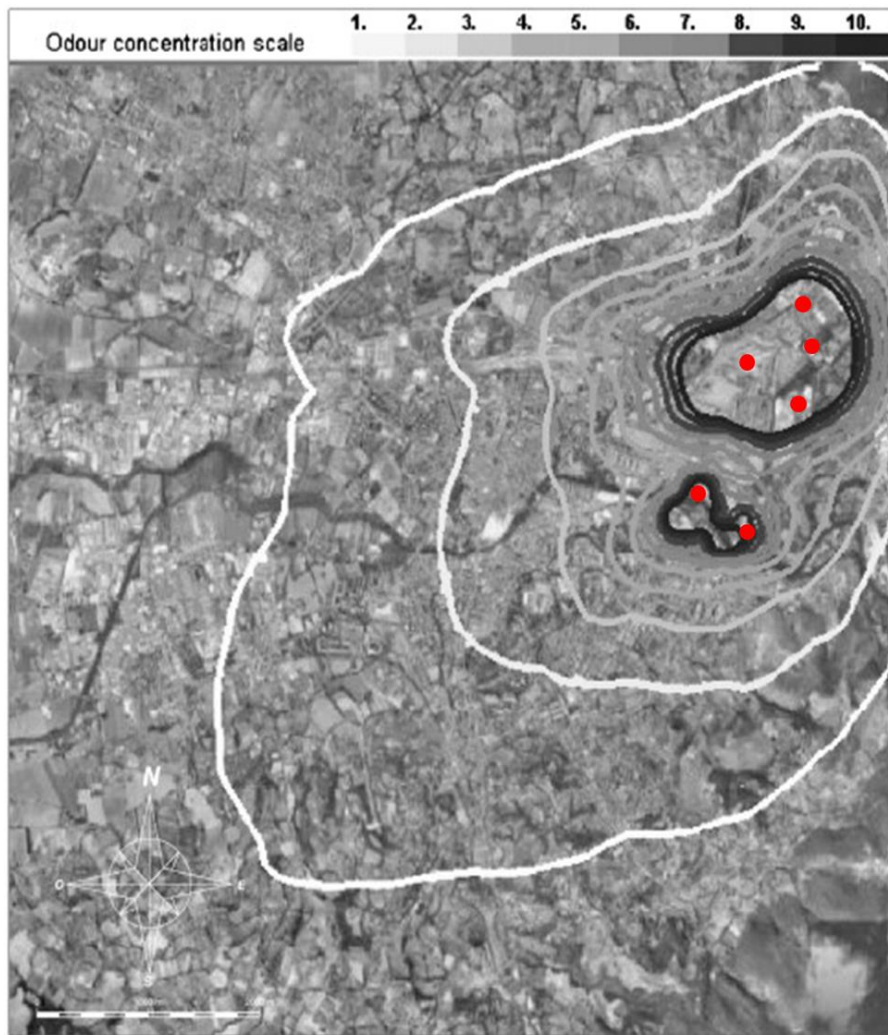


Figure 7: A map showing the 98 percentile of peak odor concentrations relevant to odorous emissions from a steel industry (the red dots) in the city of Terni, Italy (Capelli et al., 2011).



Figure 8: A Nasal Ranger[®] portable olfactometer designed by St. Croix Sensory, Inc. (St. Croix Sensory, Inc., 2008).

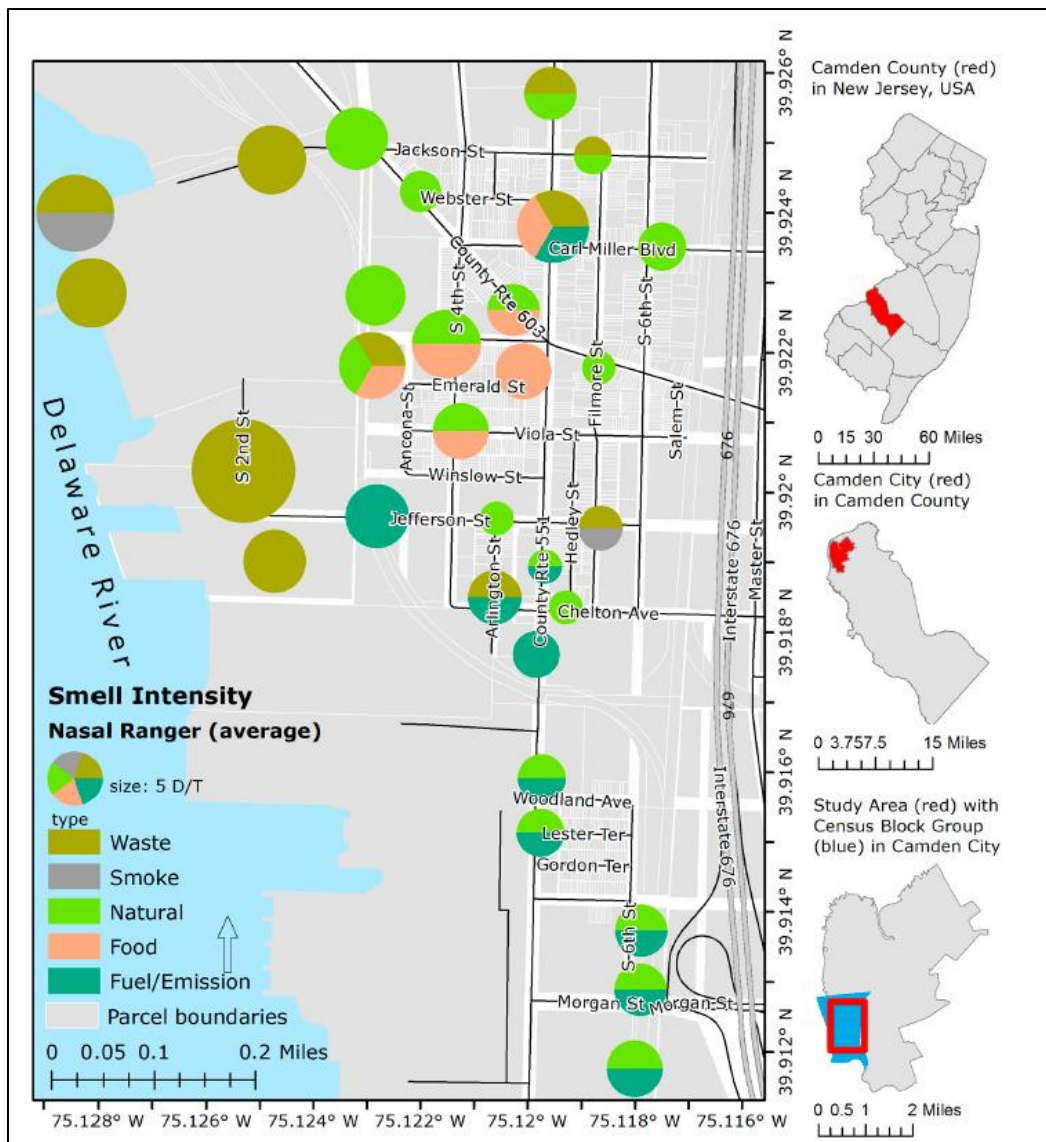


Figure 9: Odor data collected at each analysis site in the Waterfront South neighborhood in Camden, NJ (Kitson et al., 2019).

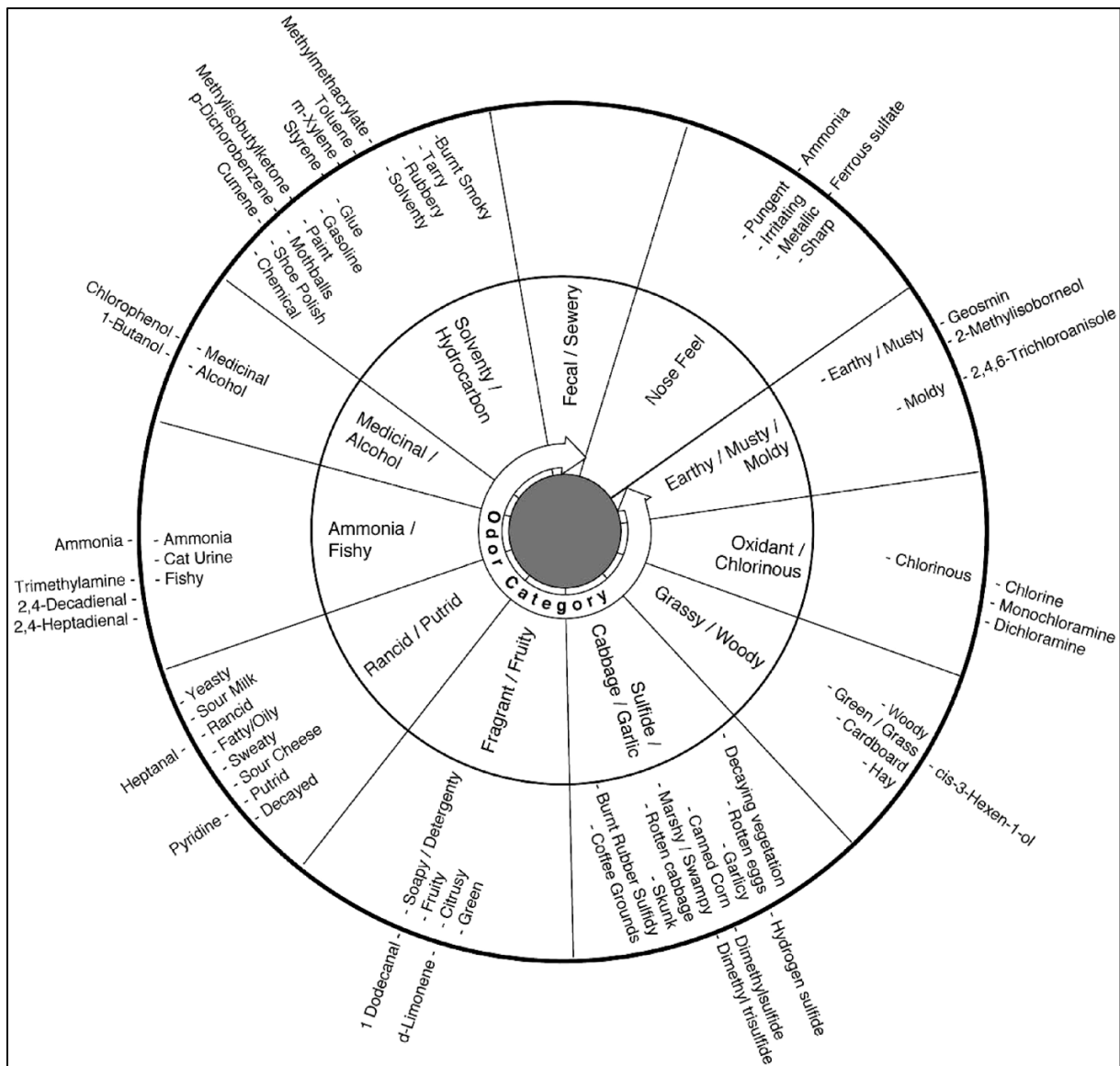


Figure 10: Odor wheel developed for wastewater treatment plants (Burlingame et al., 2004).

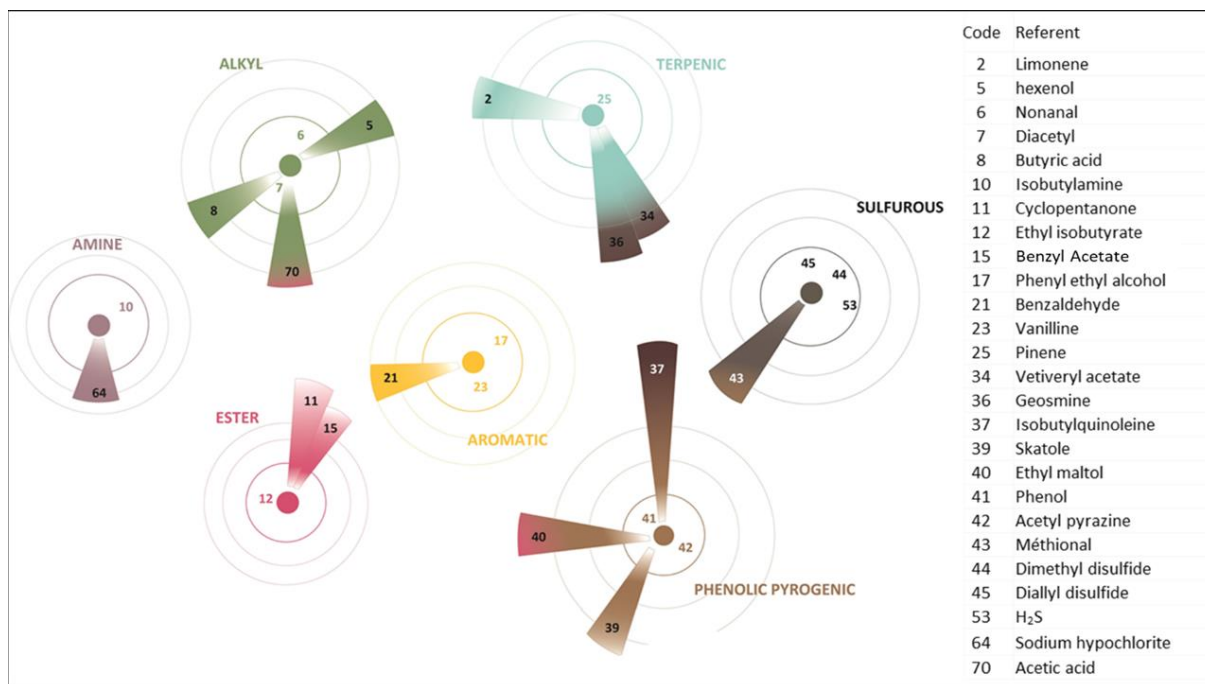


Figure 11: The 2-D representation of the 3-D olfactory space of the reference collection of LdN (Hawko et al., 2021).

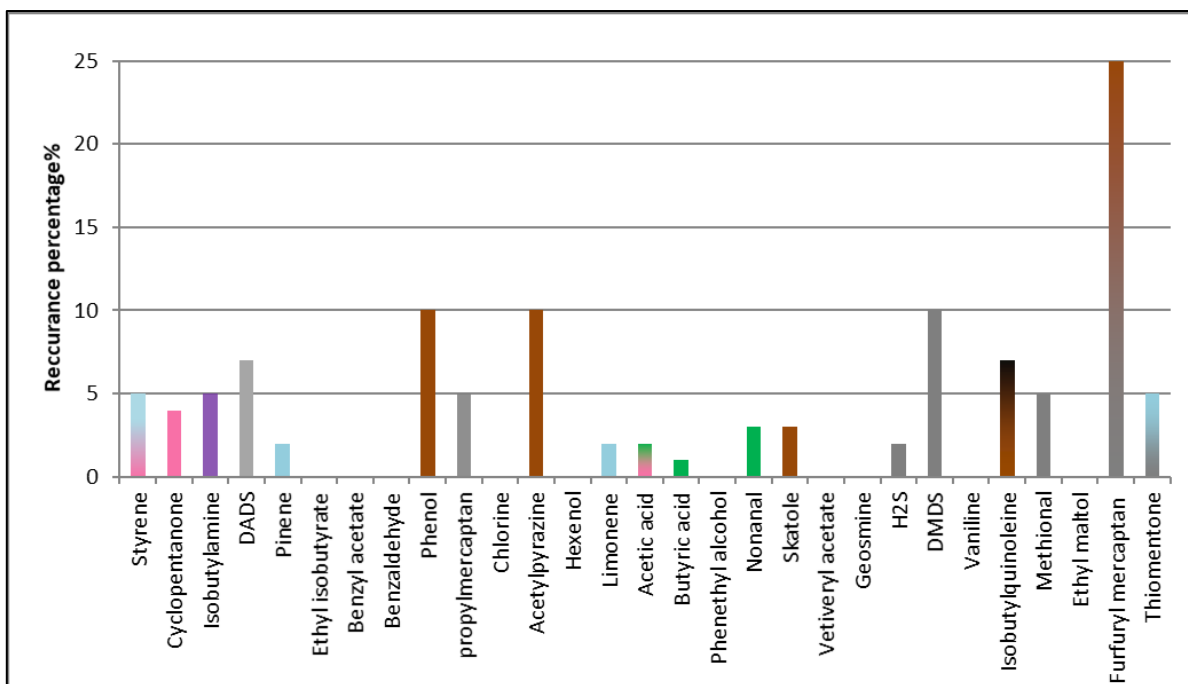


Figure 12: Recurrence percentage (%) obtained during a yearlong campaign at Le Havre, France.

Furfuryl mercaptan, thiomenthone, propyl mercaptan, and styrene were added to the basic collection as complementary referents (adapted from Atmo Normandie, 2015).

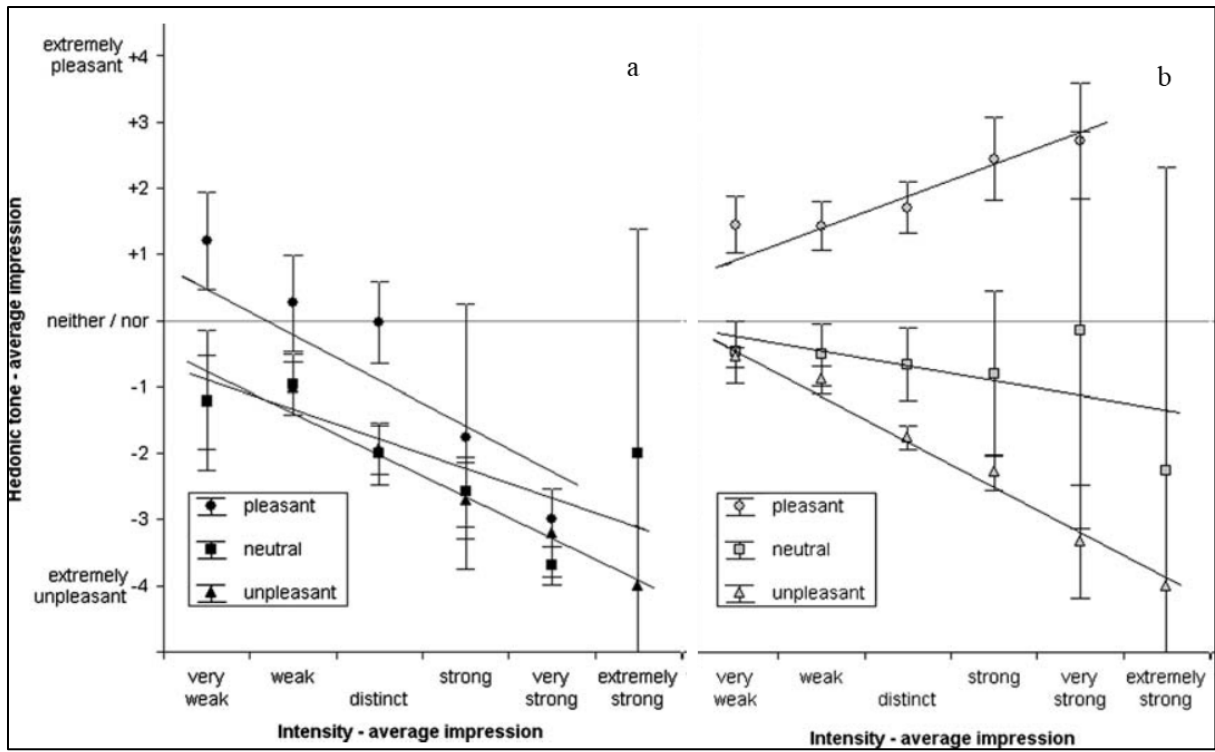


Figure 13: HT as a function of intensity for the pleasant, neutral, and unpleasant odors considered. Assessment was performed by residents (a) and assessors (b) (Sucker et al., 2008b).

1 **Table 1:** Odor intensity studies for environmental odor nuisance assessment. Scaling techniques, assessment strategies, and panel characteristics are given.

Scaling technique: category scale		
Study, Reference	Assessment strategy	Panel characteristics
Assessing odor emissions from six different industries (Sucker et al., 2008)	Field study	10-16 assessors according to EN13725, 2003; 1456 residents
Assessing odor impact from waste and sewage treatment plants on residents (Aatamila et al., 2011)	Field study	1142 residents randomly selected
Assessing odor impact from several industrial plants on residents (Lee et al., 2013)	Field study	200 residents not living in the industrial zone
Evaluating odor annoyance from a complex industrial area (Nicolas et al., 2010)	Field study	44 residents
Assessing odors in an urban area (Sówka et al., 2018)	Field study	9 assessors according to EN13725, 2003
Assessing ambient odors near a swine-finishing operation (Stowell et al., 2007)	Field study	5-7 assessors
Identifying odor sources in cities through community participation, chemical analyses, and modeling (Gallego et al., 2008)	Field study	Resident participation
Assessing waste decomposition odors and relating them to chemical composition (Qamaruz-Zaman and Milke, 2012)	Laboratory analysis	2 assessors
Studying olfactory interactions among odorants found in food waste disposal plant emissions (Wu et al., 2015)	Laboratory analysis	Not mentioned
Identifying odorants responsible for odors in wastewater effluents (Agus et al., 2012)	Laboratory analysis	8 assessors who were not anosmic
Scaling technique: odor intensity reference scale		
Study, Reference	Assessment strategy	Panel characteristics
Determining the relationship between different odor properties in odors coming from poultry and dairy barns (Huang and Guo, 2018)	Laboratory analysis	18 assessors according to EN13725, 2003
Assessing odors from a pulp and paper industry to develop an electronic nose for rapid measurements (Deshmukh et al., 2014)	Laboratory analysis	6 assessors
Characterizing odors from anaerobic treatment plants of swine manure (Heber et al., 2000)	Laboratory analysis	8 assessors according to standard ASTM, 1981
Assessing odor emissions from dairy manure (Wheeler et al., 2011)	Laboratory analysis	5 trained assessors
Assessing odors from different industrial plants (Junior et al., 2010)	Laboratory analysis	13 assessors selected using the odor intensity reference scale
Assessing odors from swine nurseries (Lim et al., 2001)	Laboratory analysis	8 assessors selected using the odor intensity reference scale
Assessing odor emissions after deodorization of a sewage treatment plant (Truppel et al., 2005)	Laboratory analysis	Trained assessors

Assessing odor annoyance in industrial zones (Quéré et al., 1994)	Field study	A panel of qualified experts
Cross-modality matching		
Study, Reference	Assessment strategy	Panel characteristics
Quantifying and identifying odors from a trash-transfer station (Curren et al., 2016)	Field study	10 assessors selected using the University of Pennsylvania Smell Identification Test (UPSIT)
Characterizing odors from a composting plant (Suffet et al., 2009)	Laboratory analysis	4 trained assessors
Assessing odors from the Huangpu river (Sun et al., 2013)	Laboratory analysis	4 assessors
Determining the relation between OC and OI when studying odor emissions from alumina refineries (Jiang et al., 2006)	Laboratory analysis	Assessors according to EN13725, 2003

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54

1 **Table 2:** The odor intensity rating and the definition of each magnitude used by Qamaruz-Zaman and
 2 Milke (Qamaruz-Zaman and Milke, 2012).

Scale	1		3		5
Intensity level	Very light	Light	Moderate	Strong	Very strong
Description	Activates the sense of smell	Activates the sense of smell	Easily activates the sense of smell	Objectionable	So strong it is overpowering and intolerable for any length of time
	Characteristics may not be distinguishable	Distinguishable and definite	Very distinct and clearly distinguishable	Cause a person to attempt to avoid it completely	Could tend to easily produce some physiological effects
		Not necessarily objectionable in short durations	May tend to be objectionable and/or irritating	Could indicate a tendency to possibly produce physiological effects during prolonged exposure	

3

1 **Table 3:** Odor intensity scale used by (Jiang et al., 2006) with equivalent temperature sensation for
 2 the magnitude categories as a reference.

Odor	OI	Equivalent temperature sensation	Comments
Extremely strong	6	>60°C	The exposure to the odor is annoying. An instinctive reaction would be to mitigate against further exposure.
Very strong	5	>50°C	The odor is annoying. Exposure to this level would be considered undesirable.
Strong	4	>40°C	The odor character is recognizable. Long-time exposure to the odor is not tolerable.
Distinct	3	>30°C	The odor character is recognizable.
Weak	2		The odor is present but cannot be described using precise words/terms.
Very weak	1		There is probably some doubt whether the odor is present. Similar to odor threshold measurement.
Not perceptible	0		No odor when compared with the odor-free port.

3

1 Table 4: Comparison of OI analytical methods: concept, advantages, and disadvantages.

Method	Concept	Examples	Advantages	Disadvantages
Category Scale	Describing OI using numbers ex: 0 for nonperceptible and 6 for a strong odor	(Aatamila et al., 2010; Lee et al., 2013; Nicolas et al., 2010; Qamaruz-Zaman and Milke, 2012; Sakawi et al., 2011; Sucker et al., 2008b, 2008a; Wu et al., 2015)	<ul style="list-style-type: none"> • Does not require too much training ¹ • Allows use of mathematical operations to predict OI out of chemical concentration² 	<ul style="list-style-type: none"> • Subjective³ • Poor repeatability (Poulton, 1989) • Problem of contrast⁴ • Affiliating numbers to sensation⁵
OIRS	Comparing OI of an odor to the OI of one defined odorant reference at different concentrations Ex: comparing to the OI of n-Butanol solutions at 320, 640, 1280 ppm.	(Deshmukh et al., 2014; Heber et al., 2000; Huang and Guo, 2018b; Quéré et al., 1994; Wheeler et al., 2011)	<ul style="list-style-type: none"> • Objective⁶ • Repeatable results from a panelist to another⁷ • May be used in mathematical operations to relate it to odor concentration⁸ • Matches stimuli (OI) to another instead of matching sensation directly to numbers⁵ 	<ul style="list-style-type: none"> • Results not repeatable from one session to another⁹ • The referent may have a different character from the odor of interest, thus leading to panel confusion¹⁰ • Difference in sensitivity towards the referent may lead to a decrease in panel homogeneity⁷
Cross-modality matching	Intensity scale that uses matching the OI to the intensity of another sensation, e.g., flavor, temperature, etc.	(Agus et al., 2011; Curren et al., 2016; Mel Suffet et al., 2009; Sun et al., 2013; Zhou, 2017)	<ul style="list-style-type: none"> • Matches stimuli (OI) to another instead of matching sensation directly to numbers⁵ 	<ul style="list-style-type: none"> • Less repeatable from one assessor to another⁹

2 1- (as stated by Curren et al., 2014)/ 2- (Wu et al., 2016)/ 3- (as stated by Wu et al., 2015)/ 4- (Lawless, 2000;

3 Risky et al., 1979)/ 5- (Cain and Moskowitz, 1974)/ 6- (as stated by Deshmukh et al., 2014)/ 7- (Atanasova et

4 al., 2004)/ 8- (Zhang et al., 2002)/ 9- (Curren et al., 2014)/ 10- (as stated by Junior et al., 2010)

5

1 Table 5: Studies using odor concentration for environmental odor assessments. The OC determination method used, the assessment strategy, and
 2 the panel characteristics are given.

OC determination: dynamic olfactometry		
Study, Reference	Assessment strategy	Panel characteristics
Determining OC and health risks from a landfill (Wu et al., 2015)	Laboratory assessment-sampling from source	Not mentioned
Determining OC emissions rates from a rendering plant and comparing them with the local standards (Vieira et al., 2016)	Laboratory assessment-sampling from source	6 trained assessors
Determining odor dispersion characteristics from a wastewater treatment plant (Baltrėnas et al., 2013)	Laboratory assessment-sampling from exposed sites	6 assessors
Assessing odor nuisance from the food industry (Sówka et al., 2011)	Laboratory assessment-sampling from source	According to EN13725, 2003
Assessing odor impact from a landfill on the surrounding area (Palmiotto et al., 2014)	Odor dispersion modeling	According to EN13725, 2003
Assessing odor impact from several industrial plants (Capelli et al., 2011)	Odor dispersion modeling	4 assessors according to EN13725, 2003
Assessing odor impact from similar sources (rendering plant) (Sironi et al., 2010)	Odor dispersion modeling	4 assessors according to EN13725, 2003
Determining odor impact from landfills: expansion scenarios (Naddeo et al., 2016)	Odor dispersion modeling	4 assessors according to EN13725, 2003
Modeling odor dispersion from waste incineration plants (Doğruparmak et al., 2018)	Odor dispersion modeling	6 assessors according to EN13725, 2003
Assessing odor impact from an organic fraction from a municipal solid waste plant (Gutiérrez et al., 2015)	Odor dispersion modeling	4 assessors
Assessing odor emissions from a composting plant (Toledo et al., 2018)	Odor dispersion modeling	4 assessors according to EN13725, 2003
Investigating air odor quality near a landfill (Geńicki et al., 2017)	Field olfactometry	4 assessors according to St. Croix Sensory, 2006
Comparing sensory and analytical methods used to assess odors from a wastewater treatment plant (Barczak and Kulig, 2017)	Field olfactometry	2 assessors according to St. Croix Sensory, 2006
Assessing odors from dairy manure (Brandt et al., 2008)	Field olfactometry	4 assessors according to EN13725, 2003
Monitoring odor emissions in agricultural biogas facilities (Nicolas et al., 2013)	Field olfactometry	6 assessors
Odor impact on the urban area (Kitson et al., 2019)	Field olfactometry	Not mentioned
OC determination: calculated from chemical concentration solely or combined with dynamic olfactometry		

Study, Reference	Assessment strategy	Panel characteristics
Comparing three odor assessment approaches during a landfill odor study (Capelli et al., 2008)	Laboratory assessment-sampling from exposed sites and source	8 assessors
Evaluating the olfactory and toxic impact of odors from industrial plants (Capelli et al., 2012)	Odor dispersion modeling	4 assessors according to EN13725, 2003
Assessing the odor impact of trace sulfur compounds coming from a landfill (Liu et al., 2018)	Odor dispersion modeling	Not mentioned

OC determination: static olfactometry

Study, Reference	Assessment strategy	Panel characteristics
A two-year-long study on a typical anaerobic landfill in China to characterize odor emission on the working face (Wenjing et al., 2015)	Laboratory assessment-sampling from the exposed working face	6 panelists selected based on their capacity to identify mixed odorants

- 4 Baltrėnas, P., Andrulevičius, L., Zuokaitė, E., 2013. Application of Dynamic Olfactometry to
5 Determine Odor Concentrations in Ambient Air. *Polish Journal of Environmental*
6 *Studies* 22, 331–336.
- 7 Barczak, R.J., Kulig, A., 2017. Comparison of different measurement methods of odour and
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21 Terni, Italy. *Science of The Total Environment* 409, 595–603.
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29 <https://doi.org/10.3390/environments4010007>
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32 biofilter. *Science of The Total Environment* 512–513, 572–581.
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- 34 Kitson, J., Leiva, M., Christman, Z., Dalton, P., 2019. Evaluating Urban Odor with Field
35 Olfactometry in Camden, NJ. *Urban Science* 3, 93.
36 <https://doi.org/10.3390/urbansci3030093>
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- 40 Naddeo, V., Zarra, T., Oliva, G., Chiavola, A., Vivarelli, A., 2016. Environmental odour impact
41 assessment of landfill expansion scenarios: case study of borgo montello (italy).
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- 49 Sironi, S., Capelli, L., Céntola, P., Del Rosso, R., Pierucci, S., 2010. Odour impact assessment
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- 53 Sówka, I., Skr, M., Szklarczyk, A., Zwo, J., 2011. Evaluation of nuisance of odour from food
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- 58 Vieira, M.M., Schirmer, W.N., de Melo Lisboa, H., Belli Filho, P., Guillot, J.-M., 2016.
59 Pragmatic evaluation of odour emissions from a rendering plant in southern Brazil.
60 *Environ Sci Pollut Res* 23, 24115–24124. <https://doi.org/10.1007/s11356-016-7509-0>
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66 coefficient and odor contribution based on binary interaction effects in waste disposal
67 plant. *Atmospheric Environment* 103, 231–237.
68 <https://doi.org/10.1016/j.atmosenv.2014.12.045>
69

Table 6: Comparison between field odor intensity assessment, field olfactometry, and odor dispersion modeling.

Approach	Concept	Examples	Advantages	Disadvantages
Field OI assessment	Quantification of the odor based on the strength of the stimulus	(Curren et al., 2016; Huang and Guo, 2018b; Sucker et al., 2008b)	<ul style="list-style-type: none"> • Simple and less expensive than the other methods • Enables community involvement, which allows more data on the olfactory nuisance¹ • Maybe objectified by the use of referent scales² • Performed directly on impacted zones and in real-time • No need for sampling 	<ul style="list-style-type: none"> • Subjective³ • Depending on the scale, maybe not repeatable and nonreproducible • Needs long-time field studies to cover several meteorological scenarios⁴
Field olfactometry	Quantification of the odor on the field using portable olfactometers	(Barczak and Kulig, 2017; Gębicki et al., 2017; Kitson et al., 2019)	<ul style="list-style-type: none"> • Less expensive than laboratory olfactometry⁵ • Performed directly on impacted zones and in real-time • No need for sampling • Repeatable within assessors⁶ • Efficient at low OC levels⁸ • Immediate results⁸ 	<ul style="list-style-type: none"> • Technical problems may occur⁷ • Not repeatable within sessions⁶ • Negative impacts on the panel, such as fatigue and distraction, may occur⁶ • Not covered by official standards
Odor dispersion modeling	Modeling the OC dispersion using odor emission flow rate (detected from field sampling and dynamic olfactometry performed in a laboratory), meteorological and topological data	(Cai et al., 2015; Capelli et al., 2011, 2008)	<ul style="list-style-type: none"> • Allows real-time surveyance and prediction of OC in an exposed area without human panel • Laboratory analyses can avoid⁹ certain drawbacks on the panel such as fatigue and distraction⁶ 	<ul style="list-style-type: none"> • Background odors from sampling bags may interfere with results¹⁰, as well as sample losses¹¹ • Careful panel selection needed¹² • Not very efficient at low levels of OC⁸

1- (Lee et al., 2013)/ 2- (as stated by Deshmukh et al., 2014)/ 3- (as mentioned by Wu et al., 2015)/ 4- (Curren et al., 2014)/ 5- (Sheffield et al., 2004)/ 6- (Brandt et al., 2011)/ 7- (Bokowa, 2008; Maurer et al., 2018)/ 8- (McGinley and McGinley, 2004)/ 9- (Capelli et al., 2011)/ 10- (Guillot et al., 2012)/ 11- (van Harreveld, 2003)/ 12- (EN13725, 2003)

Table 7: Odor nature assessments from environmental odor nuisance studies with the description methods used, the assessment strategy, and the panel characteristics.

Description method: evocations		
Study, Reference	Assessment strategy	Panel characteristics
Chemical and sensory analysis of odor emissions from swine manure (Trabue et al., 2011)	Laboratory analysis	8 untrained assessors
Assessing odors in an industrial area to optimize field assessments (Zarra et al., 2010)	Field study	5 assessors according to EN13725
Odor impact on the urban area (Kitson et al., 2019)	Field study	Not mentioned
Mapping the odors in urban streets in several cities (Quercia et al., 2015)	Field study	Between 10 and 58 participants
Developing a method that enables the industrial community to communicate (Hayes et al., 2017)	Laboratory analysis	2 assessors selected regarding their sensitivity towards n-butanol and industrial sites operators
Description method: odor profile method		
Study, Reference	Assessment strategy	Panel characteristics
Treating odor emissions from a wastewater treatment plant using seashell biofilters (Abraham et al., 2015)	Laboratory analysis	3-4 assessors
Characterizing odor nuisance from municipal wastewater residuals composting operations (Suffet et al., 2009)	Laboratory analysis and field study	4 well-trained assessors
Evaluating the total odor profile of emissions from a wastewater treatment plant and identifying the sources of different odors (Burlingame, 2009)	Field study	3-4 assessors
Quantifying and identifying odors from a trash-transfer station (Curren et al., 2016)	Field study	10 assessors selected using the University of Pennsylvania Smell Identification Test (UPSIT)
Description method: odor nature reference description (ONRD)		
Study, Reference	Assessment strategy	Panel characteristics
Surveying the ambient odor quality in the industrial city of Le Havre (Atmo Normandie, 2015)	Field study	30 trained assessors

Abraham, S., Joslyn, S., Suffet, I.H. (Mel), 2015. Treatment of odor by a seashell biofilter at a wastewater treatment plant. *Journal of the Air & Waste Management Association* 65, 1217–1228. <https://doi.org/10.1080/10962247.2015.1075918>

Atmo Normandie, 2015. Gazette N°57-Résultats les nouveaux cyrano, 3ème campagne de veille. La gazette des Nez.

Burlingame, G.A., 2009. A practical framework using odor survey data to prioritize nuisance odors. *Water Science & Technology* 59, 595. <https://doi.org/10.2166/wst.2009.872>

Curren, J., Hallis, S.A., Snyder, C. (Cher) L., Suffet, I. (Mel) H., 2016. Identification and quantification of nuisance odors at a trash transfer station. *Waste Management* 58, 52–61. <https://doi.org/10.1016/j.wasman.2016.09.021>

Hayes, J.E., Fisher, R.M., Stevenson, R.J., Mannebeck, C., Stuetz, R.M., 2017. Unrepresented community odour impact: Improving engagement strategies. *Science of The Total Environment* 609, 1650–1658. <https://doi.org/10.1016/j.scitotenv.2017.08.013>

Kitson, J., Leiva, M., Christman, Z., Dalton, P., 2019. Evaluating Urban Odor with Field Olfactometry in Camden, NJ. *Urban Science* 3, 93. <https://doi.org/10.3390/urbansci3030093>

Quercia, D., Schifanella, R., Aiello, L.M., McLean, K., 2015. Smelly Maps: The Digital Life of Urban Smellscapes. arXiv:1505.06851 [cs].

Suffet, I.H.M., Decottignies, V., Senante, E., Bruchet, A., 2009. Sensory Assessment and Characterization of Odor Nuisance Emissions during the Composting of Wastewater Biosolids. *Water Environment Research* 81, 670–679. <https://doi.org/10.2175/106143008X390762>

Trabue, S., Kerr, B., Bearson, B., Ziemer, C., 2011. Swine Odor Analyzed by Odor Panels and Chemical Techniques. *Journal of Environment Quality* 40, 1510. <https://doi.org/10.2134/jeq2010.0522>

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Table 8: Comparison of the three methods used to describe odor nature, their advantages, and disadvantages.

Method	Concept	Examples	Advantages	Disadvantages
Evocations	Describing odors based on memories and individual information	(Kitson et al., 2019; Quercia et al., 2015; Zarra et al., 2010)	<ul style="list-style-type: none"> • Easy to use 	<ul style="list-style-type: none"> • Subjective¹ • Differs from a group to another² • Panel training is needed³
OPM	A defined lexicon of a certain domain where the descriptors are arranged in a wheel according to categories. The profile of an odor is built by addressing an OI to each descriptor	(Abraham et al., 2015; Curren et al., 2016; Suffet et al., 2009)	<ul style="list-style-type: none"> • Provides a basis for standardization⁴ • Can be adapted to many domains⁵ • Potential to identify odor sources⁶ 	<ul style="list-style-type: none"> • Subjective, which leads to difficult data comparison between laboratories⁴
ONRD	Describing an odor by comparing it to an odor referent consisting of a chemical substance	(AtmoNormandie, 2013)	<ul style="list-style-type: none"> • A lexicon that links directly the word to the odor⁸ • Objective⁹ • Repeatable¹⁰ • Adapted for several domains^{8,9} 	<ul style="list-style-type: none"> • Requires much training⁷ • Requires jury upkeep⁸

1- (Baccino et al., 2010)/ 2- (Candau, 2001)/ 3- (Turin and Yoshii, 2003)/ 4- (Muñoz et al., 2010)/ 5- (Suffet and Rosenfeld, 2007)/ 6- (Burlingame, 2009)/ 7- (Leger, 2017)/ 8- (Verrielle et al., 2012)/9- (Jaubert et al., 1995)/10-(Hawko et al., 2021)

Abraham, S., Joslyn, S., Suffet, I.H. (Mel), 2015. Treatment of odor by a seashell biofilter at a wastewater treatment plant. *Journal of the Air & Waste Management Association* 65, 1217–1228. <https://doi.org/10.1080/10962247.2015.1075918>

AtmoNormandie, 2013. Résultats de la 3ème campagne de veille des Nez au Vent à Port-Jérôme. *La Gazette des Nez*, 53, <http://www.atmonormandie.fr/Publications/Publications-telechargeables/La-Gazette-des-Nez>.

Baccino, T., Cabrol-Bass, D., Candau, J., Meyer, C., Scheer, T., Vuillaume, M., Wathélet, O., 2010. Sharing an olfactory experience: The impact of oral communication. *Food Quality and Preference* 21, 443–452. <https://doi.org/10.1016/j.foodqual.2009.11.001>

Burlingame, G.A., 2009. A practical framework using odor survey data to prioritize nuisance odors. *Water Science & Technology* 59, 595. <https://doi.org/10.2166/wst.2009.872>

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