Validation of Citizen Observations to Assess the Odour Impact: the Barcelona Case Study of D-NOSES

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This paper presents the results of the pioneer case study of the D-NOSES Project (Distributed Network for Odour Sensing, Empowerment and Sustainability) in the Fòrum Area of Barcelona. A new Citizen Science (CS), bottom-up approach was tested to improve the traditional way in which odour pollution is managed, to account for geopositioned and real-time perception of odours in the impact area, using the OdourCollect (OC) App, where a WasteWater Treatment Plant (WWTP), a sludge treatment facility, a waste incinerator, and a Municipal Solid Waste (MSW) treatment plant operate very close to communities. The quadruple helix engagement model was key to involve all actors. After 15 months of engagement, 86 neighbours used the App to report 600 odour observations. The results of the Barcelona pilot paved the way for the remaining D-NOSES pilots (10 in total in Europe, Chile and Uganda) to demonstrate the validity of the methodology (Arias et al., 2018) for the monitoring of the odour impact in affected communities with complex scenarios, as a complement to traditional odour studies. They also pushed the creation of a Spanish standard on the use of CS to monitor odour pollution (Izquierdo et al., 2020), to be published by the end of 2022.

1. Introduction

A new bottom-up approach based on extreme CS (Haklay et al., 2018) to monitor odour pollution has been proposed, tested and validated in the framework of the D-NOSES project to account for geopositioned and real-time perception of odours in the Fòrum area of Barcelona. Combining citizen science and participatory strategies, the D-NOSES methodology empowered citizens to produce new sets of data that allow (i) to monitor odour pollution; (ii) to identify the situations of maximum impact; (iii) to co-create Odour Management Plans with the involved stakeholders; (iv) to participate in local decision making on a matter of their concern.

2. Materials and Methods

2.1 Context of the Fòrum Area of Barcelona

The Fòrum Area is located in the South-East (SE) of Barcelona. The area was renewed in 2004 alongside the celebration of the "Fòrum of the Cultures", a global event on sustainable development and cultural diversity, when odour complaints were made evident. The odour emitting activities already present in the area since the late 70s - waste and wastewater treatment facilities - were not acknowledged, despite the fact of being the most common odour sources in urban areas and that they treat more than half of the municipal solid waste and wastewater generated in the city. The area holds a bio-methanisation waste treatment plant, a waste incinerator, and a pneumatic collection station, located 1.5km away from a covered WasteWater Treatment Plant (WWTP, currently underneath the Fòrum Plaza), with a treatment capacity of 3M inhabitants, the biggest in Catalonia, and the corresponding wastewater sludge treatment facility (Figure 1). The affected area is characterised by a variety of demographics with different social, cultural, and economic realities. The variety of odour emitting sources and the demographic diversity made this case study complex and challenging, but proved its high adaptability and capacity to be inclusive involving citizens with different social realities.

The odour impacts caused by these plants depend on the emissions and the meteorological conditions. Along the day, one can smell fresh wastewater, odour from the wastewater biological treatment, sludge, fresh waste, decomposed residue, leachate or biogas. Other sources of odour present in the area include the sewage system, which can be mistaken by "fresh wastewater" coming from the WWTP, or waste odours associated with the collection system (bins or trucks).

2.2 D-NOSES citizen science methodology

The D-NOSES methodology proposes a novel strategy for real-time monitoring of odour pollution from the receptors' point of view. It aims to better understand the odour pollution issue in the area with the involvement of quadruple helix stakeholders (citizens, industry, public authorities and academia) so as to eventually reduce the impact over the population, while increasing transparency and improving the relationships between the actors. An effective engagement is key for success, so a highly inclusive approach needs to be applied.

2.3 Data collection

The free web-based and mobile-supported citizen science App OdourCollect (OC), inspired by the German standard VDI 3940-1:2006, was used as the specialised tool for gathering odour data at a broad temporal and geographical scale. It empowers citizens to co-create collaborative odour maps, by gathering the location and timestamp (date and hour) of the odour observation (automatically defined), the type and subtype of odour perceived by the citizens, the odour intensity (scale defined at VDI 3882-1:1992) and the hedonic tone (VDI 3882-2:1994). Users can also provide information on the duration of the odour perceived, the potential origin, or add any comments, which provide descriptive information that could further confirm the odour sources. Once a user submits an odour observation, the system visualises it on a map and it is anonymously archived on the backend database, ensuring compliance with the General Data Protection Regulation (GDPR). The plausibility of the odour observations recorded is analysed at different levels: 1) Individual level, to disregard false observations; 2) Collective level, to identify odour episodes; 3) Scientific level, to evaluate the potential origin of the odours perceived, associating them to odour emitting activities. After the analysis, it was concluded that only 14% of the total observations had to be corrected due to citizens' misclassifications associated to several reasons. The corrected results are presented below.

3. Results and discussion

The D-NOSES methodology was firstly applied during a short period of time of about 3 months, between the 5th of April and the 25th of July of 2019 (the *beta pilot*). During this period, 236 observations were reported by 51 unique users. Once the odour problem was identified and the stakeholders to get involved were mapped, co-creation workshops were held following the methodological phases: (i) Framing the problem to understand people's perception of the odour issue and to grasp local knowledge from the societal perspective; (ii) Pilot co-design together with quadruple helix stakeholders to set up common objectives and align expectations; (iii) Data collection and training in odours: type recognition, evaluation of the intensity and the hedonic tone, use of OC, sensory walks (in-field actions to collectively map ambient odours, differentiate and correctly identify the most common types and subtypes of odours perceived in the impact area, facilitating a precise use of OC); (iv) start of the data collection phase; and (v) data analysis and co-design of strategies to increase the number of citizens engaged and the number of observations collected. The beta pilot had fundamental relevance in the final definition of the engagement model and the D-NOSES methodology.

The *large pilot* continued until July 30, 2020, including the lockdown period associated with the COVID-19 pandemic from March 2020, when participation dropped. A total of 600 odour observations were collected by 86 unique users, which are under analysis in this paper with the objective to understand odour trends and to identify potential user input errors, such as odour observations mapped as pleasant but with negative comments on the annoyance perception. The distribution of the odour observations followed a long tail of participation typically found in citizen science projects, where many volunteers only participate once or twice (Boakes et al., 2016). 54.4% of the users followed this type of participation, while 12.1% of the participants collected up to 67% of the overall data. Regarding the seasonal distribution of the data collected, 57.7% of the total observations were reported in summer, followed by spring with 24.5%. This behaviour can be related to higher emission rates with warmer temperatures and odour dispersion conditions at these times of the year (Brancher et al., 2020). In terms of the hourly variability, the odour reports are consistent with people's diurnal activities, as peaks can be related to daily operations of the odour emitting activities, to unfavourable dispersion conditions, or to the habits of the citizens. "Sludge" was the main odour subtype perceived in the impact area by the involved neighbours. The maximum odour observations, as suggested by the citizens during the beta pilot, were reported at night, specially between 20h and 22h, directly related to the daily circulation of trucks removing sludge from the WWTP, increasing the perception of this type of odour. The circulation of the sludge trucks starts at 22h, as

informed by the plant operators, although the neighbours affirmed to see trucks circulating from 20h onwards, as reflected in the odour observations reported. Despite that this operation continues during night, the reports diminish from 23h onwards as citizens go to sleep.

3.1. Type, subtype, consistency and location of the reported odours
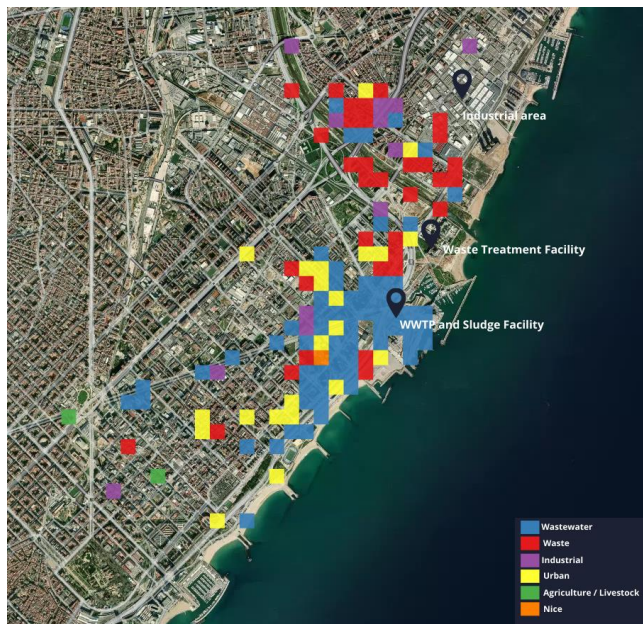

*Figure 1: Geographical grid distribution of the predominant odour types in the Fòrum area of Barcelona. Each square has a length of 100*100 metres.*

From the total number of observations (n = 600), wastewater and waste remain the predominant types of odour detected by the reports, accounting for 61.5% and 18.2% of the total number of observations, respectively - in comparison with 52.5% and 27.2% for the non-corrected data. In all seasons, the observations for wastewater surpass waste smells. Specifically, the hourly distribution per type of odour shows predominance of wastewater all day along, and an increase during the afternoon. Regarding the odour subtype for "wastewater" observations, most of the reports were classified as "sludge" (69.6%), followed by "wastewater" (21.4%). This result is coincident with traditional odour studies where sludge has been widely recognised as the main odour source in wastewater treatment processes (Kulig et al., 2019). For "waste" observations, most of the reports were classified as "decomposed waste" (64.2%), while only the 13.8% were associated with "fresh waste". 9.2% of the reports were associated with "other" waste odours, which means that further analysis shall be performed to better understand the odour sources in this case, or that citizens were not totally sure of the classification. A high degree of consistency was obtained during the whole duration of the pilot for the types and subtypes of odour reported, showing a low variability of the data collected during the beta pilot and the rest of the period, and demonstrating the ability of the neighbours, owners of the local knowledge of the issue, to correctly identify and report the odours perceived in the impact area. It also highlights that this type of studies can have a short duration (e.g. three months) and a reduced number of participants (e.g. 15-20 people, the number engaged in the early stages of the beta pilot) to obtain a comprehensive overview of the odour impact in an affected community.

Geolocated odour observations provide useful information about the real distribution of the odour impact in the studied area. They also give information on the plausibility of the allocation of the odour types as reported by the citizens in relation to the location of the emitting activities. As such, it was studied the prevailing types of odours reported in the Fòrum area in squares of 100 x 100 m. As shown in Figure 1, it was concluded that: (i) the prevailing type of odour in the studied area is "wastewater", especially in a perimeter of 500m to 1.6km from the WWTP and the sludge treatment facility, including the confluence of Passeig del Taulat and Diagonal avenue and the Fòrum square, where the WWTP and the sludge treatment facility are precisely based. Specifically, the dominant odour subtypes for this activity are sludge and wastewater, which have different ranges of perception by citizens. For sludge it is observed that the reporting of this odour subtype is often closer to the source in a range between 100m to 1.4km. For wastewater, this odour subtype has a wider impact area and is reported between 200m to 2.4km from the source. It should be noted that the reported intensity for both odour subtypes is high (strong, very strong and extremely strong) irrespective of the receptor proximity to the source. This behaviour is related to the temporal variation of the odour emission rate of the WWTP and the sludge treatment plant and the specific dispersion conditions, causing the receptor to perceive high odour intensities at different times despite being far away from the source. (ii) "Waste" odours are more relevant in the streambed of Besòs river, in the closest settlements to the waste treatment facility, and in the municipality of Sant Adrià del Besòs, especially in La Mina neighbourhood. The odour subtype for this activity is related to decomposed waste, which is reported between 300m to 1.8km. Finally, (iii) urban odours appear heterogeneously distributed, but are mainly located in the southern part of the studied area, where urban activity is denser, and where they are not masked by the main odours perceived in the area; and (iv) most industrial reports are located in Sant Àdria del Besòs, next to an industrial area. Thus, it can be observed that most of the data reported by the citizens is

consistent with the location of the emitting activities, confirming again its validity. The main impact areas and perceived odours also coincide with in house dispersion modelling and field panellist studies previously undertaken in the surrounding of the activities.

3.2. Intensity and hedonic tone of the reported odours

Table 1 shows the overall observations, for wastewater and waste odours, in terms of frequency of the observation, perceived intensity and hedonic tone, for the 600 corrected odour observations collected in the period studied. As the methodology is based on the recognition of perceived odours in ambient air, citizens were trained to report intensities from 3 (*distinct)* upwards, when the odour concentration is around the recognition threshold. Odour intensities corresponding to "very weak" or "weak" odours were reported only 6% of the time, while "distinct" odours were reported 22% of the time. Strong odours were reported 32.3% of the time; this intensity starts to be annoying and long time exposure should not be tolerable (Hawko et al., 2021). The two categories defining higher intensities ("very strong" and "extremely strong") account for 39.7% of the total observations; this level of intensity should be considered undesirable (Hawko et al., 2021). About the perceived intensities for wastewater odours, strong (38.8%) and very strong (20.9%) categories are the most observed ones, as for the general data, while extremely strong odours represent 14.9% of the observations. The wastewater subtype of odour reported most frequently with higher intensities is sludge (54.2%). In the case of waste odours, a higher number of observations were reported with high intensities: strong (22.9%), very strong (36.7%) and extremely strong (20.2%), with the subtype decomposed waste reported with higher intensities (54.1%). The results also show that users mainly use the OdourCollect app to report unpleasant odours (93.2% of the odour observations); with 28.8% reporting unpleasant odours, 37.5% very unpleasant odours, and 23.7% extremely unpleasant odours. These three categories are prevailing in the wastewater and waste odours, summing up to 96.5% and 96.3% of the observations, respectively.

According to the geolocation, most of the observations with the lowest hedonic tones (very or extremely unpleasant odours) and higher intensity for the two main types of odours present in the study zone (wastewater and waste) are located closer in the proximity of the WWTP and the sludge treatment facility. It can be seen that even though the observations associated with wastewater are more frequent, the odour observations associated with waste present higher intensities and lower hedonic tone (unpleasant), which indicates a higher level of overall annoyance to the affected communities. Finally, an interesting result of the data presented in Table 1 is that the "fresh waste" percentages of the "Intensity" and "Hedonic Hone" results are extremely correlated, with a Correlation Coefficient (CC) higher than 0.99. Also, "decomposed waste" reaches a significant CC of 0.61. However, the overall CC for all the types of "waste" is lower than both of its subtypes, 0.42. It may be concluded that the Intensity and Hedonic Tone detected by the observers have a significant correlation in the case of the "waste", but it is not so correlated in the case of the "wastewater".

Table 1: Summary of the frequency, intensity and hedonic tone of the 600 odour observations registered through OdourCollect in the Fòrum Area in Barcelona from April 5th 2019 to July 30th 2020 after correction (overall, wastewater, and waste odours).

Type of odour	Frequency (%)	Intensity (%)				Hedonic tone (%)			
		Extremely strong	Very strong	Strong	Distinct	Extremely unpleasant	Very unpleasant	Unpleasant	Slightly unpleasant
Overall		**16.7**	**23**	**32.2**	**22**	**23.7**	**37.5**	**28.8**	**3.2**
Wastewater	**61.52**	**14.9**	**20.9**	**38.8**	**19.2**	**24.1**	**43.4**	**29**	**2.4**
Sludge	69.6	9.2	15.7	29.3	12.2	16	35.2	16.8	1.1
Wastewater	21.4	2.7	4.3	7	5.1	4.9	6	8.9	1.1
Waste	**18.2**	**20.2**	**36.7**	**22.9**	**18.3**	**36.7**	**36.7**	**22.9**	**1.8**
Decomposed waste	64.2	9.2	28.4	16.5	9.2	22	25.7	16.5	0
Fresh waste	13.8	7.3	2.8	0.9	1.8	8.3	2.8	0.9	0.9

3.3. Analysis of the data plausibility and the ocurrance of odour episodes

To check the accuracy and quality of the odour data and verify if observations can be related to a certain event or activity, data were analysed at individual and collective level. One way to verify if odour observations are attributable to potential odour emitting activities is by analysing their geolocation and their respective distance to the source, regardless of time. As mentioned above, three characteristic odour subtypes are clearly identified in the study area: sludge, wastewater and waste. The odour subtype closest to the waste treatment facilities is decomposed waste with an average distance of 1.12km, while the closest odour subtypes related to the WWTP

and the sludge treatment facility are sludge and wastewater, with an approximate distance of 0.91km and 1.22km, respectively. With this information in mind, the location of the odour observations was verified, and in the case of any suspected misclassification of the user, the observation was assessed individually including the reported intensity, hedonic tone, comments and the overall user tendencies in the mapping of odour observations. Some misclassification was observed, indicating that the classification of the type or subtype of odour may not be 100% accurate in OdourCollect. The intensity and the hedonic tone also gave important information on potential misclassifications. For example, some of the more intense and with lower odour hedonic tones observations reported as "waste" in the areas next to the WWTP are probably "sludge" odour. In the same way, the "wastewater" observations located by the river in Sant Adrià del Besòs, probably correspond to "waste". It was also observed a "self-calibration" process experienced by some of the participants, i.e. the levels of intensity and hedonic tone were self-adjusted after making several observations, since the person reporting was able to compare. Finally, the revision of the citizens' comments in the App showed that, in some cases, the odour type and subtype reported did not match the comments (e.g. complaining about a burnt tyre smell and reporting wastewater in the app). Some of the "waste" odours reported came from garbage bins or were due to the circulation of waste trucks. The classification of these observations not directly associated with the emitting activities was changed into "urban odours".

After the individual analysis of the collected odour observations, in total only 14% of the data needed to be corrected, demonstrating their reliability. These data is key for the emitting activities to identify the situations of maximum impact as perceived by the affected population, and for producing odour management plans to address them. Thus, it can be concluded that citizen science is a powerful tool for monitoring odour pollution and for producing new evidence to protect affected communities. Data-driven evidence, especially when integrated with narratives, is essential for communities to make sense of local odour issues, take action and participate in local decision making to reduce the impact and increase their quality of life.

Finally, a collective analysis of the reported odour episodes was performed. An odour episode occurs when the presence of a mixture of substances in the air is responsible for varying degrees of annoyance in the population. Several odour episodes may occur on the same day. To define odour episodes based on the OdourCollect database, two or more observations of different citizens reporting the same type of odour in an area over a three-hour time period were identified. During the *large pilot* (483 days), 33 days with odour episodes were reported, which corresponds to 7% of the total duration. In total, there were 38 odour episodes, most of these were related to the wastewater odour type (70%) and 27% to waste. Within the wastewater type, 83% of the odour observations reported in these episodes were sludge, while for waste 89% were decomposed waste. The odour episode with the highest number of observations was on July 14, 2020, with a total of 16 odour records related to wastewater with a mean intensity of extremely strong and a mean hedonic tone of extremely unpleasant.

4. Conclusions

This paper presents the analysis and validation of the 600 odour observations reported in the App OdourCollect by 86 engaged citizens in the Fòrum Area of Barcelona in a period of 15 months (April 2019 - July 2020), where waste and wastewater treatment activities are located, following the citizen science methodology for the monitoring of odour pollution in real time developed and tested in the framework of the H2020 D-NOSES Project. After assessing the plausibility of the odour observations reported, the main odour perceived in the area is associated with wastewater treatment (61.5%), especially with sludge (69.6%). 57.7% of the total observations were reported in summer (n = 346), followed by spring with 147 observations (24.5%), related to higher emission rates with warmer temperatures. The maximum odour observations were reported at night, especially between 20h and 22h, which reflects the activity of the trucks transporting the sludge coming from the WWTP after its treatment from 20h onwards, when a peak appears coinciding with the start of this activity, and fades out when people go to sleep.

The main types of odours reported by the participants in OdourCollect are coherent with the activity of the emitters in the area, and are coincident with traditional odour studies previously undertaken in house by the odour emitting activities or the Metropolitan Area of Barcelona. In that sense, most of the reported odours can be related to the wastewater treatment facilities, followed by the waste treatment activities. In relation to intensity, strong odours are reported 32.3% of the total observations, while very strong and extremely strong odours account for 39.7%. This level of exposure should be considered undesirable. Regarding the hedonic tone, 28.8% of the reports correspond to unpleasant odours, 37.5% to very unpleasant odours, and 23.7% to extremely unpleasant odours. Even though observations associated with wastewater are more frequent, waste smells present higher intensities and lower hedonic tones, which may indicate a higher level of overall annoyance to the affected communities. However, a deeper analysis based on geolocation showed that some observations associated with "waste", with high intensities and lower hedonic tones in the surroundings of the WWTP and the

sludge treatment facility, probably correspond to "sludge". The same happens to some sludge observations located near the Besòs riverside, which probably correspond to waste, which were corrected. This corrected data represents only 14% of the total data. Moreover, the high level of coherence in the data reported, considering the beta pilot and the whole pilot period, demonstrates the ability of the neighbours, owners of the local knowledge of the issue, to accurately monitor odour pollution. This also highlights that this type of studies can have a short duration (e.g. three months) and a reduced number of participants (e.g. 15-20 people, the number engaged in the early stages of the beta pilot) to obtain a comprehensive overview of the odour impact in an affected community. Most of the reported odour episodes (70%) are related to the wastewater treatment activities, specifically to sludge (83%). The subtype of odour associated to the WWTP and sludge treatment facility that has the widest dispersion range is wastewater, while sludge was mapped in the vicinity of the source. It can be observed that most of the data reported by the citizens is consistent with the location of the emitting activities, confirming again its validity. In conclusion, the citizen science methodology deployed allowed to monitor and objectivise the odour impact from the receptors point of view in the Fòrum Àrea and bring complementary information with respect to traditional odour assessment methods.

Acknowledgments

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