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OCCUPATIONAL EXPOSURE TO AMMONIA DURING INDUSTRIAL-SCALE ANAEROBIC DIGESTION COMPOSTING OF HOUSEHOLD WASTE

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ABSTRACT

Biodegradable waste material can be exploited through anaerobic digestion, an oxygen-free multi-stage process often completed by a composting step, which harnesses the power of microorganisms to break down organic matter. This waste-treatment sector is growing rapidly in France as it allows the production of valuable digestates and biogas (biomethane). One of the main occupational health concerns in this sector is exposure to ammonia. The present work focused on ammonia emitted over the course of several stages in the anaerobic digestion and composting process, and assessed employee exposure to this pollutant. Exposure was measured for distinct worker activities and work areas, as well as during the various steps of the process. The results revealed non-negligible ammonia exposure for workers operating in the dehydration (until 55 ppm_v in the workplace and 17 ppm_v on the worker) and composting (until 45 ppm_v in the workplace and 17 ppm_v on the loader driver) areas on several sites. A classical monitoring approach was supplemented by the identification of explanatory parameters contributing to exposure: material emissivity, amounts stored or handled, and ventilation systems in use. Based on these elements, recommendations were made on prevention choices, including reducing emissions at source namely by process improvement and management of stored quantities, improving existing preventive systems such as capture at source or general ventilation, and employee education to raise awareness of waste management risks and improve practices.

1. INTRODUCTION

Anaerobic digestion is considered to be one of the most viable ways to exploit the organic fraction of solid waste (sewage sludge, animal waste, and industrial wastewater), it is therefore the focus of continuous study to improve its effectiveness (Khalid et al., 2011; Lin et al., 2018; RIS International Ltd., 2005). This natural biological process harnesses the capacity of microorganisms to decompose organic material in oxygen-free conditions. At industrial-scale, organic waste digestion takes place in a reactor, or enclosed chamber, where critical environmental conditions such as moisture content, temperature, and pH can be controlled to maximize microorganism proliferation, gas generation, and waste decomposition rates.

Industrial facilities use several reactor types that differ by their structural (infinitely mixed digester, reactors with stationary or moving support, etc.) and operating parameters (dry matter content in the reactor, operating temperature, etc.). In the field of domestic waste-treatment, due to the composition of the waste, dry digestion is often used. The technologies available for this process can be classified based on three main modes of operation: vertical reactors with digestate or biogas recirculation, horizontal reactors, and batch reactors (see supplementary Figure S1, online edition) (Damien, 2016; Dirrenberger, 2020; Zeshan, 2012).

To assess occupational exposure for workers in anaerobic digestion plants, it is therefore important to consider the whole waste-treatment line and the associated tasks. Indeed, upstream and downstream of the anaerobic digestion technology deployed, organic waste management requires significant pre-treatment and post-treatment. Thus, waste may be sorted at source to allow separate collection of biowaste, in some situations mixed waste may be collected, which would require waste sorting systems to

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be implemented. After fermentation, digestates can be exploited by direct application as fertilizer or by composting. A combination of anaerobic digestion and composting is often used to treat domestic waste. The steps involved in the process implemented in anaerobic digestion composting plants are presented in the Supplementary Material (see supplementary Figure S2, online edition).

Ammonium cations (NH_4^+) are produced from waste and organic effluent following biodegradation of organic matter as part of the ammonification stage (Moletta, 2015). NH_4^+ is subsequently transformed into ammonia (NH_3), volatilization of which is a physicochemical phenomenon boosted by basic pH, high temperatures, and air velocity at the solid-air interface (Beck-Friis et al., 2003; de Guardia et al., 2010a, 2010b; de Guardia et al., 2008; Fukumoto et al., 2003; Ni, 1999). Compared to the initial waste, anaerobic digestates have a significantly higher relative humidity, lower biodegradable matter content, and higher concentrations of ammoniacal nitrogen (de Guardia et al., 2010a). Consequently, compared to fresh waste, digestates have a reduced self-heating capacity – diminishing the sanitizing power of the composting process – and emit higher levels of ammonia due to their high ammoniacal nitrogen content. If the process is completed by a composting step, ammonia emissions continue to occur as the temperature increases and during windrow turning (Peigné & Girardin, 2001). In anaerobic digestion composting plants, the confined nature of treatment buildings could lead to the accumulation of gases in the workplace atmosphere (ADEME et al., 2019; Lavoie & Marchand, 1997).

High ammonia concentrations can cause irritation to the eyes and respiratory system (INRS, 2021) as well as presenting an odour issue. Ammonia can cause extensive bronchoconstriction (likened to an asthma attack), which can become permanent through the development of bronchiectasis. Chronic exposure to low levels of ammonia can also lead to sinusitis, irritation of the mucosa and conjunctiva, chronic bronchitis, or asthma-like symptoms (Sundblad et al., 2004). Consequently, in workplaces where ammonia is produced, effective collective preventive solutions must be implemented (adequate ventilation, appropriate use of loaders, filtering boxes, etc.) with or without individual solutions (respiratory protective equipment or RPE) (ADEME et al., 2019). Exposure levels can be compared to Occupational Exposure Limits or OELs (Table S1, as Supplementary Material) (INRS, 2021, 2022a, 2022b).

In composting plants, occupational exposure to biological and chemical pollutants is well documented (Lavoie & Marchand, 1997; Nadal et al., 2009; Park et al., 2020; Poirot et al., 2010; Robertson et al., 2019). These reports highlight major pollutants such as bioaerosols, dusts, endotoxins, VOCs and ammonia in particular. In anaerobic digestion plants – where waste treatment is often completed by a composting step – workers are potentially exposed to similar pollutants, including a number of biological (culturable microorganisms, endotoxins, etc.) and chemical pollutants (e.g., methane, nitrous oxide, hydrogen sulfide, VOCs, carbon oxides). In most cases, the major chemical contaminant is ammonia (NH_3), which is mainly produced downstream of the anaerobic digestion step. Ammonia has an inhibitory effect in digestates, and consequently most studies have focused on improving the efficiency of the anaerobic digestion processes (Chen et al., 2016; Krakat et al., 2017; Rocamora et al., 2023). Some papers deal with ammonia emissions from matter (Bell et al., 2016; Lemes et al., 2023; Preble et al., 2020) but only a few recent papers assess ambient concentrations and worker exposure to ammonia in this sector (Bakhiyi et al., 2018; Pöther et al., 2021).

In this context, the purposes of this study were (i) to characterize the ammonia levels in distinct areas and in loaders, depending on the process considered and any pre-treatment and post-treatment methods; (ii) to assess worker exposure for the various activities and tasks performed based on individual ammonia samples in breathed air; (iii) to characterize the explanatory variables – such as the inventory of materials present/manipulated, their overall emissivity and surface emissivity – as an additional exploratory work in addition to highlighting occupational exposure to ammonia. From this characterization, it was possible to prioritize the search for preventive solutions to reduce emissions at source (process improvement, management of stored volumes, etc.) and/or to improve preventive systems (confinement, local exhaust ventilation, etc.).

Direct reading instruments were used in addition to conventional sampling to objectify worker exposure to ammonia; these measurements are the subject of a companion article (Battais et al., 2022).

2. MATERIAL AND METHODS

2.1 Characteristics of anaerobic digestion composting plants

Measurement campaigns were carried out in six anaerobic digestion composting plants located in France (Battais et al., 2022). Plants were selected based on the variety of the processes encountered and the operation methods applied, representing all the types of dry anaerobic digestion processes currently used in France to treat domestic waste (see supplementary Figure S1, online edition ; Dranco®, OWS, Belgium; Valorga®, Urbaser, Spain; Linde-BRV®, Linde-KCA-Dresden Gmbh, Germany; Kompogas®, Vinci Environnement, Switzerland; BAL-HYBRID®, BAL Biogas, France) (Damien, 2016; Dirrenberger, 2020). Table 1 summarizes the characteristics of the plants studied, and the climate conditions prevailing during the measurement campaigns, depending on the period when measurements were taken and on the geographical location of the plants. Campaigns were held in plants not located in tourist areas, or in the off-season, so that tonnages handled were quite usual. Working conditions were typical (no major maintenance operations), including any short technical stops or failures which are usual in this kind of plant. Campaigns D1 and D2 were performed in the same site (D) on two dates, hence temperature and hygrometry were quite different (Battais et al., 2022).

Due to the diversity of the industrial sites monitored, data exploitation was simplified by grouping the activities into five major zones:

TABLE 1: Summary of the main characteristics of the anaerobic digestion composting plants investigated and climatic conditions measured during the measurement campaigns.

Plant	Type of waste (tonnage)	AD[5] process	Sampling period	Mean T°C*	Mean HR %*
A	70,000 t MSW[1] 30,000 t varied BW[2]	Valorga®	October 2017	18°C	74%
B	30,000 t MSW[1] 6,000 t varied BW[2]	BAL-HYBRID®	March 2017	16°C	75%
C	70,000 t MSW[1]	Dranco®	May 2017	25°C	59%
D	30,000 t domestic BW[2] 5,000 t varied BW[2] 10,000 t GW[3]	Kompogas®	December 2016 (D1)	8°C	78%
			September 2017 (D2)	19°C	87%
E	20,000 t OFMSW[4] 20,000 t GW[3] 4,000 t varied BW[2]	Linde-BRV®	April 2017	15°C	72%
F	85,000 t MSW[1]	Valorga®	November 2018	21°C	70%

[1] Municipal Solid Waste - [2] BioWaste - [3] Green Waste - [4] Organic Fraction of Municipal Solid Waste - [5] Anaerobic Digestion
** Measured in ambient air on site during the campaigns*

- The reception area with its unloading docks for the main materials treated, apart from green waste, which is most often unloaded in the "digestate-structuring area";
- The separation area, where waste is sorted and treated to select the finest possible organic fraction (usually less than 10 mm) for input into the digester;
- The digestate-structuring area where waste is dehydrated by centrifuging or pressing, or where outgoing digestate is mixed with structuring material (green waste, fresh waste, etc.). Green waste is generally shredded in this area;
- The composting tunnels area where "solid" digestates are composted;
- The refinement area where the last screen is performed to obtain marketable compost.

An additional fictitious "loaders" area was defined to deal separately with exposure for employees driving loaders.

2.2 Exposure measurement methods

Personal and ambient samples were collected over a continuous period lasting between 3 h and 8 h. Workers were fitted with a pump (Gilian 5000, Sensidyne, USA) and a sampling system mounted in their breathing zone. Static samples were taken at airway level. Ammonia was sampled on two-stage 37-mm diameter closed-face cassettes (CFC), fitted with sulfuric acid-impregnated quartz filters. The flow rate for sampling was 1 L/min, and its duration was 8 h maximum. Ammonia trapped on filters was desorbed with Ultra-Pure Water, and after filtration (MILLEX filters 0.22 µm) and 10-fold dilution, subjected to ion chromatography (METROHM 881 COMPACT IC PRO; METROSEO C3 column, without suppressor device and with conductivity detector), applying the INRS Metropol M-13 method (INRS, 2020).

The overall numbers of filter samples collected to monitor ammonia levels on each site are summarized in Table 2.

In some cases (namely on sites B and D), a subset of individual samples was collected over 4 h at a flow rate of 2 L/min. These samples were either used to assess ammonia exposure for a specific task or to allow other individual measurements to be taken to assess exposure to other pollutants.

2.3 Explanatory variables for exposure

Employee exposure to pollutants depends on many factors, including the activity, in particular when performed close to pollutant sources, and when it involves more general parameters depending on installations or processes (intensity of polluting sources, efficiency of localized capture, ventilation of premises, etc.).

Acquiring activity-related determinants, by recording the employee's work to identify tasks leading to exposure involves monitoring over a full working day. This approach, which may require video-type observation resources coupled with real-time sensors (Martin et al., 1999), is rarely extended to all employees on an industrial site. For this study, only a few workstations were assessed and are not described here.

Only the overall parameters explaining exposure levels were characterized: potential emission rates, based on ammonia potential surface emissivity and material surface area, and air exchange rates in the premises. These

TABLE 2: Numbers of airborne ammonia samples collected in each anaerobic digestion composting plant.

Campaign	A	B	C	D1	D2	E	F
Stationary sampling	29	35	41	42	21	18	30
Personal sampling	15	23	17	52	15	15	14
Loader sampling	3	6	11	3	3	7	9
Total measurements	47	64	69	97	39	40	53

investigations were generalized to all sites, to make their comparison easier.

2.3.1 Potential emission rate

The potential emission rate is a parameter defined to reflect the intensity of pollution sources in premises. It is calculated by multiplying the emission surface of a material present on the premises and the potential emissivity of this material. However, efficient capture and containment systems were taken into account, to subtract emission surfaces from the balance sheet. In the plants studied, the true efficiency of these systems was assessed using a smoke generator. However, in the simplified approach applied here, a binary factor was applied to efficiencies (η=0% or η=100%). Material at various stages of transformation could be present in the same room. In this case, the potential emission rate was defined as:

$$E_j = \sum (1-\eta_k).S_{k,i}.e_i \quad (1)$$

with

E_j the potential emission rate in hall j (µg.s^{-1}),

η_k the capture efficiency of any device applied to source k (%),

$S_{k,i}$ the surface of material corresponding to source k at stage i (m²),

e_i the potential surface emissivity of the material at stage i (µg.s^{-1}.m^{-2}).

Method used to estimate potential surface emissivity

Several devices are available to measure in situ surface emissivity (Eklund, 1992; Mosquera et al., 2010; Wheeler et al., 2010; Wolkoff et al., 1995). The approach applied here is described in the standard for the measurement of the emissivity of building materials (British Standards Institution, 2006) and consists of covering the emitting surface with a bell. A stream of clean air continuously sweeping through this bell becomes charged with pollutants which can then be analyzed. The air flow rate (Q_{spl}) and output concentration (C_s) can then be used to estimate the emission rate for the pollutant by applying $E=C_s.Q_{spl}$. For anaerobic digestion composting sites, a variant of this method was implemented, whereby sampled material was placed in a container to analyze emissions. This choice was governed by the following needs/constraints:

- To estimate emissions derived from liquid effluents, particularly for liquids circulating in gutters;
- To access restricted areas (risks linked to the movement of loaders, risk of collapse of the piled stored materials). In these cases, the samples were collected by site employees;
- To obtain average values. To this end, samples from distinct areas of a storage facility were mixed.

The measuring device implemented was designed using elements used for exposure measurements: Gilian GilAir Plus sampling pumps, BW GasAlertMicro5 real-time detector (INRS, 2009), and a plastic bucket with a lid (15-L dosing bucket available in DIY shops). A pump was used to draw air from the container (Q_{spl}=1 L/min), and one or more additional pumps diluted the sample (up to 15-fold) to reduce the moisture content and ensure non-saturating ammonia concentrations reached the analyzer. To avoid using inlet air pre-charged with pollutants, the measurement device was installed outdoors.

A bibliographic study showed that the air velocity at the surface of a material affects ammonia emissions. In his literature review, Ni (Ni, 1999) listed 13 empirical models to evaluate the extent of this effect. Most of these models apply a factor corresponding to surface air velocities in $V^{0.8}$. Thus, compared to an emissive material stored in an area sheltered from air currents (0.2 m.s^{-1}), the same material stored in a ventilated area (0.8 m.s^{-1}) would have 3-fold higher emissivity. In most measurement methods, the emissivity of materials is assessed using devices swept by low air velocities. Consequently, the values obtained are underestimated compared to materials stored in the open. A corrective factor could be applied based on known velocities. However, due to the risk of piles collapsing, the air velocities at the surface of stored materials could not be assessed. Consequently, the emission rates estimated here are default values, which explains the use of the term "potential" applied to all notions of emissivity or emission rate in this article.

2.3.2 Air exchange rates

General ventilation is usually an essential lever for reducing exposure. The background concentration results from dilution of emission rates by air renewal rates ("perfectly mixed room" modelling (Sandberg, 1981)). However, ventilation can induce air movement and, as indicated above, in the case of ammonia, can lead to increased emission rates, which would cancel out the benefits of air renewal. Despite this uncertain context, the general ventilation in plants was assessed by measuring the air exchange rate (R). This theoretical value indicates the number of times the air volume contained in a room is replaced every hour. For these experiments, R was measured by gas tracing, by seeding the air in the room with a gas not present in the environment (SF6) and monitoring its decrease in concentration over time (Laussmann & Helm, 2004).

3. RESULTS AND DISCUSSION

3.1 Exposure determinants

3.1.1 Air exchange rates

The air exchange rates measured by tracer gas on sites A to F are presented in Table 3. Overall, the rates measured were within the order of magnitude of those expected for industrial sites (typically between 2 and 4 changes per hour), with only two cases showing significantly different R values. In one of these cases, the very high value was the result of operating with open doors (separation area, site C, R=13.0). This situation reflected the configuration of the premises during the exposure measurement campaign, which was undertaken during a heat wave. The other case was linked to a ventilation failure due to lack of preventive maintenance (refinement area, site D, R=0.3). In this situation, the air exchange measured corresponded to that provided by natural ventilation.

TABLE 3: Air exchange rates measured (ACH *).

Site	A	B	C	D2	E	F
Separation area	4.9	3.4	13.0	2.2	1.8	1.8
Digestate-structuring area	7.1		4.9	2.1		4.9
Composting tunnels area		3.2	2.3	3.3	1.9	2.4
Refinement area			3.0	0.3	1.4	2.0

** ACH: Air Changes Per Hour*

3.1.2 Potential ammonia emissivity of various materials

The process of anaerobic digestion composting of waste involves several phases that are generally reproduced across all sites (see supplementary Figure S2, online edition). Over the course of the process, the material undergoes various transformations and as a result extensive variations in ammonia emission can be measured (Figure 1).

Before the digestion phase (separation phase), ammonia emissions were generally low. Similarly, low emissivity was recorded on site C for inputs that had undergone pre-fermentation. After the digestion phase, emissivity was at its maximum (maturation). On all sites, the peak of emissivity was recorded after digestion. The levels reached differed between sites (with a 5-fold difference between maximum and minimum). Emissions then decreased gradually (sieving, storage). Before composting, a structuring agent is often added to the material (generally green waste that does not emit ammonia), which could explain the drop in emissivity. At the end of the composting phase, the material is sieved to retain the finest fraction as the finished product. The emissivity of the sieved product was generally low, except in the case of site F, where emissivity was observed to increase. Note that on this site, composting cycles are brief (approximately two weeks). Sieve rejects and stored material were also monitored, showing emissivity levels comparable to those of the sieved product. The ammonia emissivity of the compost produced appeared to correlate with the emissivity of the digestate; the lower emissivity of the digestates on sites B and E leads to the production of materials emitting little or no ammonia. In contrast, on sites where the digestate was highly emissive (especially C and F), the materials at the end of the process continued to emit significant amounts of ammonia.

Concerning ammonia emissivity of materials from literature, comparison is not obvious because values obtained are rarely expressed by squarred meter of matter. Comparable results from anaerobic digestion sector were not available but some values were measured from composting windrows between 120 and 460 µg/s/m^2 (ADEME et al., 2011). Other available measurements concerned cow dung or pig manure and ranged from 50 to 350 µg/s/m^2 (Borka et al., 2000; Dinuccio et al., 2008; Hoff et al., 2006). The emissions rates estimated in anaerobic digestion plants are of the same order of magnitude although the nature of the treated material is different and it cannot be ensured that the same stages of the process are considered.

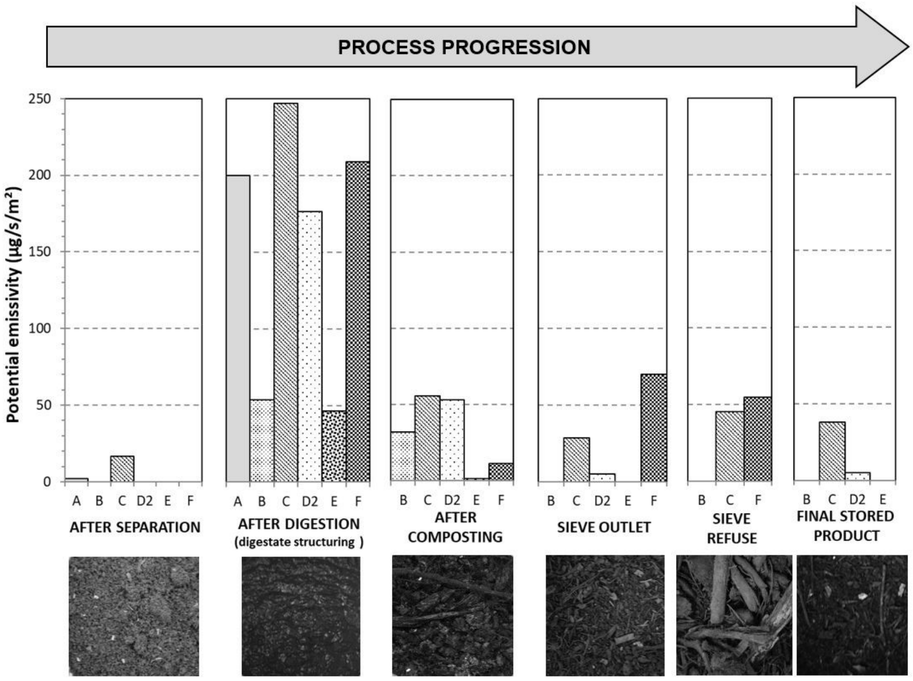

FIGURE 1: Potential emissivity from the material measured over the course of anaerobic digestion composting (a missing letter means that the measurement could not be performed). The pictures show the material at the different steps in the process.

3.1.3 Potential emission rates in each zone

Figure 2 shows potential emission rates for the different work areas on sites A to F, normalized per unit area for each of the zones where the activity takes place. The calculation of the emissivity in the composting tunnel area was made difficult by the fact that the emissive sources varied over time as tunnels were filled and emptied. To simplify estimations of potential emission rates, a static situation was considered based on the average activity in this zone during the measurement campaign. The material present in this zone may be digestate-structuring mixture, composted material directly removed from the tunnel, and/or material maturing in silos if the maturation phase takes place in the same zone.

3.2 Results from ambient air sampling

Ambient ammonia concentrations detected in the various areas are presented in Figure 3, with boxplots representing combined results for the six sites. An alternative presentation of this data is provided in Figure 4. This view highlights differences between the sites, and reveals links to trends identified from the potential emission rates Figure 2. To objectively analyze these two graphs (Figure 2 and the part of Figure 4 bounded by the dotted line), it should be kept in mind that the modelling of potential emissions is simplified, and that – due to the mobility of material in the storage facilities and loader traffic – the ambient samplers could not be positioned in the desired locations to optimize measurement of the average ammonia concentrations in the premises.

In line with the very low emissivity of the material in the reception and separation areas, (Figure 1 and Figure 2), the results for ambient samples showed that the ammonia content measured before anaerobic digestion was low, not exceeding a few ppm_V. The presence of ammonia in these areas is generally due to the early decomposition of biowaste (site C), but could also be explained by the transfer of pollutants between premises, as in the case of site D.

Values recorded in the digestate-structuring area, just after anaerobic digestion, were often very high due to the handling of ammonium-rich digestates at this stage (Figure 1) and any material left in the open air will be a source of significant emissions. For sites lacking this type of area, these emissions generally occurred in the composting area. For two sites (C and D), the average values measured were very high (almost 40 ppm_V for D). In contrast, for two other sites (A and F) where digestate transfer and treatment are contained, and emissions are captured, the potential emission rate is very low and ambient concentrations were correspondingly low (average of 3 ppm_V). On these sites, emissions will only occur during maintenance operations or production incidents. Conversely, on site D, poor design of the capture systems, lack of rigour with covering of the material transfer line systems, and leakage from the material processing tanks resulted in a high potential emission rate and consequently a high concentration despite substantial general ventilation (Table 3).

In the composting tunnels area, average ammonia levels measured varied depending on the sites. In the case of three measurement campaigns (C, D2 and F), very high values (up to 45 ppm_V) were recorded, with increased concentrations during intensive tunnel emptying. For the three other campaigns (B, D1, and E), the values measured were systematically lower than the French OEL-8h value of 10 ppm_V (INRS, 2021, 2022a, 2022b), even though the same intensive tunnel emptying task was being performed on two of the low-level sites (B and E). On site E, the potential emission rate in this area was almost nil because only small quantities of low-emissivity material were present. On the other sites, the values per square meter were of the same order of magnitude, but the differences between sites were more pronounced for ambient concentrations. In some sites, maintenance operations requiring opening

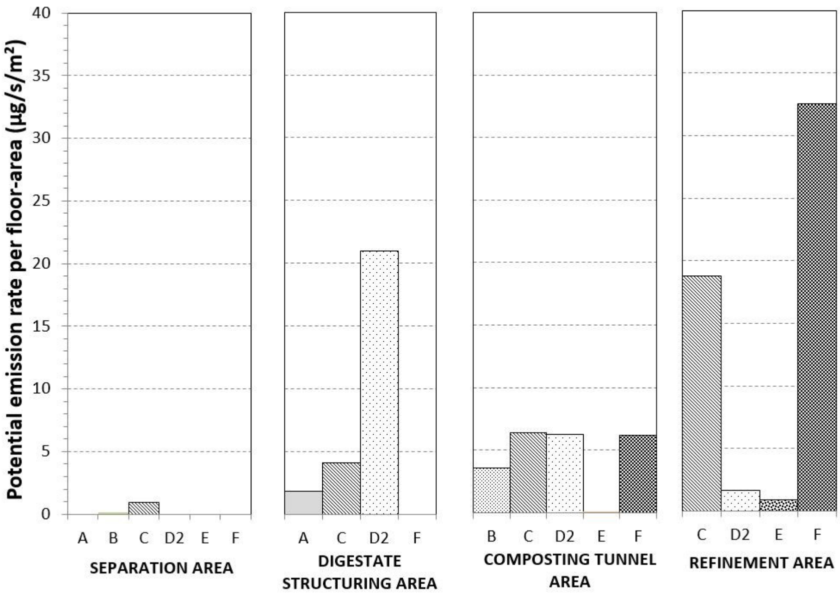

FIGURE 2: Potential emission rates in the different treatment zones, normalized with respect to floor-area.

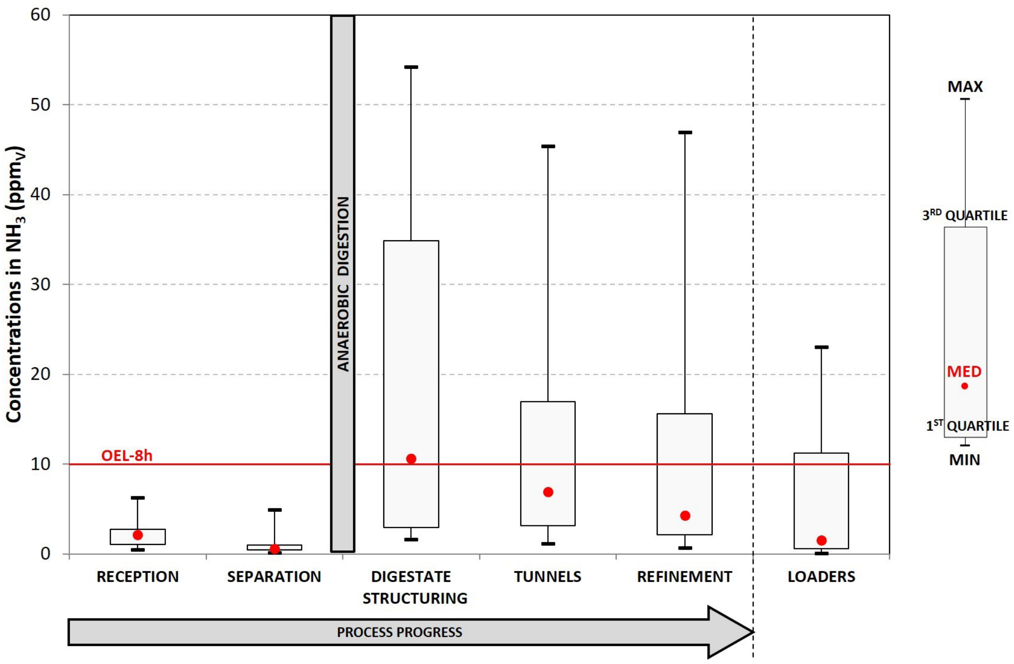

FIGURE 3: Ambient ammonia concentrations measured in various areas in six anaerobic digestion composting plants (boxplot).

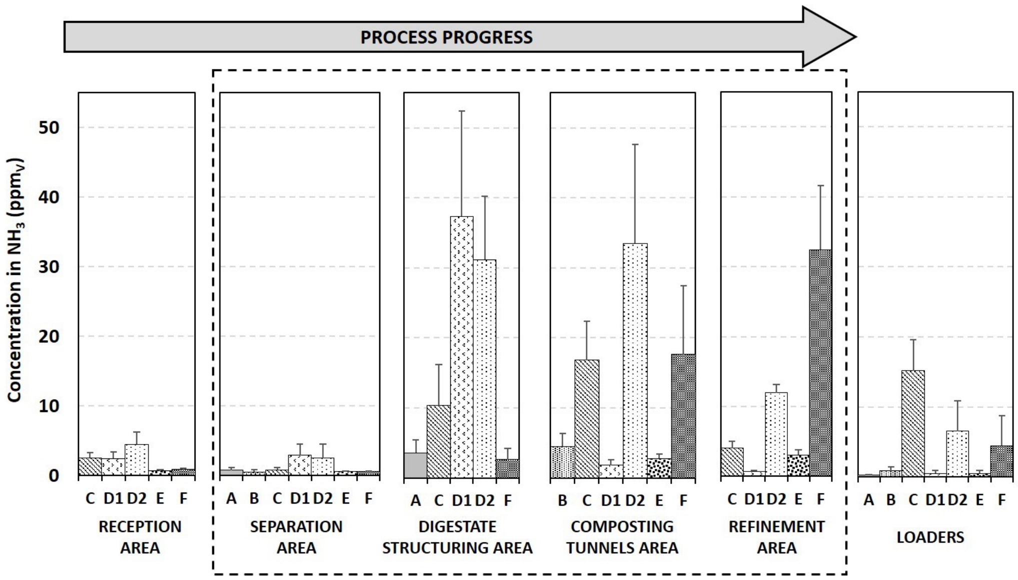

FIGURE 4: Ambient ammonia concentrations measured in various areas in six anaerobic digestion composting plants (bar chart view).

of composting tunnels explain the levels of ammonia detected in ambient samples.

In the refinement area, mainly sieved compost and sieve rejects are present. In this area in sites C and F, very high potential emission rates were measured. These rates were around 15 to 20 times higher than those measured for the other sites. The high emissivity of the material in this zone combined with the storage of large quantities of material could explain the high ambient concentrations measured – of the same order of magnitude as in the tunnels area – especially in the case of site F. Concentrations were low (i.e., less than 5 ppm$_v$) for three measurement campaigns (C, D1, and E). For two other campaigns, slightly higher values were recorded (between 10 and 15 ppm$_v$ for campaign D2, and for campaign F, six values exceeded the French OEL-8h value).

On site F, the general ventilation system used a considerable airflow rate, which, nevertheless, did not allow satisfactory concentrations to be achieved. It would be difficult to increase this flow rate because of the vast size of the premises. On site C, the ambient concentrations measured were low relative to the corresponding potential emission rates. This difference could be explained by the fact that the zone was open to the exterior and the ambient sampling point was placed close to a wall. The low emissivity of the material could explain the low potential emission rates measured on sites D (campaign D2) and E. Nevertheless, during campaign D2, a malfunction in the ventilation system (Table 3) led to a non-negligible concentration level.

In the case of loaders, results varied depending on the site, and particularly on the area where loaders were used. Four campaigns revealed very low ammonia concentrations in the loaders (A, B, D1, and E), with low ambient ammonia concentrations (up to 8 ppm_V) measured in the areas where they were used. In contrast, for three other measurement campaigns (C, D2, and F), the areas where loaders were operated had high ammonia levels, and several values exceeding the French OEL-8h value were measured in cabs, especially on site C. These values were often due to problems with the cab filtration systems or to inappropriate practices by operators.

Concerning ammonia ambient measurements from literature, Pöther et al. found that the majority of the shift average values for ammonia ranged from 3 to 13 $mg.m^{-3}$ (i.e. between 4 and 18 ppm_V approximately) but a maximum value was obtained in the delivery category, corresponding to digestate-structuring area (above 20 $mg.m^{-3}$, i.e. 28 ppm_V approximately) (Pöther et al., 2021). Bakhiyi et al. found very low values in different areas of several plants, ranging from 1 to 4 ppm_V (Bakhiyi et al., 2018).

3.3 Results from personal air samples

Personal air sampling was also carried out (Figure 5), the operations leading to the highest exposure levels results correlated with the results of ambient air samples. In the reception, separation and digestate-structuring areas, workers regularly intervene to perform verifications, for ongoing maintenance, or to deal with malfunctions. The composting tunnels area is frequented by loader drivers emptying and filling the tunnels, by maintenance operators when an intervention is necessary, and by shift managers as they do their rounds of the whole site.

Personal sampler values measured for operators working in reception and separation areas were very low (less than 1 ppm_V).

For maintenance operators, concentrations were variable, depending on the tasks performed and the areas frequented (see Figure 5). Two workers from distinct sites were particularly exposed: one was working in a dehydration area which was significantly polluted with ammonia, the other was working in a composting tunnels area. Several values exceeded the French OEL-8h threshold, in particular for these two operators.

Loader drivers were generally well protected by cab filtration when systems were adequately verified and maintained. Nevertheless, this was not always the case, and operators occasionally applied inappropriate practices, resulting in potentially significant exposure to ammonia and other pollutants. On one site, the levels measured in loaders were high, with three values exceeding the French OEL-8h, and one concentration of 9 ppm_V. For a loader driver from another site, a concentration close to 11 ppm_V was recorded, but this driver was fitted with RPE when leaving his loader to intervene in the polluted area.

Production operators work in all areas throughout sites. This role was present in two plants, in both cases individual exposure values were less than or equal to 5 ppm_V.

Polyvalent operators and shift managers generally work site-wide. Like for maintenance operators, their overall exposure during their shift depended on the level of pollution in the areas frequented, and on the time spent in these areas. On one site, significant exposure to ammonia was recorded during the two campaigns conducted. Although only one value exceeding the French OEL-8h was obtained, in many cases concentrations exceeded 5 ppm_V.

Based on these measurements and observations, personalized recommendations were made to each plant, but general recommendations were also highlighted. These include the following:

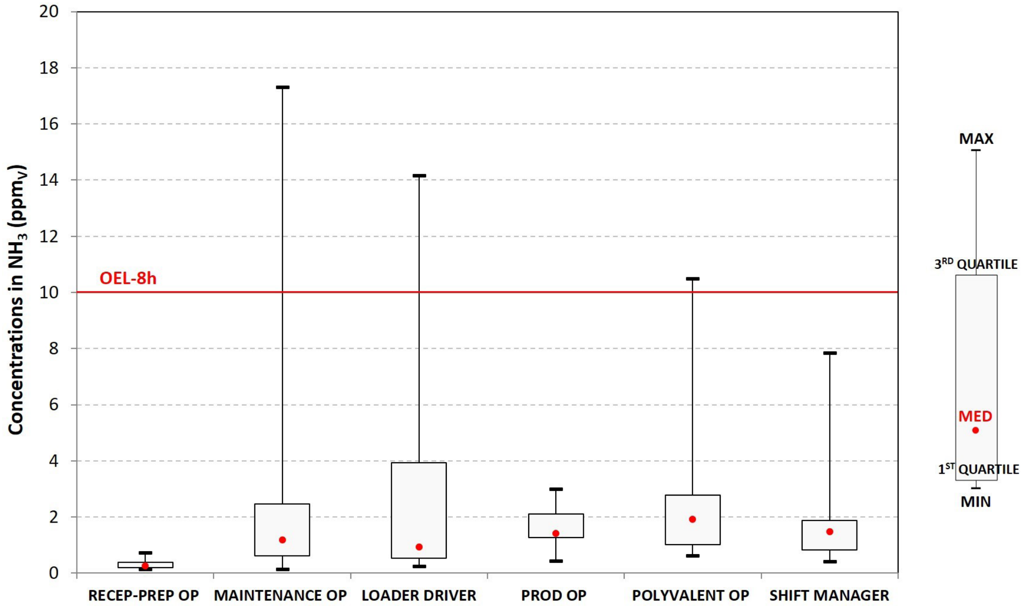

FIGURE 5: Individual ammonia concentrations measured for operators working on six anaerobic digestion composting plants.

- Well-designed and -maintained ventilation systems (sufficient renewal rates, localized capture systems, covered conveyor-belts, among others);
- Ease of cleaning and maintenance (prioritizing level-floor zones, well-organized cleaning systems, among others);
- Sufficiently long treatment cycles (namely for composting) and limited material stocks on the premises;
- Separated activities to avoid exposure due to co-activity;
- Monitored prevention measures and systems (maintenance of equipment: real-time detectors, respiratory protective equipment [RPE] and loader filter systems, …);
- Employee education to raise awareness of waste management risks and improve practices.

4. CONCLUSIONS

The present work sought to assess occupational exposure to ammonia in anaerobic digestion composting plants. Measurements were performed to sample ambient air in work areas, in workers' breathing zone and in loader cabs. Estimation of explanatory variables consolidated the interpretation of exposure levels.

The results showed significant variability between sites depending on organization, particularly with regard to quantities of waste treated, residence times of materials in the different work areas, pre-treatments applied, anaerobic digestion process implemented, and any post-treatment processes, among other aspects. At the end of each measurement campaign, the results were used to suggest tailored technical and organizational improvements, which were presented to operators and management staff.

Among the explanatory variables identified as useful, the emissivity of the materials was one of the most significant; this parameter is easy to measure using equipment that is already available to occupational hygienists. For this study, measurements were taken using a real-time detector, but conventional filter-based sampling could also be used.

The explanatory variables make it possible to better target the areas with the highest emissions, and thus to prioritize the implementation of novel preventive solutions aiming to reduce emissions at source (process improvement, management of stored quantities, etc.), and/or to improve existing preventive systems (containment, capture at source, general ventilation). In particular, the method identified the most emissive materials, for which it was recommended to limit stocks and to set up local exhaust ventilation for the parts of the process concerned. This knowledge of source flows provides a more objective picture of emissions than purely visual observations (e.g., materials emitting a flow of water vapour wrongly considered to be charged with ammonia).

The approach used in this study, combining air sampling and material emissivity measurements alongside an assessment of ventilation, could be used for an extensive panel of chemical or biological pollutants, and is applicable across all waste management sectors. Its implementation would contribute to significantly improving the information provided to workers, making them aware of their potential exposure, and could serve as a guide for occupational hygienists in their selection of preventive measures to reduce exposure levels.

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