Dioxin Contamination after a Hypothetical Accidental Fire in Baled Municipal Solid Waste Storage

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Landfill management usually entails dealing with the production of leachate and the formation of biogas, with the related environmental and public health concerns. One element that tends not to be investigated, is the risk of a fire with the consequent emission of toxic substances, especially dioxins. This study focuses on the case of an existing landfill in which the waste is placed in cylindrical wrapped bales, and where for the purposes of this study, the burning of the waste mass was hypothesized. The Austal2000 model system was used in order to estimate the average air concentrations and the deposition values of PCDD/F.The analysis showed that a landfill may be at risk in terms of fire potential with the consequent release of dioxins. Storage in bales, for various reasons, increases this risk. The analysis of the effects show that the environment and public health would be very seriously compromised. The recovery of the chosen landfill is therefore necessary, especially given the potential dioxin release. The presented analysis wants to be a warning for decision makers who could choose to implement large bale storages without an adequate attention to fire prevention.

Keywords: landfill fire, dioxins, compressed bales, modelling

The EU Council Directive 1999/31/EC and 2008/98/EC established a legislative framework for handling waste and the member states are obliged to comply with it in order to increase recycling (energy and/or material recovery) and to discourage the landfilling of waste. This resulted in an increased number of temporary storage sites, which are defined by Directive 2008/98/EC on waste material as “a storage activity pending its collection in facilities where waste is unloaded in order to permit its preparation for further transport for recovery or disposal elsewhere”. The temporary storage sites can be further sub-classified as seasonal storage sites (storage periods of up to eight months associated with incineration plants) and non-seasonal storage sites (storage periods vary between a few days and a few weeks). The need for temporary storage arises because of the insufficient operating capacity of processing plants [1] and/or the varying demand for district heating and electrical power between the summer and winter seasons. Furthermore, materials also need to be stored at temporary storage sites before sorting and recycling.

Waste materials with a high organic fraction and/or high calorific value are commonly placed in heaps, even though they are at a high risk of fires, and the associated toxic emission risks are well known [2,3]. Materials stored only for a short period also pose a substantial risk of fires.

The use of baling as a storage technique does not eliminate the risk of fires. Plastic wrapping around the bales produces a high flame-spread rate [4], and bales can easily catch fire from adjacent fires. Yasuhara et al. [5] argued that, with current scientific knowledge, it is not possible to completely prevent spontaneous ignition in solid waste fuel storages.

As the risk of fires always exists, it is appropriate to follow a *failsafe* approach; i.e. apart from efforts to prevent any fire incident, the geographical locations of temporary storage sites must be chosen in a way to cause the least possible externalities in the event of any fire incident. Unlike other industrial processes, the atmospheric emissions from open fires cannot be controlled, either by setting emission limits or by using air pollution control devices. As a result, the impact of open burning wastes on air quality is many times greater than that of controlled combustion [6,7].

Fire incidents can pose serious health risks for the population residing in the vicinity of storage sites, and people in nearby residential areas may need to be evacuated [8]. One of the most important reasons is that fires are the source of persistent organic pollutants (POPs) such as dioxins, furans and/or polychlorobiphenyls in the environment [9-11].

Polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are unintended by-products of various technological processes [12-16], and are also produced by non-industrial emission sources [9,17], however they have never been produced commercially, and they are formed during the incomplete combustion of organic materials in the presence of chlorine.

According to the United Nations Environment Programme (UNEP), in the near future, non-industrial emission sources such as landfill fires and backyard barrel burning will probably become more important and dominate the overall annual emissions of PCDD/Fs in Europe [18]. A survey of international studies consistently identifies high dioxin concentrations in areas affected by open waste burning, and a study of the congener pattern concluded that the sample with the highest dioxin concentrations was *typical for the pyrolysis of PVC* [19]. Other EU studies indicate that PVC likely *accounts for the overwhelming majority of chlorine that is available for dioxin formation during landfill fires*[20].

Although, for safety reasons, landfills are not situated near densely-populated areas, inevitably there are some

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cases where contamination is transferred to sites of agricultural production and animal rearing, and therefore ends up in the food chain [21].

PCDDs and PCDFs are considered to be the most toxic and diverse family of POPs. The toxicity of PCDD/F congeners is expressed in terms of a Toxic Equivalency Factor (TEF) in relation to the most toxic congener, 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). This approach is useful in studying the environmental incidence of single industrial plants or the role of specific industrial sectors [10,22].

The concept of TEF was first introduced in 1988 [23], defined as the International TEF scheme (I-TEF). The definition of TEF was subsequently modified and adopted by the World Health Organization (WHO) as the WHO-TEF scheme, whose formulation was revised for the last time in 2005 [24], and by the European Commission in 2011 [25]. Toxic Equivalents (TEQs) were then adopted by the WHO for direct application to the human health risk assessment [26].

Since food is generally recognized as the main source of human intake of PCDD/Fs and dioxin-like polychlorinated biphenyls (PCBs) [27], and taking into account that chronic exposure of humans to these compounds can lead to dermal toxicity, immunotoxicity, reproductive effects and teratogenicity, endocrine disrupting effects and carcinogenicity [28], food contamination caused by landfills is of great concern for public health.

This paper analyzes the potential environmental impact of dioxin release from a possible landfill fire. The landfill is located in the north of Italy where the waste is placed in compressed bales. The Austal2000 model system was applied, and two simulations were carried out (fire in the first eight days of January and in the first eight days of July), assuming constant dioxin emissions for eight days. The respective deposition values of PCDD/Fs and average air concentrations were estimated.

Experimental part

Methods

Site description and waste storage

In our study, the wrapped bales system has been widespread since the end of the 1990s, in anticipation of the construction of a planned incinerator. Today, because of the high efficiency of selective collection (SC), the quantity of residual municipal solid waste (RMSW) has decreased greatly, making its incineration economically unsuitable [29]. Solid Recovery Fuel (SRF) production and its external evaluation is the new strategy proposed for the waste management in the province where the case study is located [30].

The landfill site is approximately 38,600 m^2 and the maximum filling is approximately 18 m. The waste is placed in cylindrical wrapped bales, piled on top of each other. The average height and diameter of the bales are 1.20 m, the average volume is 1.4 m^3, and the average bulk density is 0.7 t m^{-3} [31].

Cylindrical bales are produced by a single mechanical press, which shreds, compresses and plastic-wraps the municipal solid waste (MSW). The shredded material is fed into a cylindrical chamber to reach the compression pressure required to achieve the required density value. The compression degree of the bale increases as the material is forced into the chamber. The tumbling and crushing expels the air rather than compressing it, therefore the oxygen content in the bale is minimized [32]. A high density polyethylene (HDPE) plastic net is introduced to fix the shape of the bale and to prevent the compressed material from expanding when the press is opened. When the press is opened, the bale is transferred to the wrapping unit, which is separated from the compression unit but integrated into the same machine. The bale is then wrapped with a Low Density Polyethylene (LDPE) film (fig. 1). Once the bale has been removed, a new cycle begins.

Fig. 1. HDPE plastic net wrapping (L); LDPE film protection (R)

The landfill contains only RMSW contained in bales with a good compression resistance and an elastic elevate capability. A quantity of 404,000 wrapped bales was placed, for a total of 384,608 t_{RMSW} [31]. The landfill was in operation between 1999 and May 2014.

Austal2000

Austal2000 [33] is a freely available atmospheric dispersion model based on a stochastic Lagrangian particle model for simulating the dispersion of air pollutants in the ambient atmosphere. Stochastic Lagrangian particle models assume that each source emits a large number of particles, and each particle follows a random path around the mean wind vector. This path is updated at each time step. The concentration distribution is determined by counting the number of particles in a given volume of air sampling and is expressed as mean values over the volume elements and time intervals.The main advantages of the Lagrangian particle model are that it largely reflects the natural phenomena involved in turbulent diffusion, and the method eliminates numerical diffusion [34]. The method always yields non-negative mass densities and is mass-conserving. It can be applied to any source geometry desired for any temporal behavior of a spatially variable source.

Stochastic Lagrangian particle models potentially follow the actual physics of air dispersion better than any other model. Hence, models of this type are very accurate and can be used up to long distances (thousands of kilometers) [35]. However, they are computationally very intensive, because tens of thousands to millions of particles need to be considered for each source, making this model only practical when there are a small number of sources.

The Austal2000 model was chosen for the simulations as it is suitable for point sources and because it takes into account the topography influence on wind field and then on the pollutant dispersion (essential in this case study because the landfill is located at the bottom of a closed valley). Austal2000 also offers a high degree of spatial detail (the domain is small and the accuracy is essential) and represents the state of the dispersion.

Austal accounts for turbulence, building effects, and terrain influence however it is limited to the dispersion of neutrally buoyant or light gases. The calculation of three-dimensional wind fields in terms of the terrain profile and/or buildings, is carried out by the diagnostic wind field model TALdia [36].

Austal2000 works non-interactively. Before the calculation, all input data must be provided in the project directory and the calculation process is logged to a log file. The calculation is carried out in a Cartesian coordinate system, where the x-axis runs from West to East and the y-axis from South to North. The calculation grid is a rectangular shape with constant cell size in the horizontal and increasing cell size in the vertical (z-axis) [33].

The following input files are required:

- *austal 2000.txt* with the calculation domain information and emission sources.
- *dtm.asc* with digital terrain model descriptions.
- For time-dependent emission parameters: time series of parameter values in *series.dmna*.

The substance and their properties are defined in the settings file of Austal2000 (*austal2000.settings*).

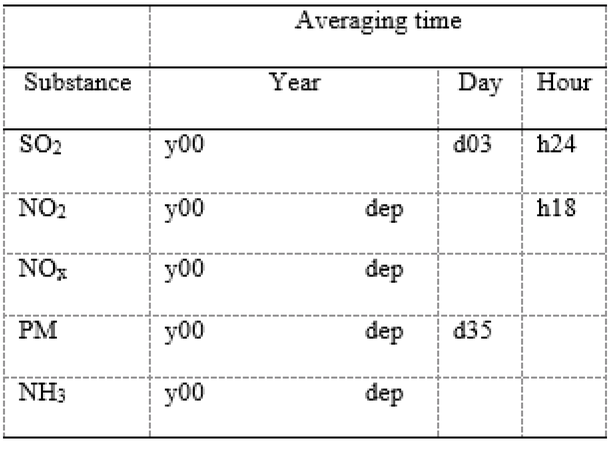
The model was applied to a region of 27.29 km^2, its center being the barycenter of the landfill area. The cell size was 50 m and the period of the application was a full calendar year (2013), which, within the framework of the current study, was considered sufficient for presenting the variability in meteorological conditions of the region with sufficient accuracy. Eight days is the assumed duration of the fire, which is the hypothetical time required to burn all the deposited waste. Two simulations were carried out: in the first eight days of January and July, respectively. Two different scenarios were chosen, due to the different climate conditions - atmospheric stabilities and temperatures - therefore, different capacities to disperse pollutants.

The source, constituted by the landfill, was simplified with a rectangle with an area of 0.04 km^2. Since it is not realistic to consider the simultaneous burning of the whole landfill, the original source was divided into four identical parts, with another starting two days after the first fire. A total of eight days were thus considered, taking into account the extension of the landfill and the propagation time of a fire inside a mass of waste [3].

The results of the dispersion calculation were separated in terms of the different substances. The types of results written out depend on the types of limit immission values for the given substance. The following table gives an overview of the applicable types.

Table 1

TYPES OF RESULTS FOR SOME SUBSTANCE BY WAY OF EXAMPLE



	Averaging time		
Substance	Year	Day	Hour
SO_2	y00	d03	h24
NO_2	y00 dep		h18
NO_x	y00 dep		
PM	y00 dep	d35	
NH_3	y00 dep		

In this case study Particulate Matter (PM) was considered because PCDD/Fs cannot be taken into account directly in Austal2000. The amount of input dioxins was then treated by the model as particulate matter, whereas dioxins adsorb on PM. Annual mean concentration and annual mean deposition were also analyzed.

Model input data

Austal2000 requires at least three different kinds of input data: meteorological, topographical, and emission [37]. The acquisition and pre-processing of meteorological data is of crucial importance for atmospheric dispersion modelling [33]. The meteorological data required for the chosen dispersion model includes ind speed, wind direction, and information on the atmospheric stability conditions (i.e. turbulence), which were derived from other meteorological parameters, such as humidity, temperature and wind speed profiles, as well as cloud covering or solar radiation. Austal2000 can input a 3D dataset of meteorological information. This model computes dispersion coefficients internally with various refined parametrizations using imported values [38]. Meteorological data were obtained from one single meteorological station, which was located in the same valley.

The spatial domain of the simulations was chosen in order to include all the emission sources to be studied, as well as the receptors that were believed to be affected by the emitted dioxins, and their geographical coordinates, i.e. latitude and longitude, both in the Gauss Kruger System, were indicated.

In terms of the dispersion simulation of dioxins the pollutant concentration was not enough, also the air flow associated with the dioxin source needs to be accounted for. Emission estimates of PCDD/Fs were based on the emission factors adopted from the technical literature [4,39]. The studies examined in the literature did not consider the coverage of the waste mass. In our case study, capping was considered to be negligible [40].

We used the values reported in Nammari et al. [4] for the dioxin concentration in smoke produced by the combustion of two eco-bales. This concentration was multiplied by the rate of the smoke flow, thereby obtaining the emitted dioxin (g_{TEQ} s^{-1}) from the combustion of two eco-bales. The result was then applied to the total landfill waste, which was divided into equal four parts for ease of use. From the waste mass, derived from the known volume and density, the smoke flow was calculated:

$$Q = m_{waste} / m_{experience} \cdot Q_{experience} \quad (1)$$

where:

Q is the estimated smoke flow from the chosen landfill [Nm^3 h^{-1}]

m_{waste} is the waste placed in the chosen landfill [kg]

$m_{experience}$ is the waste mass [kg] [4]

$Q_{experience}$ is the smoke flow [Nm^3 h^{-1}] [4]

The hourly dioxin emission was obtained by multiplying the smoke concentration by the estimated smoke flow and dividing it all by 3600 in order to obtain g_{TEQ} s^{-1}:

$$E = C_{experience} * Q/3600 \quad (2)$$

where E is the estimated emission of dioxins from the landfill [g_{TEQ} s^{-1}] and $C_{experience}$ is the dioxin concentration taken from Nammari et al. [4] [ng_{TEQ} Nm^{-3}].

We focused on the dioxin concentration and flow of the emitted smoke. The fire duration was not considered, therefore the results obtained from Nammari et al. [4] were combined with the test of Lemieux et al. [39], which calculated open burning as an emission factor.

The total amount of emitted dioxins was calculated by multiplying the estimated emitted dioxins from the chosen landfill by fire duration (eight days) expressed in seconds:

$$D = E * 8 * 24 * 3600 \quad (3)$$

where D are the dioxins from fire from the chosen landfill [gTEQ].

The emission factor was calculated by dividing the emitted dioxins by the waste placed in the chosen landfill:

$$B = D / m_{waste} \quad (4)$$

where B is the calculated emission factor.

The dioxin emission considered in the Austal 2000 simulations was calculated by multiplying the estimated emitted dioxins from the chosen landfill [g_{TEQ} s^{-1} calculated with Nammari et al. (2004) results] by the emission [39], and dividing it all by the calculated emission factor:

$$P = (E \,.\, \Lambda) / B \qquad (5)$$

where P is the dioxin emission [g_{TEQ} s^{-1}] and A is the emission factor [39].

Results and discussions

The computational domain is an area of 5,355x5,102 m^2, which includes the chosen landfill (represented in all the maps by a rectangle with black border). Figure 2 shows the PCDD/F deposition map obtained with Austal2000, assuming a fire in the first eight days of January. It represents the deposition caused by the 8-day long event, averaged over 365 days, which was the whole period of the simulation. The analysis shows that the higher deposition values are in and around the landfill. Moving away from the landfill, the amount of dioxin deposited decreases. Lower values are on the western side of the landfill. The deposition values are from 0.0 pg_{TEQ} $m^{-2}d^{-1}$ to 19,930 pg_{TEQ} $m^{-2}d^{-1}$. Most of these values considerably higher than the deposition guide value of 1.4 pg_{TEQ} $m^{-2}d^{-1}$ [41], calculated from the diet of people living in an Alpine region of Italy and from the WHO guide value for the tolerable daily intake (TDI) [41].

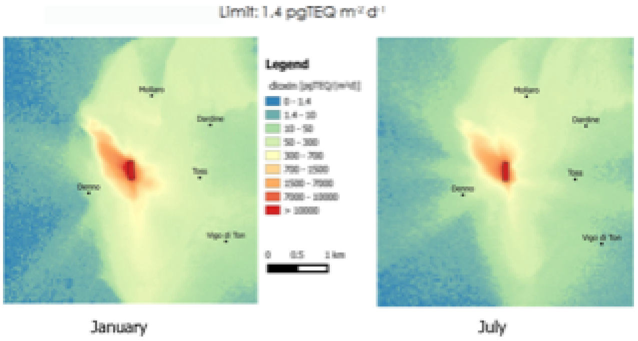


Fig. 2. PCDD/F deposition map (fire in the first eight days of January and July).

January and July have different atmospheric stabilities. The simulation of fire in July is less burdensome because the air turbulence is greater, therefore the deposition values are lower, between 0 pg_{TEQ} $m^{-2}d^{-1}$ and 14,410 pg_{TEQ} $m^{-2}d^{-1}$ (fig. 2). The estimated production of dioxin from the stored bales of the chosen landfill, considering an 8-day long fire, is about 0.035 kg_{TEQ}.

On July 10, 1976, the rupture of a bursting disc on a chemical reactor in Seveso (Italy) (from which the specific technical discipline related to the risks of relevant accidents originated) resulted in the highest known residential exposure to PCDD/Fs. According to the Agency for Toxic Substances and Disease Registry's estimates, about 1.3 kg_{TEQ} were emitted [42]. Even today the effects of the Seveso accident persist, thus the potential dioxin emission from the chosen landfill would have devastating environmental consequences.

Figure 3 shows the PCDD/F concentration map obtained with Austal2000, assuming a fire in the first eight days of January. It represents the concentration caused by the 8-day long event, averaged over 365 days.

The analysis shows that the higher concentration values are in and around the landfill. Moving away from the landfill, the concentration of dioxin decreases, in accordance with the deposition results. The concentration values are from 0.0 pg_{TEQ} m^{-3} to 76.85 pg_{TEQ} m^{-3}.

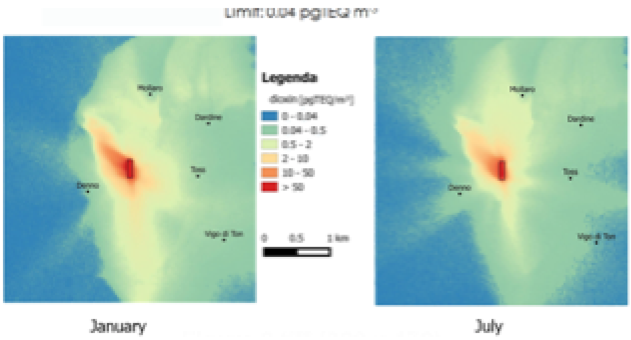


Fig. 3. PCDD/F concentration map (fire in the first eight days of January and July)

Italian regulations require dioxin limits only for reclaimed soils [43], not for air. For comparisons and evaluations, the value proposed by the National Technology Advisory Commission of 0.04 pg_{TEQ} m^{-3} can be used [44]. This guide value is exceeded in most of the domain, and near the landfill the limit value is exceeded by up to 2000 times.

Although the domain is relatively small, the dispersive action of wind is evident in the July simulation. Indeed the concentration values are lower, between 0 pg_{TEQ} m^{-3} and 54.63 pg_{TEQ} m^{-3} (fig. 3). The western area of the landfill is the exception in terms of the wind direction.

Conclusions

Baling as a storage methodology is becoming increasingly popular among waste management companies. In spite of that the combustion behavior of MSW bales has been rarely studied. Thus, the potential environmental impact of dioxin release resulting from a hypothetical fire in a landfill where the waste is stored in wrapped bales was estimated in this paper. Our main conclusion is that the chosen landfill is a potential source of dioxins that should not be underestimated. Indeed the simulations with Austal2000 showed that PCDD/F guide values, for deposition and concentration, would be exceeded alarmingly in case of fire. The effect on the territory could be similar to a small *Seveso*. Thus the landfill should be recovered, despite the very high costs involved. Recovered bales could be treated to be converted into Solid Recovered Fuel.

More in general our work demonstrates that the baling strategy should be accompanied by a particular attention to fire prevention. As PCDD/F emissions depends also on the amount of MSW baled, its storage should be limited in time and volume. The methodology adopted in this paper could help decision makers to set these criteria case by case.

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