Health risk assessment from combustion of sewage sludge: a case-study with comparison of three sites

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Abstract: This paper analyses some aspects of the steps to be developed for the assessment of the health risk from combustion of sewage sludge (after thermal drying). In order to choose the best localization for a sewage sludge combustion plant, three sites were considered in this case-study. The steps analyzed are: site characterization, plant characterization, modeling of emissions to the atmosphere, health risk assessment, role of sludge transportation. The role of the background characterization of the best site in term of unconventional pollutants presence is discussed too.

Key-Words: combustion, health risk, heavy metals, human exposure, PCDD/F, waste-to-energy

1 Introduction
Combustion of waste is one of the options available for waste management. In the European Union (EU) this option can be implemented for the treatment of the waste that is not viable for reduction/reuse/recycling. The EU criteria for waste management and the international economical crisis will affect the trend of waste generation: after many decades showing an increasing rate of waste generation, in a few countries the yearly overall amount has shown a decrease. This phenomenon is not common to all the streams of waste. In fact, there is a special waste that is more and more growing in the EU: sewage sludge. The expected increase of sewage sludge generation in EU depends on two phenomena:
a) in countries as Italy, Germany, Austria, etc. with an old tradition in the sector of wastewater treatment plants (WWTPs), the need of complying with more and more enhanced regulations (i.e. with more and more stringent limits at the discharge) is going to generate increasing amounts of sludge as a result of more efficient treatments;
b) in countries recently entered into the EU (for instance Romania and Bulgaria) the structural funds available for a few years are supporting the implementation of new WWTPs with a new generation of sewage sludge.
Few years ago, solutions as landfilling (of thermal dried sludge), composting and direct application on land were considered viable options in all the EU countries. Today the sector is going quickly towards a crisis as sludge is no longer accepted for landfilling (because of its biodegradability) and its application on land (direct or indirect) is more and more suspected to be hazardous for hygienic aspects. As a consequence of this situation, the problem is faced with according to two principles: minimizing and/or thermally destroying.
Sludge minimization is widely studied in the research fields, but in real scale only few plants can be visited. It must be pointed out that the minimization of sludge does not solve the overall problem. Its adoption must be made taking into account a strategy for the remaining sludge. Thermal treatment at high temperature can be made either by conventional or by innovative options. In the first case combustion is the typical approach. In the other case solutions of pyrolysis / gasification are fascinating but only few plants have been implemented in real scale.
Apart from the problem of the choice of the most suitable process for sewage sludge thermal treatment, an important aspect concerns the identification of the site suitable for its implementation. To this concern, the present paper analyses some aspects of the steps to be developed for assessing the health risk from combustion of pre-dried sewage sludge (thermal pre-drying is compulsory in order to obtain a water content suitable for direct combustion). In order to choose the best localization for a sewage sludge combustion plant with a lower impact, in this paper three sites were proposed.

2 Materials and methods
2.1 Sites characterization
In all the three sites (A, B, C) a wastewater treatment plant is already present. Site A is characterized by high population density, a complex road network and a wide production area. Today the sector is going quickly towards a crisis as sludge is no longer accepted for landfilling (because of its biodegradability) and its application on land (direct or indirect) is more and more suspected to be hazardous for hygienic aspects. As a consequence of this situation, the
emissions, industrial activities and domestic heating especially regarding nitrogen oxides. Yearly background concentrations are 48 µg m\(^{-3}\) for NO\(_2\) and 31.5 µg m\(^{-3}\) for PM\(_{10}\).

**Site B** is also located in a valley, at the confluence of three mountain valleys. In winter, thermal inversion is frequent and persistent, resulting in stagnation and poor ventilation. Site B is characterized by high population density, a complex road network and a wide production area. Air quality is strongly influenced by traffic emissions. Regarding PM\(_{10}\), there is the high number of overrunning of the daily average of 50 µg m\(^{-3}\). Background concentrations are 35 µg m\(^{-3}\) for NO\(_2\), and 36 µg m\(^{-3}\) for PM\(_{10}\).

**Site C** is located in a wide valley, oriented in North-South direction. In winter, thermal inversion is frequent and persistent, resulting in stagnation and poor ventilation. Site C is characterized by medium population density, a complex road network and a lot of small industrial activity. Even if this is a rural area, air quality is influenced by emission from the neighboring areas.

### 2.2 Multidisciplinary approach

In order to assess the health risk for the population exposed to the emissions from a plant, a multi-step modeling chain must be implemented. The overall approach is shown in Figure 1.

In this case study, emissions from a sewage sludge combustion plant (fluid bed) have been taken into account. As no official design was available, the average concentrations of each pollutant have been taken from an existing plant having similar characteristics. Apart from the pollutants concentrations at the stack, some design parameter have been preliminarily set: height of the stack, off-gas temperature at the stack, off-gas velocity at the stack. Of course, the flow-rate of the off-gas from combustion has been calibrated taking into account the amount and the composition of sewage sludge in the region of the case-study.

The dispersion of pollutants was assessed through the use of the Industrial Source Complex dispersion model (ISC). ISC model was developed and implemented by U.S. EPA; it is a 3-D stationary Gaussian model, based on convention-diffusion equation, taking into account weather conditions and topography.

This model can be applied for preliminary comparisons as requested for this case study. Deeper analyses can be developed changing the model depending on the amount of available data for the characterization of the case study and on the target of the Health Risk Assessment (HRA): generally the deepest analysis is performed when a tender has allowed choosing a winning proposal (with a detailed design).

In the presented case-study a squared area (10 km x 10 km), centered on the stack has been analyzed. Air concentrations at ground level and ground deposition due to emissions of particulate matter (PTS), carbon monoxide (CO), nitrogen dioxide (NO\(_2\)), sulfur dioxide (SO\(_2\)), HCl, HF, NH\(_3\), PAH, dioxins and furans (PCDD/F) and heavy metals (As, Cd, Cr, Cu, Hg, Ni) have been assessed. The obtained geo-referenced maps are overlayered with maps of population density and maps of use of soil. This overlaying is the base for crossing information on carcinogens concentrations / depositions and characteristics of the area in order to develop a HRA.

A HRA is a report developed to describe the potential a person or population may have of developing adverse health effects from exposure to the emissions of a plant. The pathways that can be included in a HRA depend on the toxic air pollutants that a person (receptor) may be exposed to, and can include breathing, the ingestion of soil, water, crops, fish, meat, milk, and eggs, and dermal exposure [1].

Once the concentrations of the substances of interest, related to the amounts emitted from the studied source, are estimated in air, soil, water, plants, and animal products, they are used to evaluate an estimated exposure to people related to the plant to be studied. Exposure is evaluated by calculating the lifetime average daily dose (LADD). The international literature has developed specific algorithms for calculating this dose for exposure through inhalation, dermal absorption, and ingestion pathways.

Dose-response assessment describes the quantitative relationship between the amount of exposure to a substance (the dose) and the incidence or occurrence of an adverse health impact (the response).

Risk characterization is the final step of the health risk assessment. In this step, information developed through the exposure assessment (e.g., modeled concentrations, inhalation or oral doses, and exposure pathway information) is combined with cancer potency factors and Reference Exposure Levels (RELs) to quantify the cancer risk (and non-cancer health impacts, respectively).

For non-carcinogens, dose-response information is presented in the form of RELs. RELs are concentrations or doses at or below which adverse effects are not likely to occur following specified exposure conditions.
For carcinogens, the toxicity criterion, or health guidance value, is the cancer potency slope (potency factor), which describes the potential risk of developing cancer per unit of average daily dose over a 70-year lifetime. Cancer risk is calculated by multiplying the dose by the cancer potency factor to yield the potential excess cancer risk. Generally, in case of areas with a significant density of population, a plant is assumed to have an acceptable impact when the potential excess cancer risk is lower than \(10^{-6}\) (individual risk).

Traffic emissions have been taken into account with a different approach. Trucks bring dewatered sewage sludge from the WWTPs to the combustion plant site. Traffic emissions have been estimated using the COPERT model [2]. The model predicts emission factors according to the characteristics of the trucks (age and weight) and to the driving conditions (speed and road slope). This approach allows developing pollution balances.

3 Results and discussion

3.1 Results

To compare the results obtained in three different sites, a dilution factor can be used, defined as the ratio between the maximum annual average concentration (point of maximum impact) and the off-gas flow from the stack (g s\(^{-1}\)). As reported in Table 1, site C has the lower value, that represents the best dilution of pollutants.

<table>
<thead>
<tr>
<th>Site</th>
<th>Dilution factor [s m(^{-3})]</th>
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<tbody>
<tr>
<td>Site A</td>
<td>9.44 (\times) 10(^{-6})</td>
</tr>
<tr>
<td>Site B</td>
<td>1.59 (\times) 10(^{-5})</td>
</tr>
<tr>
<td>Site C</td>
<td>3.08 (\times) 10(^{-6})</td>
</tr>
</tbody>
</table>

Pollutant concentrations caused by the plant in the point of the highest impact have been assessed for each site. The comparison referred to different intervals of emission are reported in Figure 2 and 3. Of course the absolute values of increment of concentration can be compared to the regulation for the air quality.

The importance of the interval of assessment of the pollutant concentration depends on the characteristics of the pollutant and on the regulation. \(\text{NO}_2\) concentration is important as yearly concentration and hourly concentration: the regulation set values for both the cases. Chromium (VI) is a carcinogen important for the pathway of inhalation, thus the interest in this case is for knowing the concentration in air on yearly base.

Regarding other pollutants, the annual average deposition to the ground has been assessed and compared in Fig. 4.

The annual deposition is useful for assessing the impact of carcinogen pollutants having effects through pathways different from inhalation. In this case the calculation has been based on the collection of data on population distribution and use of land. Concerning this last case a critical aspect is the setting of a coefficient of local consumption of agricultural products. Considering the aim of this preliminary comparison study, the percentage of local consumption has been set equal to 10\%. It must be pointed out that the final result of the HRA is very sensible to this coefficient.
More in general the output of the HRA is (for each site) a high number of maps and resuming calculations. Each map has data calculated referring to a pre-defined grid: in the presented case the mesh is 50m x 50m, giving a total of 40,000 meshes in the studied area. For each mesh, calculations of health risk for each pollutant and each pathway of exposure are available. In Fig.5 an example of map is reported: each side measure 10 km; the chromatic scale refers to the highest health risk among the three sites for one of the pollutants of interest. Data about population location and use of land are not reported in Fig.5, but are available for the same area.

The total individual risks assessed for each site overlying dozens of maps (depending on the overall amount of pollutants taken into account) resulted lower than $10^{-6}$, with some differences from site to site. Differences depend strongly on the use of land: the influence on the local diet, depending on the interaction with agriculture, gave the most important contribution in the calculation of the risk. Concerning sludge transportation, in Fig.6 the comparison among the three sites is reported.

3.2 Discussion
The above results suggest the following considerations:

- The development of the overall approach needs integrated competences: the approach is strongly interdisciplinary.
- The emissions concentrations to be used as input of the modeling chain can be related to operating conditions (the presented case), guaranteed conditions (in case of a tender), authorized conditions (equal or lower than the regulation emission limits); in case of operation conditions the set of pollutants can be more completed than the case referred to the authorized case; this contradiction depends on the fact that some parameters in the regulations are assumed as a sum (for instance, some heavy metals taken into account as a sum); the adoption of the presented modeling chain in this case must be adapted with the introduction of a few hypotheses.
- The design step can be optimized using the dispersion model with different sets of parameters (stack characteristics, emissions to be guaranteed, etc.). For instance the optimization of the height of the stack is one of these results. The importance of this aspect is often underestimated giving plants that can have a high impact even if the stream of pollutants released into the atmosphere seems to be not relevant.
- The transportation role has been studied in terms of pollutant balance as the three sites are far from residential areas. More in general in case of proximity of population to the roads used from the trucks, a deeper analysis must be developed in order to assess the health effect induced (in particular the role of nitrogen oxides must be analyzed).
- It must be pointed out that an additional result of a transportation analysis can be the assessment of mortal accident risk related to the overall mileage from the trucks. This risk can be compared with the risk calculated by the HRA.
- The comparison of the three sites by the presented approach gives to the decision makers a lot of information and parameters in order to find the best solution. An additional aspect must be taken into account anyway: the implementation of a new combustion plant gives and additional load of pollutants on an area with a pollution level of background that in general is known for macro-pollutants. Unconventional characterizations of PCDD/F in soil and other micro-pollutants) must be planned in order to check if the soil is not in critical conditions and in order to generate a background data-base useful for future comparisons, when the plant will be operating. This characterization requires a specialized laboratory with a know-how also in terms of sampling for unconventional characterization.
The sum of the effects of each pollutant has been assumed linear. This hypothesis can be assumed in case of low concentrations of pollutants (as in the case-study). In case of high concentrations of carcinogens it could be necessary a deeper analysis.

An aggregated result about the potential excess cancer risk is a preliminary information on the effects of the plant. After a site comparison a more detailed analysis must be developed.

Hazard identification entails the identification of potential adverse effects associated with exposure to the agent. A major source of uncertainty comes from the fact that in the human environment, agents are usually, if not always, encountered in combination with untold numbers of other agents, rather than in the pure form in which they have been studied in most clinical or toxicological experiments. Furthermore, because individuals vary in susceptibility on the basis of differences in genetic background, age, gender, physiological state, diet, lifestyle, health habits, histories of smoking and occupational exposures, and other variables, a risk assessment that is based on the distribution of a risk within a particular population cannot be assumed to apply to any given individual in the population or to any other population as a whole. The answer to this problem come from the predictive toxicology that is clearly an interdisciplinary science with contributions from chemistry, biology, and medicine as well as statistics and computer science.

4 Conclusions
The HRA of the emissions to air of a sewage sludge combustion plant can be performed by a multidisciplinary approach. The same approach can be adopted for other punctual sources as MSW incinerators, cement works, thermal power plants, etc.

A few steps of this approach need a particular attention as the overall assessment is sensible to some parameters (for example the percentage of local consumption of agricultural products).

An important role is played by unconventional characterizations of PCDD/F in soil (and other micro-pollutants). This characterization must be planned in order to check if the soil is not in critical conditions. Additionally a background data-base is useful for future comparisons, when the plant will exist.

One of the problems still open in this field concerns the need of a deeper analysis on how individuals vary in susceptibility: the predictive toxicology can give an important contribution to this concern.

Another topic that has to be still studied in details is the role of the combination of agents.

More in general an improvement of the presented approach seems to need a strong cooperation between expert of many sectors: from the environmental chemistry, to the physics of the atmosphere, to the fluid-dynamics, to the sanitary engineering, to the predictive toxicology.

Finally, the presented paper refers to a case-study of comparison among three sites in order to check their suitability for the implementation of a new thermal treatment plant. The aim of the Authors has been the presentation of the overall approach, pointing out the modeling chain necessary for its development and the perspectives given by the predictive toxicology. The specific results are of secondary importance, thus the presentation of the results not in term of absolute values, but in terms of comparison has been preferred.

References: