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Criteria for the Assessment of Health Risk from a Waste Gasification Plant

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Abstract **– In mountainous regions, the atmospheric dispersion of air pollutants is limited by complex terrain morphology. Trentino (a province located in the Italian Alps) is characterized by a high population density, highly developed agriculture and farming, and the presence of civil and industrial activities, whose emissions tend to be trapped inside the valleys. These conditions translate into exposure levels that are potentially higher than other geographical contexts (e.g., flat or coastal regions). The academic research carried out in Trentino since 2005 has produced a series of publications on topics related to the risk for health derived from waste management and other activities. These publications has focused on: 1) the evaluation of the emissions of organic pollutants from the waste sector; 2) the monitoring of persistent organic pollutants (POPs) in various environmental matrices; 3) a methodology to carry out a comprehensive health risk assessment considering all the relevant exposure routes in an area; 4) the role of the local diet in the exposure of a population to POPs; 5) methodologies to define new regulatory limit values for dioxin and hexavalent chromium; and 6) the role of dispersion modeling in assessing the exposure to air pollutants. The present paper will review these publications and provide a reference document to evaluate new project proposals that require a health risk assessment and facilitate the work of proponents, clarifying the requirements of a health risk assessment. The paper will refer to waste gasification, but the considerations expressed in this paper may apply to other activities.**

Keywords **– Air pollution; cancer risk; dispersion modeling; emissions; exposure; hexavalent chromium; persistent organic pollutants (POPs).**

Nomenclature	
MSW	Municipal Solid Waste
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyls
PCDD/Fs	Polychlorinated dibenzo-p-dioxins and furans
POPs	Persistent Organic Pollutants
rMSW	Residual Municipal Solid Waste
VOCs	Volatile Organic Pollutants

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WtE	Waste to Energy

1. INTRODUCTION

Mountainous regions are characterized by complex topography that makes anthropic activities and built-up areas coexist at valley bottoms, which are the most favourable zones for human settlements. The proximity between population and anthropic activities makes valley bottoms geographical contexts that favour the contact between the air pollutants released by human activities and the population. In addition, the dispersion of the air pollutants emitted in valleys is affected by peculiar conditions that are typical of mountainous areas, i.e. the formation of valley/slope winds, favoured by different heating and cooling conditions between valley bottoms and slopes, due to the different levels of exposure to solar radiation [1]. Such conditions favour the stagnation of air pollutants near the ground in valley bottoms and potentially increase the human exposure to air pollutants compared to more favourable geographical situations [2]–[4]. Besides industrial activities, an additional element that concurs to increase the human exposure to air pollutants is biomass burning. The use of wood and pellet for domestic heating has been recently appointed as the main contributor of organic particulate matter (80–90 %) in the French Alps [5]. Biomass burning is widely adopted as heating system in rural areas of the Alps as well as other areas characterized by cold winters, especially because it is cost-effective compared to other fuels or heating systems [6], [7]. Though carbon-neutral, the combustion of wood-based biomass generates a large variety of air pollutants. Biomass burning in single household stoves, rather than in centralized biomass burning stations, produces higher amounts of PM, volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), even with respect to fossil fuels [8]. This further increases the level of exposure in mountainous regions.

Like every populated area, mountainous regions generate waste that must be disposed of. In Europe, the recent requirement of limiting the landfilling of municipal solid waste (MSW) to 10 % of the total MSW generated by 2035 [9] indirectly assigns a crucial role to direct and indirect waste combustion processes, like incineration and gasification, whose main aims are the reduction of the volume of residual MSW (rMSW) and energy recovery. Following this regulation, the number of thermal waste-to-energy (WtE) plants may increase in the next decade.

Among WtE technologies, gasification has proved to be economically preferable to incineration at a medium-small scale (<100 000 t/year of input waste) and is expected to be more flexible in terms of input waste, since advances have been achieved to avoid rMSW pre-treatments (e.g., conversion to refuse-derived fuel or solid-recovered fuels) before gasification [10]. Lower environmental impacts are expected compared to incineration and pyrolysis, respectively in terms of the emissions of polychlorinated dibenzo-*p*-dioxins/furans (PCDD/Fs) and nitrogen oxides, and because no solid fuels are burnt during the process. However, as large combustion plants, waste incinerators (direct combustion plants) and gasifiers with in-situ syngas burning (direct combustion plants) generate high emission rates of air pollutants whose compatibility with the presence of population must be carefully assessed, especially in problematic areas like mountainous regions. Indeed, the contribution of waste combustion to the release of air pollutants would add to the other emission sources.

Although the release of air pollutants from direct/indirect waste combustion has been considerably reduced in the last decades (in particular regarding PCDD/Fs), the unfavourable conditions of mountainous regions demand caution when carrying out an environmental impact assessment of a new proposal. This sensitivity has emerged since 2005 in a region located in the Italian Alps (Trentino), when the local academic community started writing a series of scientific papers on the environmental and health risk impacts of waste management activities. The reasons for this intensive research on environmental monitoring and modelling, exposure assessment methodologies, environmental modelling, health risk assessment and, in general, new criteria for environmental impact assessment can be explained with recent environmental issues that have involved this region.

First of all, the area of Trento was affected by a serious event of aquifer contamination in the 1970s, due to leakage of tetraethyl lead from a local company [11]. This caused the outbreak of mental and neurological issues in children in the following years and raised the awareness of the local community towards environmental preservation. In addition, this area is crossed by a strategic communication route, namely the Brenner highway, which is part of the European E45 route and connects northern Italy with Austria and Germany through the Alps. This highway contributes to about 25 % of the emissions of nitrogen oxides in the region and generates mean annual ambient air concentrations of nitrogen dioxide that exceed the European limit value of 40 $\mu g/m^3$ [12]. For this reason, this highway was the object of a recently concluded European project (EU-Life BrennerLEC), aimed at developing strategies for the dynamic management of traffic in response to meteorological conditions that may favour the stagnation of air pollutants within the valley crossed by the highway [13]. Furthermore, this area hosts a steel plant that was the object of worries and complaints by the local population and an association of medical doctors regarding the emission and deposition of POPs. In 2011, the Province of Trento decided to activate a group of experts to clarify the role of the plant. Finally, in 2009, The Province of Trento has studied the possibility of installing an MSW incinerator in its territory. However, due to the complex orography of the area, the high population density and the presence of several existing sources of air pollutants, this idea had to face the opposition of politics and citizens, leading to different versions of the project proposal that were not considered as environmentally and economically sustainable.

The present paper has a double aim: 1) to provide environmental assessors with a reference document to evaluate new project proposals of waste gasification plants with in-situ syngas burning and 2) to facilitate the work of proponents, clarifying the requirements of a comprehensive health risk assessment supporting their proposals. The reference document will recall the series of studies published in Trentino, which will be used as a guide to highlight critical aspects of a correct health risk assessment.

Waste gasification is considered as the reference WtE process in the present paper, due to the limited size of Trentino in terms of served population (about 500 000 inhabitants) and rMSW produced (about 62 100 t/year), which is anyway typical of the whole Alpine region. However, the considerations that will be made in the present paper can be applied to other waste management processes and, in general, industrial activities requiring a health risk assessment for their approval.

2. METHODS AND METHODOLOGY

Since 2005, a total number of 23 peer-reviewed publications were identified as written by authors affiliated to the University of Trento (Italy) on the main topic of the environmental impacts related to waste management and other activities characterized by similar emissions, in both qualitative and quantitative terms. The publications are indexed in the Scopus database and were organized according to their subject in the following six topic categories:

- emissions of organic pollutants from the waste sector;

– monitoring of persistent organic pollutants (POPs) in different environmental matrices;
– health risk assessment procedure;
– role of the local diet in the exposure to POPs;
– methodologies to define new regulatory limit values;
– atmospheric dispersion modeling.

The complete list of publications is reported in Table 1. Publications are divided according to their respective topic category. Most publications belong to the topic category 'Monitoring of POPs in different environmental matrices', followed by 'Emission of POPs from the waste sector', 'Health risk assessment procedure', 'Atmospheric dispersion modeling', 'Role of the local diet in the exposure to POPs' and 'Methodologies to define new regulatory limit values' (Fig. 1).

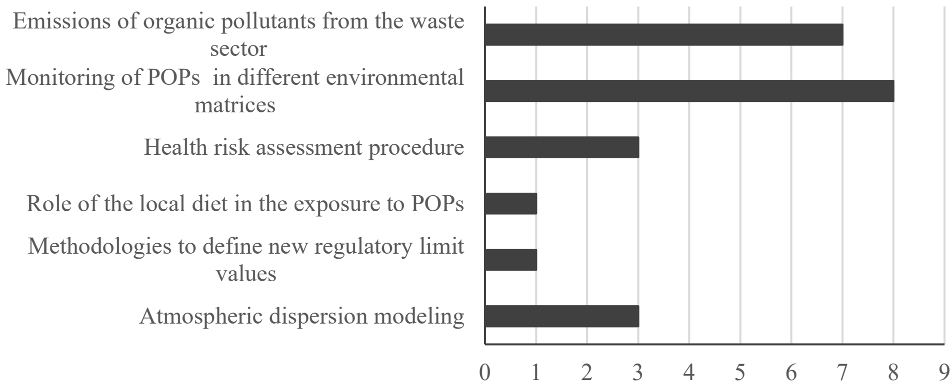

Fig. 1. Number of publications considered in the present paper according to their topic.

3. Results

3.1. Emissions of organic pollutants from the waste sector

The emission of POPs from the waste sector has often been associated with thermal WtE plants. Although thermal WtE processes must be regarded as concerning sources of air pollutants, some publications have pointed out that other waste management processes, if not optimized and not equipped with adequate air pollution control technologies, may induce significant health impacts nearby. This is the case of mechanical-biological treatments (MBTs) like MSW bio-drying, whose potential contribution in terms of PCDD/Fs has been studied in Trentino since 2005 [14]. PCDD/Fs are not generated during MBTs but are already present in the incoming waste and stripped by the process air used to dry MSW. A first quantification of the PCDD/F emission factor from MSW bio-drying was carried out in another publication [15], resulting as 8 pg I-TEQ kg^{-1} of volatile solids of MSW. This emission factor was derived by an experiment made on a pilot-scale bioreactor simulating bio-drying conditions. In this case, a sample of MSW produced locally was used. In another study, a pilot-scale experiment was carried out to investigate the emission factors of more than 20 volatile organic compounds from MSW bio-drying and the removal efficiency of biofiltration [16]. The study included the carcinogenic benzene, whose maximum emission factors was quantified as 8.85 µg kg^{-1} of MSW. In the same years, the role of anaerobic digestion in the emissions of PCDD/Fs was also investigated [17]. Trace emissions can be released both by biogas combustion in anaerobic digestion plants equipped with a combined heat and power generator and by anaerobic digestion processes occurring in MSW landfill and associated to biogas fugitive emissions.

A multi-step approach was elaborated to compare different WtE technologies in terms of emission factors and expected impact at ground level [18]. The steps are the following: 1) selection of the case study of an existing thermal WtE plant, including the results of dispersion modeling and a health risk assessment, preferably in an unfavorable location from the point of view of atmospheric dispersion; 2) retrieving of the characteristics of the primary emission source (stack) and calculation of the dilution factors for the regulated pollutants, i.e. the ratio between the maximum pollutant-specific concentration at ground level induced by the plant and its respective emission rate; 3) retrieving emission factors for the reference technology and of other technologies to be compared; 4) verification of the representativeness of the case study through a validation based on typical values for emission factors and emission source characteristics of WtE plants; 5) estimation of the maximum air pollutant concentrations/depositions at ground level from other technologies, based on the dilution factors calculated in step 2); 6) selection of reference values for ambient air concentrations (e.g., limit values); 7) comparison between the different technologies considered.

TABLE 1. LIST OF ACADEMIC PEER-REVIEWED PUBLICATIONS WRITTEN IN TRENTINO ON THE ENVIRONMENTAL IMPACTS OF WASTE MANAGEMENT AND OTHER ACTIVITIES CHARACTERIZED BY SIMILAR EMISSIONS

Topic category	Publication title	Ref.
Emissions of organic pollutants from the waste sector	Some research perspectives on emissions from bio-mechanical treatments of municipal solid waste in Europe	[14]
	Modelling of PCDD/F release from MSW bio-drying	[15]
	Material and energy recovery in integrated waste management systems: An innovative approach for the characterization of the gaseous emissions from residual MSW bio-drying	[16]
	Critical analysis of PCDD/F emissions from anaerobic digestion	[17]
	Multi-step approach for comparing the local air pollution contributions of conventional and innovative MSW 658 thermos-chemical treatments	[18]
	A critical analysis of emissions and atmospheric dispersion of pollutants from plants for the treatment of residual municipal solid waste	[19]
	Maintenance strategies and local impact of MSW incinerators	[20]
Monitoring of POPs in different environmental matrices	Management of atmospheric pollutants from waste incineration processes: The case of Bozen	[21]
	Characterization of metals in air and soil near a steel making plant in the North part of Italy	[22]
	Characterization of the PCDD/F in the Province of Trento	[23]
	PCDD/Fs in the soils in the province of Trento: 10 years of monitoring	[24]
	Assessment of the local role of a steel making plant by POPs deposition measurements	[25]
	Assessing the influence of local sources on POPs in atmospheric depositions and sediments near Trento (Italy)	[26]
	State of the art and advances in the impact assessment of dioxins and dioxin-like compounds	[27]
	Seeking Potential Anomalous Levels of Exposure to PCDD/Fs and PCBs through Sewage Sludge Characterization	[28]
	Methodology for the human health risk assessment from the thermoelectric plants	[29]
	A contribution for a correct vision of health impact from municipal solid waste treatments	[30]

Topic category	Publication title	Ref.
Health risk assessment procedure	Integrated methodology for the management of human exposure to air pollutants	[31]
Role of the local diet in the exposure to POPs	A proposal for a diet-based local PCDD/F deposition limit	[32]
Methodologies to define new regulatory limit values	A regulatory strategy for the emission control of hexavalent chromium from waste-to-energy plants	[33]
Atmospheric dispersion modeling	PCDD/F environmental impact from municipal solid waste bio-drying plant	[34]
	Atmospheric dispersion modelling with AERMOD for comparative impact assessment of different pollutant emission sources in an alpine valley	[35]
	Assessing the air quality impact of nitrogen oxides and benzene from road traffic and domestic heating and the associated cancer risk in an urban area of Verona (Italy)	[36]

Ionescu *et al.*, 2012 [19] summarize the pros and cons of different waste management treatments connected by integrated waste management schemes in terms of emissions of air pollutants. The best combination must be evaluated case by case, since atmospheric dispersion can strongly influence the expected impacts at ground level.

Finally, the effects of an appropriate scheduling of maintenance stops of a WtE plant were discussed [20]. Optimizing shut-down periods in the worst season of the year in terms of dispersion of air pollutants (winter) is expected to reduce the local impact of PCDD/Fs by about 23 % in the case studied by the authors. However, if a WtE plant feeds a district heating network, such conclusions must be carefully evaluated to avoid heating suspension in the area.

3.2. Monitoring of POPs in different environmental matrices

Since 2013, a group of publications has focused on the monitoring of POPs at both emission levels and in the environment. In a monitoring campaign carried out in 2013 on the rMSW incinerator of Bozen (the nearest incinerator to Trentino) [21], the short-term PCDD/F stack concentrations resulted as 10–80 % the emission limit value, i.e., 0.1 ng nm^{-3} expressed in the international toxic equivalent (I-TEQ) scheme, which is typical for modern incinerators. Concerning ambient air concentrations, which were measured with directional air samplers along the North-South direction around the plant, the authors found that the PCDD/F concentrations measured in areas downwind the plant were comparable with rural PCDD/F concentrations measured in summer. On the contrary, in areas upwind the plant and downwind the near town of Bozen, PCDD/F concentrations were significantly higher and influenced by other human activities. This study thus demonstrates the importance of monitoring campaigns coupled with numerical simulations to correctly characterize the situation before the construction of the plant, to simulate the incidence of the plant and to verify its contribution with the plant in operation.

A couple of publications focused on the characterization of the ambient air [23] and soil concentrations [24] of PCDD/Fs in Trentino, in view of the possible construction of a MSW incinerator. Although no significant source of contamination was found in air and soil samples, complete characterizations like these are extremely important to define the situation before the construction of a potential source of POPs, like a thermal WtE plant.

Along with air and soil sampling, atmospheric deposition sampling plays a crucial role in characterizing the contribution of civil and industrial activities in terms of air pollutants that may accumulate in the food chain. Steel-making plants are characterized by emissions that are similar to thermal WtE plants, being steel making a high-thermal process. In one paper [22], the continuous monitoring of heavy metal depositions around a steel-making plant, during operation and shutdown periods, allowed concluding that the contribution of this activity was not significant and that other activities in the area might have been responsible for the measured depositions. However, the paper revealed that diffuse emissions require attention, since the presence of the plant could be anyway detected in the surrounding area. The same plant was considered for the evaluation of the PCDD/F deposition in the area [25]. The authors observed that long-term deposition sampling and the comparison between the congener profiles of the depositions collected, and typical profiles of civil and industrial activities are useful to identify the primary source of POPs in an area and act accordingly with local provisions. Besides deposition sampling, the sediments of a pond were studied in the same years as a suitable environmental matrix to evaluate the contribution of different local sources to POPs and PAHs in the same area [26]. Analyzing the concentration of POPs and PAHs at different depths allows revealing if past events concurring to change the emissive contribution of a nearby industrial plant (e.g., shutdown/operation periods, adoption of improved air pollution control technologies) have positive/negative consequences on the local environment. Another publication suggests that the analysis of the PCDD/F content in dewatered sewage sludge may be an interesting method to quickly identify potential anomalous levels of exposure to POPs in the food chain [28]. Like the previous monitoring methodologies, sewage sludge analysis may be also used to characterize the population exposure before the construction of a potential emitter of POPs.

A comprehensive overview of PCDD/Fs and polychlorinated biphenyls (PCBs) was published in 2016 to present the toxic short-term and long-term effects associated with the exposure to these substances, the congener-specific toxicity parameters for non-cancer and cancer risk assessment according to the different classification schemes adopted over the years, the fate of PCDD/Fs and PCBs in the environment, their typical concentrations and the available limit and guideline values in environmental matrices, typical and emerging emission sources, exposure assessment modeling, conventional and unconventional monitoring and analytical techniques [27].

Fig. 2 illustrates a summary of the possible monitoring approaches for POPs that could be implemented in an Alpine valley.

3.3. Health risk assessment procedure

Preliminary discussions on the health risk assessment related to the emissions from WtE plants were made in 2008 and 2009 [29], [30]. A more detailed discussion on the preferred approach to follow in health risk assessment was presented in a later publication [31]. The methodology describes a multi-step approach that proponents can follow to adequately assess the relevant exposure route and pollutants, from the definition of the computational domain in dispersion modelling to the calculation of the exposure and the estimation of the cancer risk (for carcinogenic effects) and hazard index (for non-carcinogenic effects). The paper contains a step-by-step explanation of the necessary tasks to carry out a comprehensive health risk assessment, which can be applied to any activity, including of course MSW gasification. For more detailed explanations of the formulation for the estimation of contaminant concentrations in different environmental matrices (e.g., soil, vegetables and fruit), an in-depth guide is available in [27]. The paper also discusses the main limitations of the current approach, especially concerning a universal methodology to account for the dietary exposure to meat, dairy products and eggs. Specific formulations have been proposed in the last decades by different authors [37]–[39].

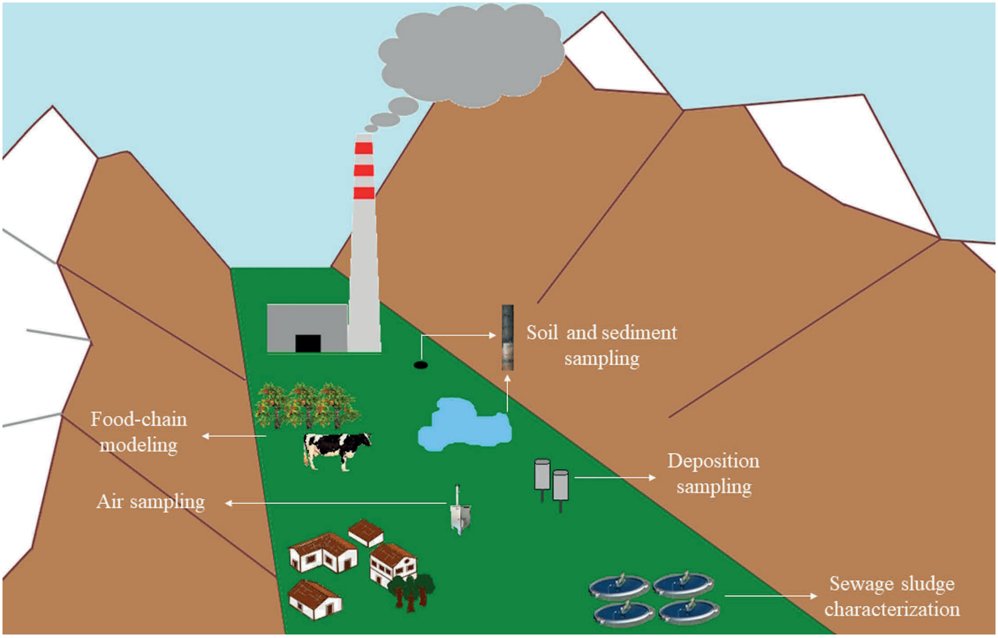

Fig. 2. Scheme of the possible POP monitoring approaches in an Alpine valley.

Besides illustrating the health risk procedure of the U.S. Environmental Protection Agency (U.S. EPA), the paper presents the approach to be considered to evaluate the non-carcinogenic effects of the exposure to macro-pollutants, following dose-response relationships based on local healthcare statistics. Based on this approach, it would be possible to account for externality costs related to hospitalization and mortality.

3.4. Role of the local diet in the exposure to POPs

POPs are able to accumulate in the fat tissues of animals and vegetables and contaminate the food chain. Ingestion is the primary route of exposure to POPs [40]. As mentioned above, the standard approach of the U.S. EPA is currently missing a clear methodology for the health risk assessment via dietary exposure to specific food products. In a publication written in Trentino [32], the authors developed a methodology to estimate the PCDD/F intake of a target population based on the local diet and verify the dominant contribution given by dairy products. A reverse food-chain model, based on the local diet, was developed to determine a PCDD/F deposition value that gives a tolerable dietary intake of PCDD/Fs according to the lower limit value of the range proposed by the World Health Organization (1 pg WHO-TEQ kg_{bw}^{-1} d^{-1}). This methodology could be applied to any context where statistics on food consumption, land use data and PCDD/F deposition measurements (as control reference) are available.

3.5. Methodologies to define new regulatory limit values

Besides the methodology presented in the previous section to define a deposition guide value to limit the exposure of a population to PCDD/Fs, a recent publication focused on the role of hexavalent chromium (Cr VI) from thermal WtE plants [33]. Cr VI is considered as an emerging contaminant in this sector, following the reductions in PCDD/F emissions achieved in the past decades. Compared to other heavy metals, the cancer potency of Cr VI is higher by 2–3 orders of magnitude. The current European legislation does not set a specific limit value for Cr VI, but only a cumulative limit value for a large group of heavy metals. Considered the potential repercussions on human exposure, the authors developed a methodology for the control of Cr VI emissions and defined a provisional emission limit value, based on the Cr VI ambient air concentration that gives an acceptable cancer risk, according to the results of a dispersion modeling and the related health risk assessment. In Italy, a cancer risk of 10^6 is considered as the acceptable excess cancer risk related to the long-term exposure to a single pollutant [41].

3.6. Atmospheric dispersion modeling

Compared to thermal WtE plants, this emission factor is approximately two orders of magnitude lower. However, the release mechanism of the process air from MBTs is completely different with respect to thermal WtE plants. In the first case, the process air is released close to ground level, usually from biofiltration systems that are not equipped with a stack. This may potentially entail a weaker dispersion of the air pollutants emitted compared to combustion plants. To verify this, a dispersion model (AERMOD) was applied to the case of a MSW bio-drying plant serving a population of about 500 000 inhabitants [34]. Considering an average emission factor derived from the literature (20 pg I-TEQ kg^{-1} MSW), two release mechanisms were studied: one concerning the use of a biofilter at ground level (release height: 2 m) and on the roof of the plant (release height 17 m) and one regarding the use of a regenerative thermal oxidizer (release heights: 25 m and 35 m). Thanks to the higher release high and temperature of the regenerative thermal oxidizer, PCDD/F deposition to soil reduces by three and one orders of magnitude compared to the use of a biofilter at ground level and on the roof, respectively. However, within about 600 m from the plant, even the use of the regenerative thermal oxidizer may expose the population to a cancer risk $>10^6$.

Another study focused more deeply on the atmospheric dispersion of air pollutants in an Alpine valley close to Trentino [35], revealing the complexity behind numerical simulations in areas characterized by multiple emission sources of different types (e.g., point, line and area sources). In the specific case of this study, the authors observed the major role of road traffic in determining the total NO_2 ambient air concentrations in the valley.

The impact of urban fabrics on the dispersion of air pollutants was also studied [36]. Similarly to orography, the obstacles created by buildings in an urban area are responsible for trapping air pollutants within streets, especially along canyon-like roads. The authors assessed the cancer risk induced by benzene inhalation in a portion of an urban area of Verona (about 30-km far from the southern boundary of Trentino) and found critical hotspots in urban street canyons. When planning the construction of a MSW gasification plant near urban areas, the proponents should also consider the potential accumulation of air pollutants within the urban fabric, which is possible to forecast with appropriate dispersion models.

4. Conclusions

Carrying out a comprehensive health risk assessment in mountainous regions is a complex task, especially in the case of important emission sources like MSW gasification plants with local syngas combustion or other large combustion sources. The history of publications written in Trentino in the last 20 years on the environmental impacts of waste management activities and related monitoring, modelling and health risk estimations allows environmental agencies to make use of a large amount of information to evaluate new project proposals. On the other hand, proponents of new projects may refer to the guidelines developed in many of the works presented in this paper to implement solid health risk assessment studies supporting their proposals. However, additional efforts should be made by national and international environmental protection agencies to level out the different formulations for the transfer of persistent pollutants through the food chain and generate a consolidated document that could be taken as a reference for health risk assessment studies.

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