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Development of innovative systems to contain the odorous impact of industrial plants

Dottorando:

Gabriele Pietro Bigi

Tutor universitario:

Prof.ssa Francesca Beolchini

Co-Tutor universitario:

Dott.ssa Alessia Amato

Tutor aziendale (Pan Eco Srl)

Dott.ssa Cristina Baldini

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1. Summary

This PhD project deals with the development of innovative systems for the abatement of odorous emissions from industrial plants, focusing on two industrial sectors developed in Marche Region: the wood industry and vegetable waste recycling.

The odor impact of industrial activities is a serious problem for the production activities themselves; indeed, the competent authorities for control are often forced to take action. The main cause of such impacts is not always due to an overcoming of the concentrations imposed by the legal limits; indeed, an ineffective urban planning in the past has led to industrial plants located near residential areas: olfactory harassment becomes reason for citizens reports, that hinder the correct operation of companies.

The problem of odorous emissions mainly concerns the following companies (Bertoni, 1993):

- Companies in the industrial sector (wood industry, chemical industry, oil and gas refineries, foundries, plastic and paint production);
- Agri-food companies (meat processing);
- Companies that deal with waste and wastewater treatment (landfills and composting companies).

In particular, the main odorous compounds are (Bertoni, 1993):

- **VOCs** (*Volatile Organic Compounds*): aliphatic and aromatic hydrocarbons, phenols, aldehydes and ketons;
- **VSCs** (*Volatile Sulfur Compounds*): hydrogen sulfide (H_2S) and mercaptans (SH);
- Nitrogen compounds: ammonia (NH_3) and amines.

The odorous emission from industrial facilities can be the cause of annoyance to the people living in the surrounding area. A long-term exposure may bring up serious damage to human health such as nausea, headaches and other related respiratory problems (Lebrero et al., 2011; Zarra et al., 2009b).

In this context, the development of effective innovative systems is fundamental, aimed at containing odors from the production processes. The present PhD research project has been cofunded by a company (Pan Eco srl), whose mission is to support the various industries in the field compliance with environmental regulations; in

this sector, it obtains authorizations and develops projects aimed at respecting all environmental constraints.

Considering the scenario just described and the company mission, the general goal of the research program was the development of innovative systems for the containment of odorous emissions into the atmosphere by various industrial plants. The general goal of the project has been achieved through specific objectives and activities:

- definition of the state of the art of the systems currently applied for the abatement of atmospheric emissions of organics compounds, including the legislative context. Through bibliographic research, a summary was made regarding the main techniques for sampling, analysis and abatement of odor emissions, also referring to the main laws at national and European level;
- identification of companies in the Marche region (at least two) with problems associated with the odor impact of industrial production. Two companies have been identified, one operating in the wood industry and the other operating in the recycling of organic waste;
- design and implementation of innovative emissions abatement system. In both sectors taken into consideration, an innovative odor abatement system was identified and implemented: UV painting for wood sector and vermicomposting for the recycling of organic waste;
- sampling, characterization of emissions and assessment of the performance. In both companies, the sampling of emissions using consolidated techniques was carried out and the effective abatement of odor emissions was assessed.

The impact from the research results has been on multiple fronts: on the cofunding company, who has acquired advanced know-how on innovative odor abatement systems, on the companies with environmental problems related to the release of odorous compounds into the atmosphere, on citizens, whose health has been protected by a more efficient control of emissions.

The research has also allowed to produce a scientific publication in a per reviewed international journal with impact factor:

- Amato A., Bigi G.P., Baldini C., Beolchini F. (2021). *Sustainable reduction of the odor impact of painting wooden products for the interior design*. Sustainability, in press.

The most relevant results of the research are reported in the following chapters.

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2. Characteristic, sampling, analysis and abatement of odors emissions: state of the art.

Abstract.

The odors are one of the aspects with the greatest negative impact on the environment; indeed, they cause a strong and persistent annoyance for the population. For this reason, in the last few years, the topic of monitoring, control and evaluation of the odors impact produced by some industrial activities is the subject of increasing attention for the Public Administration. Waste gas is one of the main emission pathways of many industries and production processes; airborne emissions are highly mobile and, depending on their composition, can cause environmental problems at the local, regional, or even global scale. Thus, treatment of gaseous emissions is an important measure to protect both public health and the environment. As odor problems are very complex issues and finding a suitable odor control technique is not less complicated, a general odor management approach should be made. This approach should always start with a thorough odor assessment, where all emission sources are recorded, characterized, and evaluated. Emissions that cannot be avoided need to be captured before being introduced into a treatment system. According to the chemical composition and physical condition, a suitable treatment system should be selected. In order to do so, detailed knowledge is needed about the advantages and disadvantages of the various technologies available for off-gas treatment.

2.1 Introduction.

2.1.1 Definition of odor.

The odor is the property of a substance, or rather, of a mixture of substances, dependent by their concentration, capable of activating the sense of smell and such as to trigger the sensation of smell (Brennan et al., 1993; Belgiorno et al., 2009). Odor is a sensation produced by the biological olfactory system when exposed to air with volatile chemical species (Leonardos et al.,1969) such as hydrogen sulphides, ammonia, hydrocarbons, VOC's, etc. Meanwhile, the gaseous compounds responsible for transmitting odors are defined as odorants (Gostelow et al., 2000).

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2.1.2 Olfactory nuisance.

The perception of an odor can be described as pleasant or unpleasant, producing, in both cases, immediate reactions; an unpleasant smell, since it is often associated with one harmful or dangerous situation, it can activate a protection and defense mechanism while, at conversely, a pleasant smell can generate an opposite mechanism of attraction and approach. The concept of olfactory nuisance is linked to the negative effects produced below exposure to an odor for a typically extended and repeated period over time (Brancher et al., 2017). In particular, the odors emission from industrial facilities can be the cause of annoyance to the people living in the surrounding area. A long-term exposure may bring up serious damage to human health such as nausea, headaches and other related respiratory problems (Lebrero et al., 2011; Mudliar et al., 2010; Zarra et al., 2009b). This impact may lead to a poor quality of life and generate a perception of a risk to the community (Chemel et al., 2012; Zarra et al., 2009a). Odors may cause a variety of undesirable reactions in people, ranging from annoyance to documented health effects. In communities exposed to odorous emissions, even though there may be no immediately apparent diseases or infirmities, there certainly is not an atmosphere of complete mental, social, or physical well-being. Moreover, prolonged exposure to foul odors can generate undesirable reactions ranging from emotional stresses such as unease, discomfort, headaches, or depression to physical symptoms including sensory irritations, headaches, respiratory problems, nausea, or vomiting (National Research Council Committee on Odors et al., 1979). Exposure can also lead to psychological stresses and symptoms such as insomnia, loss of appetite and irrational behavior (Gostelow et al., 2001). Sub-irritant levels of odorants may also trigger acute symptoms through non-toxicological, odor-related mechanisms. Odor emissions are considered air pollutants that required immediate attention, and this is a long-overdue concern in the society as well as one reason of complaints to the operators (Sarkar et al., 2003; Szczurek and Maciejewska et al., 2005; Bindra et al., 2015; Shammay et al., 2016; Talaiekhozani et al., 2016; Liu et al., 2018). As a remedy, a comprehensive odor management program in the aspect of measurement, characterization, control and treatment and continuous monitoring can be implemented. In this way, the negative impacts can be minimized and allow the operators to function in an environmentally sound manner.

Several factors related to each other contribute to the definition of olfactory nuisance; in literature, it is used the parameter called **FIDOL** (acronym for Frequency, Intensity, Duration, Offensiveness, Location) (Watts et al., 1995; Freeman et al., 2002) that summarizes the contribution of the following factors:

- Frequency: number of times an odor is detected in a time interval;
- Intensity: magnitude of the sensation generated by an odor;
- Duration: time interval in which an individual is exposed to an odor;
- Offensiveness or hedonic tone: degree of unpleasantness or pleasantness of a smell;
- Location - type of receptor that perceives the smell: defines the type of land use and the nature of human activities detected near an odor source.

The mechanism leading from an emission of odorants into the atmosphere to determine the olfactory nuisance results complex enough to describe; generally, the main factors can be described are (Van Harreveld et al., 2001):

- odor characteristics (perceptibility, intensity, hedonic tone);
- dilution in the atmosphere (turbulence or atmospheric stability, wind direction, wind speed, etc.);
- exposure of receptors (e.g. location, time spent outdoors);
- receptor characteristics (exposure history, psychological factors, reaction patterns, perception of health risks).

2.1.3 Characteristic of odors substances.

The sensory perception of odorants can be described by the following characteristics:

- Perceptibility: an odorous substance can be perceived when it reaches a concentration in the atmosphere minimum, called the "perceptibility threshold" required to provoke a stimulus in the olfactory system. The perceptibility threshold (**Odor Threshold – OT**) is defined as the minimum concentration of odorant that is perceived by 50% of the exposed population (Centola et al., 2004); in presence of mixtures, the different substances can interact in a complex way giving rise to additivity effects, synergy and antagonism (Centola et al., 2004; Belgiorno et al., 2009); schematically:
  - additivity: $R_{AB} = R_A + R_B$
  - synergy: $R_{AB} > R_A + R_B$
  - antagonism: $R_{AB} < R_A + R_B$

  where R_A and R_B represent the threshold of perceptibility of two pure substances, while R_{AB} is the threshold perception of the mixture obtained by combining the two substances. When dealing with toxic odorants it is useful to compare the OT values with the toxicity threshold, normally referring to the Threshold Limit Value (TLV).

- Intensity: represents the property that expresses the strength of the olfactory sensation; it is a measure of the sensation that the stimulus generates and is clearly dependent from the odorant and the individual who feels it (McGinley and McGinley et al., 2002). In olfactory perception, the number of stimulating molecules is related to them concentration in the breathed air. Usually, the higher the concentration of the odorant, the more intense the sensation it generates. It can therefore be said that the odorant concentration "C" is the quantity that controls the strength of the olfactory stimulus and that the strength of the olfactory sensation "I" depends on the strength of the stimulus. Several proposals have been made mathematical functions that qualitatively describe the dependence of intensity on concentration; the most used is that of Stevens (Sberveglieri et al., 2003; Centola et al., 2004):

  $\mathbf{I = K_S (C - C_0)^n}$ with $C > C_0$

  I = intensity of the odorous sensation;

K_S = Stevens coefficient, depends on the substance considered;

C = concentration of the odorant (OU/m^3);

C_0 = concentration at the perception threshold (olfactory) (OT) (OU/m^3);

n = exponent that depends on the substance, between 0.2 and 0.8, provides an important indication regarding the effect of possible dilution in reducing odor, which, obviously, is increasing as n.

- Diffusibility (volatility): an odor is perceived when a gas molecule dissolves in the olfactory mucosa and binds to a receptor. All substances capable of producing an odorous sensation they must therefore be able to emit vapors. A parameter indicative of capacity of odor diffusion of a single substance is the **Odor Index** (**O.I.**), defined as the relationship (dimensionless) between the vapor pressure of the odorant, expressed in ppm, and the minimum concentration perceivable by 100% of the panels selected for analysis (always in ppm). In particular, compounds with an O.I. $< 10^5$, are considered little odorous, like alkanes and some ketones, while sulfur compounds such as mercaptans (e.g. isopropylmercaptan) can achieve O.I. values of 10^9 (Ziemacki and Settimo et al., 2007).

- Hedonic tone: is the property that binds an odor to the pleasure or repulsion stimulus it can cause, expressing the degree of pleasantness or unpleasantness; normally, the hedonic tone is defined by a scale (generally 7 or 9 steps) (Lisovac e Shooter et al, 2003) (Fig.1).

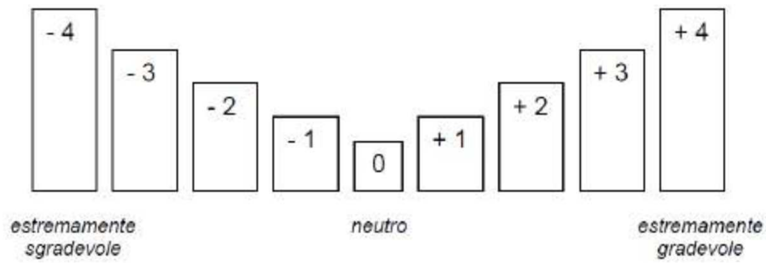

Fig.1 Hedonic Tone’s scale

2.2 Current regulatory framework.

2.2.1 European Legislation.

The need for an appropriate method to measure the concentration of odor has led the introduction of olfactometric standards that allow to evaluate in a standardized way the olfactory nuisance produced by emissions of odorous substances into the atmosphere. In Europe, such standard is dictated by the European standard **EN 13725** "Odor concentration measurement by dynamic olfactometry" developed by CEN (European Standardization Committee) in the 1990s and published in April 2004. This standard provides for the standardization, at European level, of the measurement of odors using ***dynamic olfactometry***. According to UNI EN 13725: 2004 the odorous impact is expressed in odorimetric or olfactometric units per cubic meter (**ou_E/m^3**); the odorimetric units represent the number of dilutions to make the odor sample not perceptible by 50% of panelist. The UNI EN 13725:

- Describes how the sampling procedure should take place;
- Indicates the characteristics of the rooms in which to allocate the instrumentation and perform the analysis;
- Defines the characteristics of the people that form the panel;
- Defines the two methods of odor analysis by the panel.

2.2.2 National Legislation.

The current national environmental legislation is affected by a systemic lack of specific references and adapted to the complexity of the problem of the olfactory impact; that misalignment causes multiple difficulties for supervisory authorities to assess the impact of odors emissions.

However, it has been recently approved the Legislative Decree n. **183/2017** (15/11/2017), implementing the directive (EU) 2015/2193; that Decree made changes to part V of Legislative Decree 152/2006; in particular, the **art. 271** provides:

- Emissions limit values expressed in concentration (mg/m^3) for odors substances;
- Specific maximum flow rates or maximum concentrations of odorous emissions expressed in units odorimetric (ou_E/m^3 or ou_E/s) for the plant's sources of odor emissions.

2.3 The sampling.

To determine the emissions from the main odor sources it is necessary to prepare a monitoring plan; sampling and analysis must be conducted for to obtain representative results of the emissions of the monitored system. For that purpose, it is important to obtain sufficient information on the system and its emissions before sampling; first, a thorough knowledge and analysis of the production cycle and of all the activities of the plant are fundamental in order to identify the main odorous sources. Sampling represents the most critical phase of the analysis strategy for the most part of environmental investigations; in fact, during sampling, it is particularly important, and at the same time difficult, to keep the composition unchanged original of the sample (Freeman et al., 2000). The sampling technique varies according to the type of emission source; in particular, there are different types of sources (D.g.r.n. IX / 3018, 2012):

- Point source: the smell is emitted from a single point, normally through a chimney; in this case, sampling consists of taking one fraction of the aeriform conveyed.

  In the case of a point source, it is possible to calculate the gas flow at the outlet by measuring the air speed and the cross section of the duct:

  $OER = Q_{eff} \times C_{od}$ with:

  OER = odor flow rate (OU/s)

  Q_{effl} = volumetric flow rate of the effluent (m^3/s)

  C_{od} = measured odor concentration (OU/m^3)
- Volumetric sources: they are typically buildings from which smells come out, either intentionally, through natural ventilation ducts, both unintentionally, through doors, windows, or other openings.
- Areal sources: in this case, there are typically emissions from extended solid or liquid surfaces; they can be: with induced flow (active): they are sources with an outgoing air flow (biofilters or ventilated heaps); without induced flow (passive): the only flow present is that due to the transfer of matter from the surface to the air above (landfill).

  In this case a **static hood** is used for sampling which isolates a part of surface and allows to convey the flow into the outlet duct of the hood, where it comes taken the sample, in the same way as for source sampling point. In this case, to calculate the OER, it is necessary to go through the calculation of another parameter significant, i.e., the specific odor emission rate (**SOER**), expressed in odorimetric units emitted per unit of surface and time ($OU/m^2/s$):

$SOER = (Q_{effl} \cdot C_{od})/A_{basis}$ with:

$SOER$ = specific odor flow ($OU/m^2/s$)

Q_{effl} = volumetric flow of air leaving the hood (m^3/s)

C_{od} = measured odor concentration (OU/m^3)

A_{basis} = basis area of the hood (m^2)

Finally, to calculate the OER it is sufficient to multiply the SOER by the emissive surface, i.e., the total area of the source considered:

$OER = SOER \cdot A_{emiss}$

2.4 The analysis.

The methods present in the scientific literature for the odorimetric investigation can be divided into three main classes:

- analytical or instrumental methods (gas chromatography / mass spectrometry);
- sensory methods that use the people for detection (dynamic olfactometry, questionnaires and field analysis);
- sense-instrumental (electronic nose).

2.4.1 Chemical analysis.

Gas chromatography combined with mass spectrometry (**GC/MS**) is a chemical-analytical technique very powerful that allows to perform accurate analyzes on the chemical composition of a data gas sample; GC is a highly efficient component separation technique of complex mixture which, combined with an extremely sensitive and selective detector such as the mass spectrometer, allows the identification and quantification of practically all chemical species present. These analyzes therefore provide a complete list of concentrations of all substances present in the odorous sample (Centola et al., 2000; Freeman et al., 2000).

Analytical determinations, for the analysis of odors, offer the following <u>advantages</u>:

- objectivity;
- reproducibility and repeatability;
- accuracy.

However, they have some disadvantages:

- for some odor compounds with a very low olfactory threshold (mercaptans and other sulphides) there may still be problems with the sensitivity of the instrumentation analytical, since the concentrations that cause perceptible odors can be lower than the instrument detection limit;
- in most cases there are no significant relationships between the exact composition of the mixture and the smell sensation that it generates;
- high cost and relatively long analysis times.

Modern analytical techniques are therefore powerful tools for the exact determination of the composition of odorous effluents, allowing identification and the quantification of practically all the chemical species present; however, they don't provide no information on the overall sensation of smell that the individual substances generate (Mugnani et al., 2003).

2.4.2 Sensory method (dynamic olfactometry).

Dynamic olfactometry is a sensory technique based on the use of the olfactory sensitivity of a panel of evaluators, through which it is possible to obtain significant results, in that directly related to the effect generated by the smell; this method provides a measure objective of the sensation generated by a single or complex odorant (De Gennaro et al., 2007). Contrary to chemical analysis, the olfactometric analysis does not provide the identification of a substance or group of substances, but the "odor units" of the gas mixture; in this way it is therefore possible to create a method to measure the real olfactory nuisance, however entirely subjective (Sberveglieri et al., 2003).

The olfactometer (fig. 2) is a dilution apparatus which, through a management software of the instrument, it mixes the sample with neutral air supplied by the compressor, according to defined relationships, and sends it to the panelist workstation for analysis.

Fig.2 Olfactometer.

The panel represents the group of qualified assessors to be used as "sensors" in the olfactometric analysis; the choice of panelists takes place according to appropriate criteria, considering subjects having an average olfactory sensitivity to represent the population. The choice is made in terms of perception threshold with a reference odorant: *n-butanol*; the most common presentation method adopted is the **yes/no method** (from the door can exit the odor sample diluted with neutral air, in a defined dilution ratio or a white consisting of only the reference air, which serves as a control); the panel responses are acquired and statistically processed by the software it supports the olfactometer. The odor concentration is numerically equal to the dilution factor at perception threshold; for example, a concentration equal to 100 OU/m^3, means that the original sample was diluted by a factor of 100 to reach the panel threshold (De Gennaro et al., 2007).

The second method is that of "**forced choice**", this is applied for olfactometers equipped with two or more sniffing ports, only one of which dispenses the odor sample, while reference air comes out of the others; each evaluator in turn is called to smell the gas that comes out of the doors in front of him and indicates which of them the odorant comes from.

2.4.3 Electronic nose.

The electronic nose (fig.3) is a device designed with the intent to emulate the functioning of the olfactory system biological (Di Francesco et al., 2001). The sensory analyzer is based on the use of one matrix of chemical sensors (conducting polymers, semiconductors), with partial specificity, which can respond to the volatile compounds present in a gas sample by modifying some physical parameters (electrical resistance, oscillation frequency, work function).

Fig.3 Electronic nose.

The metal oxides (MO) constitute the most common detectors of electronic nose systems in environmental applications; these sensors are based on the decrease of the electric resistance of the sensors in the presence of volatile compounds. Moreover, the MO exhibit high sensitivity, fast response, low recovery times and low production costs. In this case, one of the primary limitations of this technique consists in a response variability associated with environmental factors, particularly temperature and relative humidity.

2.5 Odor treatment technologies.

Very high process efficiencies are required for the treatment of odorous emissions as humans are sensitive to very low concentrations of odorous substances. The applicability of the different treatment processes mainly depends on the composition and amount of the waste gas; additionally, temperature, moisture and particulate content must be considered. Nearly any treatment process can be designed large enough to meet the required efficiencies. Thus, selection and design of suitable treatment processes must aim at finding an optimum where the required treatment efficiency is achieved as cost-effectively as possible, using a technology that is adapted to the specific conditions. Often, a combination of different treatment methods is advantageous (M. Shlegelmich et al.,2005). The main odor treatment technologies are listed below:

- **Adsorption**: is the process whereby the molecules of odors compounds attach to solid surfaces; commonly used adsorbents include *activated carbon*, *activated alumina*, *silica gels* and *zeolites*. In industrial applications, adsorbers are mostly designed as fixed bed reactors, with the gas passing through a stationary bed. Simultaneous adsorption and desorption are required for continuous operation of adsorbers. This may be achieved by parallel operation of several adsorbers or by using an adsorber wheel (Fischer et al., 2001). Regeneration of the adsorbent is usually conducted by *means of hot gas or steam*. A disadvantage of this technology is the relatively low heat capacity of the regeneration gases, resulting in large regeneration gas flows, which are re-diluting the desorbate (Cartellieri et al., 2005).

  Electrothermal regeneration is a variant of thermal desorption where the energy input is decoupled from the flushing gas flow, resulting in better process control and higher desorbate concentrations (Bathen and Schmidt-Traub et al., 1999). One method of electrothermal regeneration frequently investigated in recent years is microwave desorption. Although this method showed promising results in some applications (Stegmann and Hensel et al., 2004; Robers et al., 2004), it must be considered that hot spots and electric discharges between the particles may occur. Thus, flammable adsorbents may be subject to spontaneous ignition in the presence of oxygen (Price and Schmidt et al, 1998).

  Other possibilities of electrothermal regeneration include inductive desorption, where an electric current in the adsorbent is induced by a magnetic field (Bathen and Schmidt-Traub et al., 1999) and adsorption on activated carbon mats, which are regenerated by directly conducting an electric current through the material (Muller and Schottler et al, 2003). In both cases, the active principle is ohmic heating. Obviously, these technologies can only be applied to electrically conducting adsorbents, like activated carbon. In full-scale applications, electrothermal desorption is much less commonly used than thermal regeneration. Adsorption is commonly used as an enrichment step prior to thermal gas treatment (Anguil et al., 1998). It can also be combined with other technologies, like biofiltration. This combination may be especially suitable for companies with varying exhaust air concentrations, e.g., due to discontinuous production, because biofilters tend to be less effective under transient conditions. In these cases, the adsorbent can be loaded in times of high raw gas concentrations and desorbed when the inlet concentrations are low, e.g., at night. That way, the biofilter can be loaded with a relatively constant concentration (Paul et al., 2001; Herzog and Thißen et al., 1997). High moisture contents, however, often have a negative effect on the adsorption process.

- **Absorption**: During absorption, off-gas compounds are dissolved in a scrubbing liquid. Mass transfer is mainly controlled by the solubility of the substances and the gas-liquid interfacial surface (Buonicore et al., 1992b). The solubility can be affected by selection of a suitable solvent, as discussed by Freudenthal et al. (2005). *Packed columns* are used most frequently to provide a large interfacial surface. Other devices which are used include *jet* and *venturi scrubbers*, *plate columns* and *spray scrubbers* (Fischer et al., 2001; Heining et al., 1998; Buonicore et al.,1992b). Accumulation of the waste gas components in the scrubbing liquid would result in a cease of mass transfer after establishment of equilibrium according to Henry's law. Thus, the scrubbing liquid must be exchanged or regenerated (Fischer et al, 2004). Regeneration of the scrubbing liquid can be conducted by means of *stripping* with air or steam. As in adsorption, the aim is to obtain a desorbate flow with considerable higher concentration than the original exhaust air which can be treated more efficiently. Aqueous scrubbing liquids can also be biologically regenerated. In many applications, *chemicals* are added to the scrubbing liquid which will react with the dissolved waste gas compounds and thus add to the scrubbing liquid regeneration (chemical scrubbers). In these cases, removal of reaction products must be ensured. The use of oxidants is the most common application in chemical scrubbing. Besides ozone (O_3) and hydrogen peroxide (H_2O_2), mainly sodium hypochlorite (NaOCl) is used because it is both relatively inexpensive and easy to handle. However, a drawback of hypochlorite is the tendency to not only oxidize but also chlorinate the compounds. Furthermore, some chlorine gas (Cl_2) also is formed. For the removal of ammonia, particularly from piggeries, sulphuric acid scrubbers have been successfully applied. The advantage of this process is the formation of an ammonium sulphide solution, which can be sold as a fertilizer. This process often is combined with a subsequent biofilter to remove remaining odors (Hahne and Vorlop et al, 2001; Sattler et al., 2000). Acidic substances, like hydrogen sulphide (H_2S) can be treated with caustic scrubbers using diluted sodium or potassium hydroxide. This way, organic Sulphur compounds can also be removed (Dammann et al., 2001). However, salts or sludges are generated which may cause considerable costs for disposal (Fischer et al., 2004).

- **Biological treatment system**: biological waste gas treatment systems rely on the activity of *microorganisms*, which can degrade organic contaminants from the air stream (Bardtke,1990). The microorganisms feed on odorous substances and oxidize them, at best to CO_2 and H_2O or other odorless products. Thus, biological systems sustainably reduce odors emissions and do not shift the problem to other media like scrubbing liquids or adsorbents, which remain as problematic residues. Furthermore, if at all, few chemical agents must be added and energy costs are relatively low, as they are operated at atmospheric pressure and ambient temperatures. Accordingly, investment and operational costs for biological waste gas treatment systems are comparably low (Ergas and Cardenas-Gonza´les et al., 2004; Devinny et al., 1999). There are two biological systems commonly used for the treatment of odorous emissions: ***biofilters*** and ***bio scrubbers/bio trickling filters***.

- **Biofilters**: can be described as biochemical fixed bed reactors where the waste gas is treated while passing a biofilter bed. Microorganisms settle on its surface and form a biofilm in which the airborne substances are absorbed. An important criterion for biofilter media is to provide optimum environments for the microorganisms, thus an essential property is the ability to store water. Additional criteria are a low pressure drop to assure an even air distribution and a large specific surface for the mass transfer and the microorganisms to settle on. Frequently used biofilter media are compost, peat, root wood, bark, wood chips (normally used as bulking agent) and different kinds of combinations (VDI 3477, 2002). In most of these cases, the biofilter material already provides stable mixed cultures of microorganisms, which mostly adapt to the condition and composition of the waste gas. The adaptation phase may range from several days to several weeks (Streese et al., 2005; VDI 3477, 2002). Inoculation of the biofilter with e.g., biosolids or specialized microorganisms especially for inorganic media can be considered to shorten the starting phase (Kennes and Thalasso et al., 1998). One of the key parameters of biofiltration is the moisture content of the biofilter material. The optimal range for biologically active organic media is between 40% and 60% (VDI 3477, 2002; Heining, 1998; Kennes and Thalasso et al., 1998). To avoid drying of the filter media, the waste gas should be saturated with water vapor. Usually, the air is humidified using wet scrubbers or even bio scrubbers; however, not only dry air streams can cause drying of the biofilter material.

Biofilters may be designed as open to the atmosphere or enclosed; in *open biofilters* the air passes through the bed in an up-flow direction. A problem with open biofilters is the direct exposure of the biofilter media to climatic conditions which may influence its functionality. A hot and dry climate may result in a drying of the filter media; the opposite problems have been reported from places with very humid climate. *Enclosed biofilters* are less affected by weather conditions than open filters, and offer a better moisture distribution, as they can be operated under down-flow conditions. Traditionally, biofilters were used to treat off-gases from sewage treatment plants, composting facilities and rendering plants, which mainly contain biological intermediate degradation products (Schlegelmilch et al., 2005; Sabo et al., 1994; Schroder et al., 1994; Eitner et al., 1990). In recent years, further applications have been opened to this technology including in food and tobacco producing and processing industries (Ottengraf et al, 1986; Eitner et al., 1992; Kersting et al., 1992), as well as the treatment of waste gases containing industrial solvents and other volatile organic compounds (Fell et al., 2002; Herzog and Thißen et al., 1997; Hubner et al., 1997).

Problematic substances regarding biofiltration are sulphureous and nitrogenous organic or inorganic compounds, as they cause acidification of the biofilter media due to their oxidization products, sulphuric and nitric acid (Hartikainen et al., 1996; Fetzner and Roth et al., 1995). For these applications, a combination with other treatment processes should be considered.

- **Bio scrubbers and bio trickling filters**: In bio scrubbers and bio trickling filters, the microorganisms generally are suspended in a scrubbing liquid but may additionally be immobilized on packing material. The most important component of these devices is the absorption column where the mass transfer between gaseous and aqueous phase takes place, and thus the airborne substances are made available to the microorganisms. Usually packing materials are installed to enhance the contact surface of both phases. In most applications the gaseous and the aqueous phases are distributed in counter flow to each other. However, if no packing materials are installed, crossflow systems often are used. Once the odorous substances are dissolved in the scrubbing liquid, if degradable they are removed by the microorganisms. The degradation process may take place in the liquid, usually water, or in the biofilm that grows on the packing materials. These internals not only enhance the surface for the mass transfer but also provide an additional surface for the microorganisms to settle. During the adaptation phase the microorganisms start to grow and form a biofilm which has a large effect on the degradation efficiency of the scrubber. Attention must be paid to the fact that clogging of the scrubber might be a problem. To avoid clogging, the packed bed should have large pores and should be cleaned frequently. The scrubbing liquid is subsequently drawn off and continuously cycled. An activation tank may be implemented into this cycle to allow further regeneration time (VDI 3478, 1996). The degree of regeneration can be influenced by the size of the activation tank and consequently the retention time of the scrubbing liquid. It may be necessary to install an additional aeration system to provide enough oxygen (Schippert et al., 1994; Gust et al., 1979). Furthermore, nutrients may be added to the scrubbing liquid to provide lacking elements like phosphorous, nitrogen, potassium, etc., for the microorganisms. The superficial air velocity in a bio scrubber should be in the range of 0.5–2.5 m/s.

- **Bio scrubber/biofilter combination**: This biological system combines the advantages of both technologies. The bio scrubber acts as a humidifier and degrades a high portion of the odor load. It also shows a buffering effect (Schlegelmilch et al., 2005), which prevents high concentrations of odors substances from entering the biofilter, which otherwise might lead to a rise in temperature in the biofilter material due to increasing degradation processes.

- **Thermal waste gas treatment (e.g. post combustor)**: Thermal treatment can be basically applied to any exhaust air. However, since the concentration of VOCs is often low, the addition of natural gas or a preconcentration, e.g., by adsorption, is usually required. Generally, the lower limit for autothermal combustion is a concentration of organic compounds of 1 g/m^3. For thermal treatment, *catalytic* and *non-catalytic techniques* are applied. Catalytic processes can be operated at lower temperatures, resulting in considerably lower energy demand. On the other hand, the costs for the catalyst itself must be considered. In addition, for non-catalytic processes, energy costs can be significantly reduced by using advanced systems with heat recovery (recuperative thermal oxidizers, regenerative thermal oxidizers). Drawbacks of thermal waste gas treatment are the high operating costs in the case of natural gas addition and the formation of secondary emissions like nitrous and sulphur oxides.

- **Non-thermal oxidation technologies**: besides thermal oxidation, several ‘‘cold’’ oxidation techniques for the treatment of odorous exhaust air, like UV treatment or non-thermal plasma, have been investigated in the last few years.

  UV treatment is successfully used for sterilization of drinking water or treatment of persistent wastewater components. The technology is based on the UV induced formation of highly reactive radicals and ions which can oxidise organic molecules. Repeated efforts were conducted to apply the positive experience from water and wastewater treatment to waste gas treatment. However, significant efficiencies were only measured when high performance UV radiators were used, resulting in a very high energy demand not considered suitable for treatment of odorous waste gas (Fischer et al., 2001, 2004).

The *non-thermal plasma technology* uses strong alternating electrical currents or microwave radiation to induce highly activated molecules. Like with UV radiation, reactive radicals and ions are subsequently formed and react with odorous compounds. The ‘‘ionized air’’ can be generated in an additional air flow that is merged with the main waste gas flow, or directly in the main flow. Both non-thermal plasma and UV radiation result in the formation of excess ozone, which must be removed by a subsequent catalyst (Fischer et al., 2001).

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3. Sustainable reduction of the odor impact of painting wooden products for the interior design (a case study in the Marche region)

Abstract.

Construction and building field represent a key sector for the recent Circular Economy Action Plan of March 2020. Therefore, the production of low impact materials represents an essential step towards the implementation of a sustainable market. In this regard, the present paper focused on the production of painting wooden products for interior design. These industrial processes include an essential phase of reduction of the odor emissions which produce negative impacts on the environment and persistent annoyance for the population close to the facilities. The main cause of the odor emissions in wood painting manufacturing is the production of volatile organic compounds (VOCs). In this context, the present research aimed at the development of an innovative process able to combine the use of lower impact paints with a more efficient UV system for the abatement of the emissions.

3.1 Introduction.

All kinds of product have an environmental impact during their life cycle, from the production to the final disposal. The product design defines more than 80% of the environmental load, therefore, sustainable choices must be made in this phase (European Commission et al., 2014). It is evident that the product sustainability represents a priority for the European market policies which promote the decrease of hazardous chemicals and the increase of energy and resource efficiencies of products, with positive effects on the environmental footprint (European Commission et al., 2020). The building field represents one of the key sectors included in the recent European Circular Economy Action Plan, because it has been estimated that it causes about 10% of the total national greenhouse gas emissions (European Commission et al., 2020). The interior design market is strongly related to this sector since each building needs to be furnished (Baldinelli et al., 2014). In this regard, wood manufacturing painting shows many criticalities for its significant contribute to poor air quality and electricity consumption (Baldinelli et al., 2014; Tong et al., 2019). Doors are typical wood components inside the buildings. The door production sector involves the use of different solvent-based paints with the consequent emission of volatile organic compounds (VOCs) and odor pollutants, with effects on environment, human health, and the personal welfare (Wu et al., 2018; Balasubramanian et al., 2012). VOCs represent an important category, since they may be toxic also at low concentrations, causing severe effects when inhaled. For these reasons, their detection is important for the assessment of the indoor air quality (Morin et al., 2019; Suzuki et al., 2019). These pollutants, emitted into the atmosphere, participate to the photochemical smog phenomena (US EPA et al., 2019). Further significant impacts related to VOCs are the odor emissions which often cause a strong and persistent annoyance for the population (Zarra et al., 2019). More in detail, the odor is the property of a substance, or rather of a mixture of substances, dependent on their concentration, capable of activating the sense of smell and such as to trigger the sensation of smell (Brennan et al., 1993; – Brancher et al., 2017). This aspect is the subject of increasing attention for the Public Administration and it could be translated into a consent decrease and economic loss for the emitting companies. Indeed, in communities exposed to odor emissions, even though there may be no immediately apparent diseases or infirmities, there is not an atmosphere of complete mental, social, or physical well-being (National Academy of Sciences et al., 1979). Odor emissions are considered air pollutants that require immediate attention (Sarkar et al., 2003; Liu et al., 2018). The World Health Organization has defined the air pollution as the environmental risk with the highest mortality among developed countries, causing more than 150,000 deaths per year (Montecchio et al., 2018). This reason has pushed the European Commission to issue Directives focused on the emission reduction, with a particular attention on VOCs with reduction targets of 28% between 2020 and 2029 and 40% from 2030 in the EU area (European Commission et al., 2016; European Commission et al., 2008). As a consequent of both the legislation and the circular economy pillars, companies are moving towards the development of high efficiency abatement systems and environmentally friendly products to reduce the release of hazardous substances into the environment (Freitag et al., 2008; Schieweck et al., 2015). The control of VOC (and odor) emissions can be carried out by different approaches, depending on the possible separation or destruction (Brancher et al., 2017; Krishnamurthy et al., 2020; Maurer et al., 2016). The applicability of the different treatments mainly depends on the composition and the amount of the waste gases; additionally, temperature, moisture and particulate content should be considered. A combination of different treatments is often advantageous. The main approaches of odor emission abatement include adsorption (by activated carbon, activated alumina, silica gels and zeolites), absorption, thermal oxidation, catalytic oxidation, photocalysis, membrane use (Krishnamurthy et al., 2020; Buonicore et al., 1992; Freudenthal et al., 2005). Furthermore, biological treatment systems mainly include biofilters and bioscrubbers/biotrickling (Krishnamurthy et al., 2020; Devinny et al., 2017; Ergas et al., 2004). Thermal treatment is one of the most common approaches, it involves high temperature (900-1000°C) to oxidate VOCs to CO_2 and H_2O and it can be applied to any exhaust air (Krishnamurthy et al., 2020). The combustion system can be completely powered by VOCs. However, if the pollutant concentration is too low (common situation for a company), the addition of natural gas is necessary. In order to reduce the environmental impact due to VOC abatement systems, two options could be taken into account (better if combined): the possibility of thermal abatement substitution (e.g. with a photocatalytic approach) and the use of more sustainable paints for the reduction of emissions to treat. Concerning the second possibility, the innovative paints, UV-based inks, show many advantages: the reduction of solvent content (water-based paints which can be dried by polymerization ensuring higher efficiency of dye), the reduction of environmental impacts thanks to the lowest solvent content and the consequent VOC releases. In this context, the present paper aimed at evaluating two systems for the door production: a traditional line which uses conventional paint with a thermal abatement of VOCs and an innovative painting process able to combine the lowest solvent content paint with an UV system for the abatement of the emissions. The scientific literature reports many sustainability assessments in building construction field, nevertheless the interior design sector is often neglected (Yilmaz et al., 2019; Vilches et al., 2017). Furthermore, most research is based on lab scale or literature data, not yet optimized for a real scale implementation and it excludes the study of emissions detected during the production process (Hesser et al., 2017; Cobut et al., 2016). The present paper aimed to help fill the gap thanks to the cooperation with a company which allowed to consider a full-scale manufacturing chain of wood doors to prove the effectiveness of the optimized improvements. With this aim the study of emissions to air (quantified as VOCs) was combined with a sustainability assessment by LCA tool.

3.2 Materials and Methods.

3.2.1 Case study description.

The object of this study is an Italian company specialized in wood manufacturing, mainly in door production. Considering the sustainability target and the strong interest for the environmental impact reduction, the company developed an innovative production chain. This manufacturing line uses low solvent content paints combined with an innovative emission abatement system, able to substitute the current approach (a post-combustor). More in detail, the abatement system consists of the UV painting and drying (Cefla UV2000); this technique uses paints with a lower content of VOCs and it allows high efficiency reduction of odor emissions. The UV system allows the polymerization and drying of the paints in a short time thanks to the photochemical reactions. The high-speed reaction makes possible the incorporation of VOCs during the reticulation, preventing the evaporation phenomena and the consequent environmental impact.

3.2.2 The emission sampling.

The emissions of door production lines, object of the present study, consisted of a point source, since they were conveyed to a chimney equipped with a sampling point, as required by the standards UNI EN 15259:2008 and UNI EN 16911:2013. The sampling activity started with the study of the stationarity and homogeneity of the flow inside the chimney, using a Pitot tube. This step ensured the representativeness of the whole duct section, in the absence of vortices and turbulences. The sampling took place through a grid to evaluate the distribution of the measures (the recorded parameters must be $\Delta P > 5$ and maximum and minimum speed ratio < 3). The emissions were characterized by an on-site Flame Ionization Detector (FID, T0574-PF-300), according to the technical standard UNI EN 12619:2013. The sampling devices included the filter, necessary to remove fine particles, which could clog the burner. The system design ensured the minimum residence time (less than 60 seconds) of the sample gas to reduce the response time of the measuring system. Furthermore, the use of combustion air or fuel gas with VOCs lower than 0.2 mg/m^3 (as carbon), and purity of 99.998% avoided possible interferences during the analysis. The instrument allowed continuous measurement (every 12 seconds) of TOC (mg/m^3). At the end of the sampling activity, the TOC value was converted into VOCs by a multiplication factor of 1.5, assessed on the basis of the average molecular mass of the main solvents present in the used paint. To ensure both the precision and the accuracy of results, three samples were collected, following the UNI EN 12619:2013, UNI EN 15259:2008 norms and the Legislative Decree 152/2006. The detection was carried out during the painting of the wooden doors, both in the classic painting line and in the UV painting line, in order to make a quantitative comparison between the two different techniques.

3.2.3 The environmental sustainability analysis.

The assessment of the sustainability, by LCA approach, allowed to evaluate the environmental load of the door production processes, estimating the gain resulting from the use of innovative paint, combined with an UV system for VOC abatement. More in detail, the analysis focused on the environmental impact due to the different energy consumptions to verify the real advantage of the innovative technique. The study was carried out following the recommendation of ISO 14040:2006 and 14044:2006 norms. The thinkstep GaBi software-System, integrated with Database for Life Cycle Engineering (compilation 7.3.3.153; DB version 6.115) was used for the production processes of energy and raw materials and the quantification of the environmental load of the treatments. The analysis included the phases of classification and characterization, normalization and weighting and the method selected was EF 3.0. Figure 1 describes the system boundaries considered for the assessment. More in detail, the three considered scenarios took into account the energy request of all the steps for the door manufacturing (both wood processing and painting). Scenario 1 represents the most common option which includes a traditional paint and the following VOC abatement by post-combustor. Scenario 2 includes the use of the UV painting and drying system, without the necessity of further emission treatments. Scenario 3 represents an additional improvement of Scenario 2, thanks to the substitution of the average grid mix with the renewable photovoltaic technology for the electricity production. The wood flow was excluded from the system boundaries since it was the same for the three scenarios. The same assumption was carried out for the paints since the lowest impact of the low-solvent content paint was granted and its estimation was not considered of interest for this study. The main limitation of the assessment was the focus on the door production, excluding both the use and the end-use phases. Nevertheless, considering the target of the comparison among the possible scenarios of manufacturing at company facility, this choice did not affect the effectiveness of the presents study.

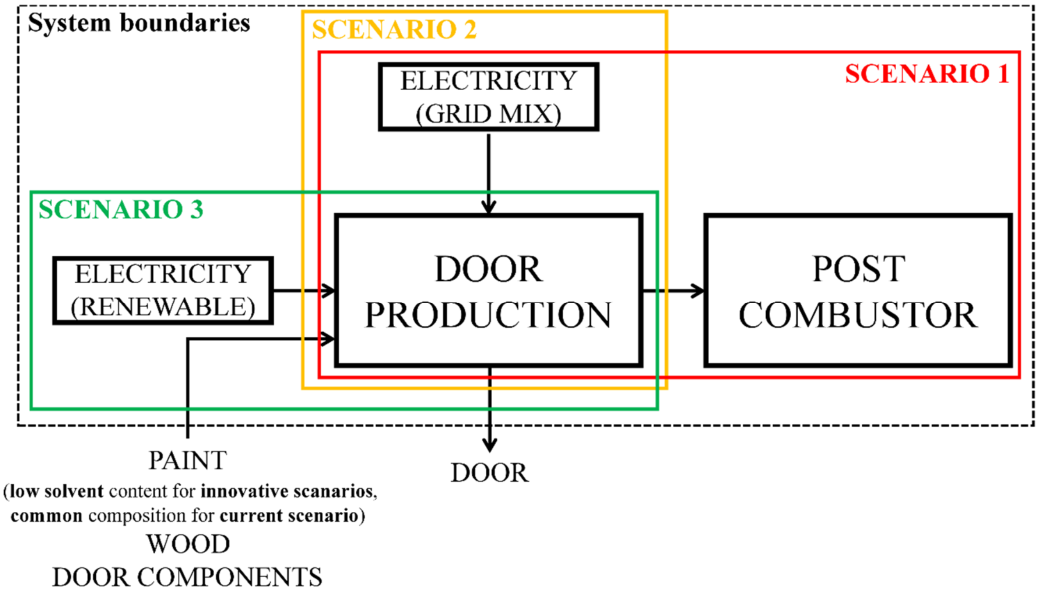

Figure 1. System boundaries considered for the LCA

The functional unit selected for the analysis was 10 tons of wood products, estimated as the average daily production of the considered company. The same company provided the data used for energy balances and to estimate the methane consumption of post combustor (Table 1). The variability of electricity consumption was due to the different models of door included in the assessment with the aim to obtain more consistent results. The highest efficiency of dye of the innovative paint allows a lower variability of electricity consumption, irrespective of the door model. For the electricity impact assessment was selected an average European grid mix (in scenarios 1 and 2) and a European mix of photovoltaic technologies (scenario 3). As concern the methane consumption, it considers an operative time of post combustor of 12 h. Table 1 reports an average amount of methane supplied; nevertheless, this date could be increase up to 900 m^3 in VOC absence (e.g. during the daily steps of: ignition, cooling and work break) and it could reach 0 if VOCs quantity is enough to power the combustor (this condition was excluded because extremely rare).

Table 1. Process consumptions considered for the LCA (functional unit: 10 tons of wood products).

Input flow	Amount
Electricity consumption for door production with common paint (KWh)	460 ± 90
Electricity consumption for door production with innovative paint (KWh)	240 ± 10
Average methane consumption of post combustor (m^3)	600 ± 300

3.3 Results and discussion.

3.3.1 Emission abatement.

The analysis of the emissions resulting from the door production processes using two different paints (current paint vs low solvent content paint + UV abatement) allowed to confirm the effectiveness of the innovative approach. As reported in Figure 2, the implementation of the innovative scenario produced emission values lower than the legal limit defined by the Legislative Decree 152/2006, of 112.5 mg/Nm^3. The positive effect achieved by the UV painting (scenario 2), is proved by the decrease of VOCs of about 13 times, compared to the current option (scenario 1). This decrease, also confirmed by the minimum data variability (the results included three replications for each scenario), is mainly explained by the lowest organic solvent content in UV paints, compared to the traditional coating. From the observation of these data, the necessity of the further post-combustion integrated with the current scenario is evident to comply with the limits fixed in the Italian Regulation.

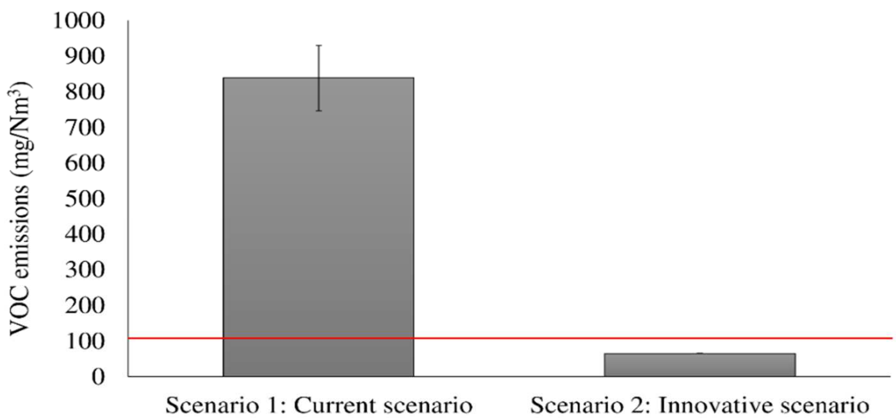

Figure 2. Emissions from door production chain: current vs UV abatement systems. Red line represents the Italian legal limit for VOC emissions.

3.3.2 The environmental sustainability analysis.

The promising results of the innovative approach, observed in the reduction emission terms, were confirmed by the assessment of the process impacts, in most categories included in the LCA. Indeed, the implementation of the UV painting and drying system, without the necessity of further emission combustion (scenario 2), produced an environmental load on average 5 times lower than scenario 1. The absence of the post-combustion treatment was mainly highlighted in the categories of: acidification terrestrial and freshwater (Figure 3a), cancer and non-cancer human health effects (Figure 3b, i), climate change (Figure 3b), eutrophication marine and terrestrial (Figure 3f-g), photochemical ozone formation (Figure 3j), resource use, energy carriers (Figure 3l) and respiratory inorganics (Figure 3o), where the methane consumption caused about 50% of the scenario 1 impact. The innovative treatment also acted on the reduction of emission variabilities, indeed the highest dye efficiency of water-based paints, decreases the energy request for painting, irrespective of the door model. As concern the post combustor impact, the results variability was connected to the VOC flows to treat, considering both the daily working operation and the possible monthly production changes of the company. The additional combination of the new manufacturing chain, with renewable energy use (by photovoltaic technology) further enhanced this achievement with an impact reduction higher than 90% (scenario 3). The exceptions of the categories of ozone depletion and resource use, mineral and metals (Figures 3m-n) were explained by the unitary data considered for the energy from photovoltaic sources. Indeed, to make the data as representative as possible, they included both the production and end-of-life of photovoltaic technologies affecting the categories connected to the raw materials consumption.

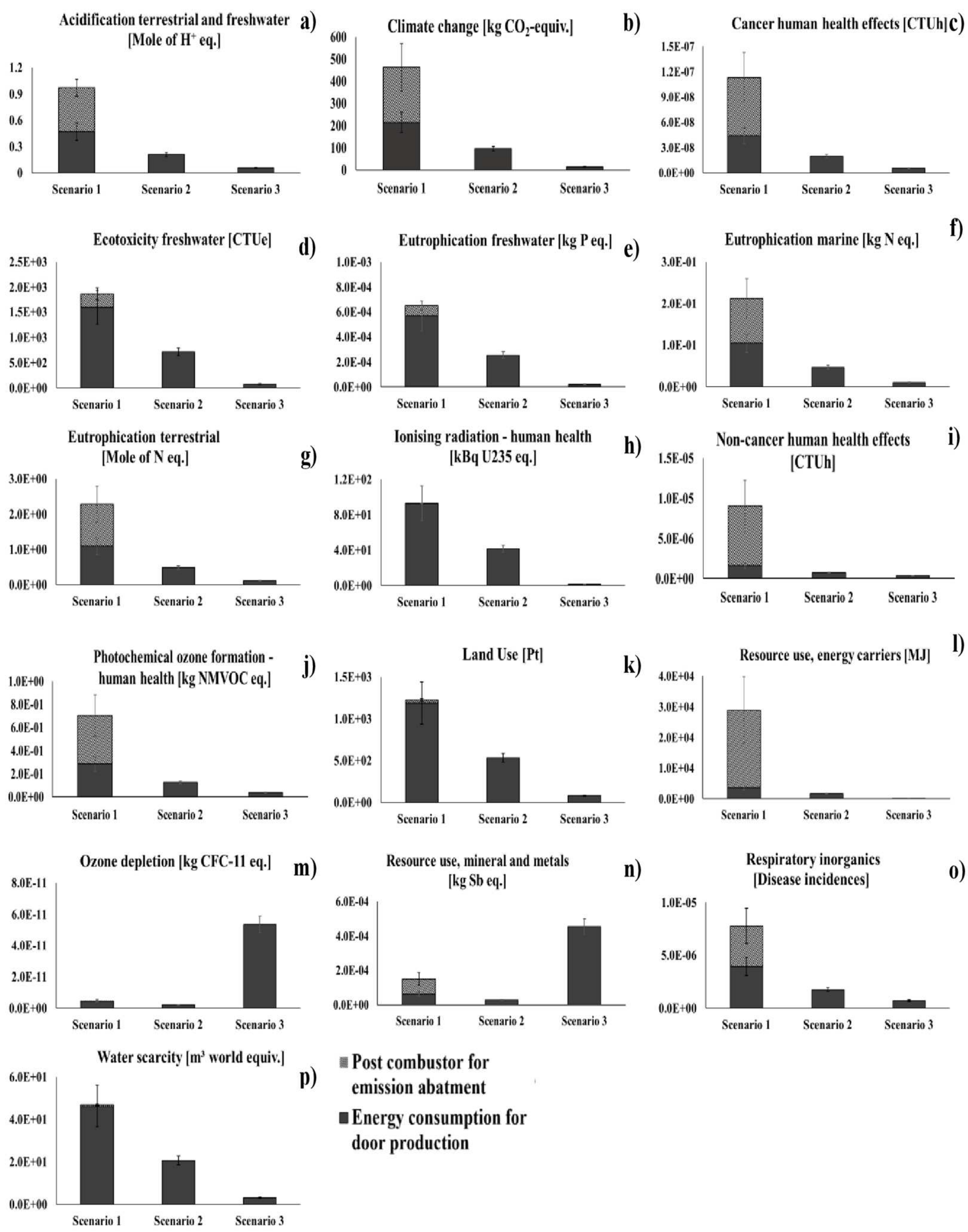

Figure 3. Results of LCA: classification and characterization steps (scenario 1: current scenario; scenario 2: innovative scenario; scenario 3: innovative scenario combined with renewable energy use), functional unit 10 tons of wood products. Each letter represents an impact category.

Nevertheless, this aspect did not affect the whole result, as confirmed by Figure 4 which shows an impact decrease (expressed as person equivalent, p.e.) of 75%, thanks to the improvement of door production chain from scenario 1 to scenario 2, considering the normalized and weighted results. The percentage grew up to 95% by the renewable energy use. The whole achievement was mainly connected to the positive effect of innovative approach on the categories of ionizing radiation, resources use, energy carriers and climate change, responsible for the 40%, 40% and 14% of the impact of scenario 1. The effect on ionizing radiation was mainly due to the electricity demand of door production process, indeed the European grid mix selected for the analysis includes about 26% of energy production from nuclear sources which cause, combined with the mineral oil and gases extraction, the release of radionucleide (Frischknecht et al., 2000; Amato et al., 2019).

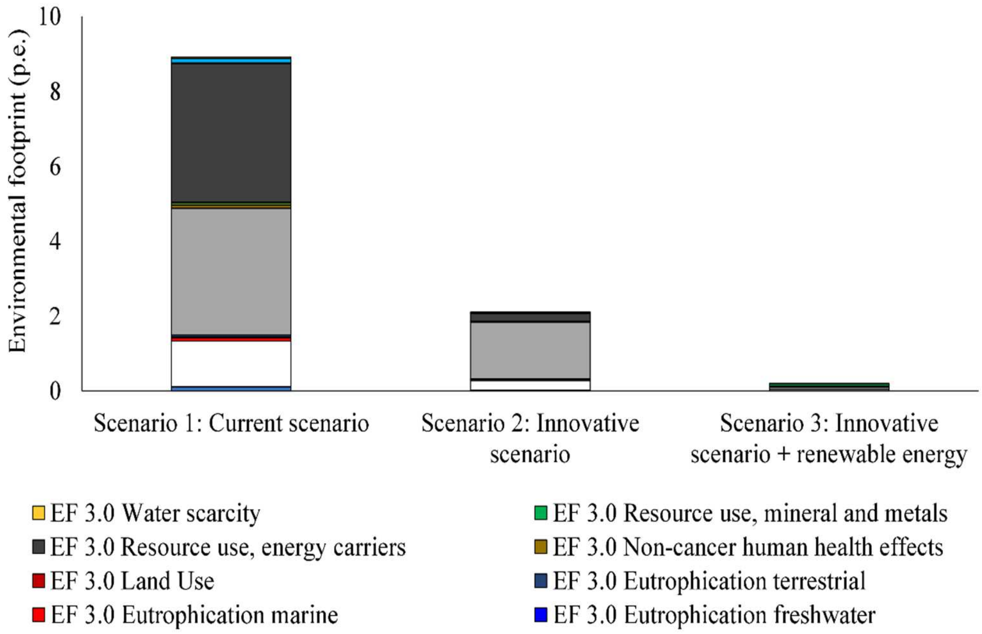

Figure 4. Results of LCA: environmental footprint, expressed as p.e. (functional unit 10 tons of wood products).

3.4 Conclusion.

The development of sustainable manufacturing processes represents a priority during the circular economy era. In this context the present paper showed a high efficiency process to produce wood doors for the interior design. The new approach aimed at the substitution of the current high impact manufacturing with an innovative system able to combine low solvent paints with an UV system for the emission abatement. The results were satisfactory with resulting VOC emissions well below the regulation limit. This achievement was combined with a significant decrease of energy consumption, translated into an environmental gain higher than 75%, further enhanced by the possibility of supplying renewable energy. The opportunity to test a real production chain represented a strength of the present research since it allowed the collection of representative data. Furthermore, it proved the real interest of the company to move towards the reduction of the environmental impact, with an increase of the sensitivity for these topics, often translated into an economic and social gain.

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4. Reduction of the odorous impact in vegetable waste processing (a case study in the Marche Region)

Abstract.

The odors are one of the aspects with the greatest negative impact on the environment; in fact, they cause a strong and persistent annoyance for the population. For this reason, in the last few years, the topic of monitoring, control and evaluation of the odors impact produced by some industrial activities is the subject of increasing attention for the Public Administration. This problem concerns various industrial companies, including those operating in the vegetable waste treatment: in this case, the main cause of the odors emissions is represented by the emissions of **organic substances**. The goal was to create an innovative system for the abatement of odors emissions for a waste treatment in the Marche Region. In particular, the company identified was a company that deals with the treatment of special non-hazardous waste, and the innovative emissions abatement system consisted in the biological waste treatment technologies such as ***vermicomposting***.

4.1 Introduction.

Organic solid waste poses a serious threat to the environment as the world struggles to keep up with its rapid generation. Biological waste treatment technologies such as composting and vermicomposting are widely regarded as a clean and sustainable method to manage organic waste. World cities generate approximately 13 billion metric tons of solid waste annually, which is almost double the amounts that were generated a decade ago (Hoornweg and Bhada-Tata et al., 2012). By 2025, solid waste generations will double again (Hoornweg et al., 2013). The annual increase in solid waste generation is inextricably link to the rapid rise in global population and rate of urbanization. Among the total solid waste generated globally, organic waste is the largest proportion with 46% (Hoornweg and Bhada-Tata et al., 2012). The organic waste includes food scraps, yard waste and agricultural waste. The rest of the waste is inorganic like paper, plastic, glass, metal, and others.

Current methods of solid waste managements are landfilling, incineration, recycling, reuse, source reduction and others (Wuet et al., 2014). Both landfilling and incineration are characterized as waste disposals, which are the least preferred options in the waste management hierarchy. In many parts of the world, landfilling remains the dominant method for waste disposal as it is the cheapest in terms of capital costs (Laner et al., 2012). In developed countries, the landfills are equipped with a combination of waste containment systems such as leak detection and management systems for collecting leachates and biogas (Hoornweg and Bhada-Tata et al., 2012). In recent years, controlled landfilling in these countries is increasing (Sim and Wu et al., 2010) but open dumping is still a common practice (Hoornweg and Bhada-Tata et al., 2012). Management of leachate is also a problematic issue because the raw leachate contains high organic load in chemical oxygen demand (Romero et al., 2013), which requires proper management and disposal that will add cost to the landfill operation (Zavodska et al., 2014). Management of leachate is also a problematic issue because the raw leachate contains high organic load in chemical oxygen demand (Romero et al., 2013), which requires proper management and disposal that will add cost to the landfill operation (Zavodska et al., 2014). Greenhouse gas emissions due to solid waste decomposition in the landfill is also a cause for concern (Pozza et al., 2015); moreover, one of the main problems related to landfills is the production of ***odors emissions***. Furthermore, the limitation of land and the value of waste as resources are concrete reasons to move away from landfilling and shift towards more sustainable waste management strategy (Marshall and Farahbaksh et al., 2013); recent study done by Yang et al. (2015) also showed that over the next 10 e 15 years, an increase in the proportions of incineration and composting is more feasible than landfilling in municipal solid waste management.

Waste incineration could be the solution for reducing the degradation of land, generation of methane gas and leachate production caused by improper landfilling. Incineration is suitable for non-biodegradable waste with low moisture content (Tan et al., 2014). Besides, reduction of waste volume of up to 90% and recovery of energy are possible during incineration (Hoornweg and Bhada-Tata et al., 2012).

Other solid waste management options are 3Rs, consisting of source reduction, recycling, and reuse (Zaman et al., 2013). Waste management options using 3Rs are in line with the cleaner production initiative which involves continuous application of preventive environmental strategies to all processes to maximize the efficiency and minimize the impact on the environment (UNEP, 2015).

Waste avoidance and reduction technology are the prime challenge rather than the development of new waste treatment technology (Zaman et al., 2013). Source reduction involves redesigning processes and managing products to reduce the amount of generated waste and greenhouse gas emission. If no waste is generated, there is no need for treatment or disposal.

Recycling also helps reduce the amount of waste such as paper, glass and metal generated by returning the materials consumed to the economy (Shekdar et al., 2009). Recycling rates are higher and effective in developed countries as compared to developing countries due to the better collection services and facilities for sorting and processing. These facilities are highly equipped, common, and regulated (Hoornweg and Bhada-Tata et al., 2012). Developing countries are often lacking waste recycling and treatment facilities, where waste is still dumped in the open environment (Song et al., 2015).

Reuse is another waste management strategy for waste that cannot be recycled and helps reduce the amount for disposal (Shekdar et al., 2009). Examples of reuse of organic solid waste are composting and vermicomposting processes. Composting is a biological decomposition of organic waste under either aerobic or anaerobic conditions. Similarly, **vermicomposting** is also a biological decomposition process of organic waste but with an addition of earthworms to speed up the biodegradation process. The composts and vermicompost produced from organic waste can be reused as nutrient-rich organic fertilizers or for land application (Wu et al., 2014).

These two processes are also highly favored to manage solid waste owing to the high percentage of organic waste in the waste composition. Moreover, lesser costs are incurred in both composting and vermicomposting process, making them a good option to be applied in developing countries.

Composting and vermicomposting could be the most promising option for organic waste management, especially in lower income countries, because they incur lower cost and have lesser impact on the environment. Mechanisms of both composting and vermicomposting processes in producing organic fertilizer from the waste show that they are meeting the cleaner production concept. Moreover, the driving force behind the introduction of composting and vermicomposting (or other reuse processes) in organic solid waste management is the global recognition of the need to recover useful organic materials and return them to the soil. Thus, this research focused on the potential of introducing composting and vermicomposting in biotransforming organic waste into fertilizer as a sustainable waste management strategy.

Composting is a biological decomposition of organic waste either in an aerobic (Makan et al., 2014) or anaerobic (Minale and Worku et al., 2014) environment with the former being more common. The organic matters in the waste are consumed by aerobic thermophilic and mesophilic microorganisms as substrates and converted into mineralized products such as CO2, H_2O, NH_4^+ or stabilized organic matters (Qian et al., 2014). The resultant compost is a stable, humus-rich, complex mixture that can improve physical properties of the soil (Watteau and Villemin et al., 2011). Factors affecting composting process are temperature, initial C/N ratio, aeration, porosity, moisture content and pH (Shafawati and Siddiquee et al., 2013). During composting process, these parameters are regulated and controlled to provide an optimum environment for the microorganisms to degrade the organic waste (Lopez-Gonzalez et al., 2015). Like composting, vermicomposting process is also a biological decomposition of organic waste to produce stabilized organic fertilizer, namely vermicompost. Unlike composting, vermicomposting process involves interactions between earthworms and microorganisms to biodegrade organic waste at a faster rate (Sim and Wu et al., 2010). Vermicomposting is accelerated by the combined activity of diverse group of microorganisms. One of the possible ways of increasing the nutrient content of vermicompost is a microbial enrichment technique with nitrogen fixers, and phosphorous solubilizes (Kumar et al., 2010; Busato et al., 2012). The incorporation of vermicompost along with microbial fertilizers had a beneficial effect on the crop yield. Microorganisms produce enzymes that cause biochemical decomposition of organic matter, but earthworms are the crucial driver of the process as they are involved in the indirect stimulation of microbial population through fragmentation and ingestion of fresh organic matter. This, in turn, results in a greater surface area available for microbial colonization, thus dramatically increasing microbiological activity (Aira et al., 2002). Earthworms act as the main drivers in the decomposition of organic waste by fragmenting and conditioning the substrate. In doing so, earthworms increase the surface area of the organic waste that is exposed to the microorganisms. Thus, the microbial activity and decomposition process of solid waste are enhanced. Vermicomposting results in the production of vermicompost or earthworm cast that has low C/N ratio, high porosity, water-holding capacity, and available nutrients (Lim et al., 2015b). Like composting, efficiency of vermicomposting process is also influenced by several factors such as initial C/N ratio, moisture content, pH, and nature of the organic waste. In comparison with the composting process, all the factors influencing vermicomposting process are also inextricably linked to the earthworm species which are used during the biodegradation process. In addition to the vermicompost, earthworm biomass is also produced during vermicomposting. After the completion of vermicomposting process, earthworms were removed from the vermicompost.

Earthworms used in the vermicomposting process must possess the following characteristics: 1) high rates of organic matter consumption, digestion and assimilation; 2) high tolerance of environmental stress; 3) high reproductive rate; 4) rapid growth. Earthworms are classified into three different categories, namely epigeic, endogeic and anecic; among these earthworms, epigeic earthworms are the most suitable earthworms to be used in vermicomposting process as they live in organic horizons and feed primarily on decaying organic matter. Epigeic species are the most efficient in biodegrading organic waste and releasing nutrients into the soil. In addition, the latest study revealed that surface-dwelling mode of life guarded the epigeic earthworm against their exposure to pesticide (Suthar et al., 2014). Among the epigeic earthworms, Eisenia fetida and Eisenia andrei are the most used in vermicomposting because both earthworms are peregrine and ubiquitous with a worldwide distribution, resilient and have wide temperature tolerance (Edwards et al., 2004).

The recovered nutrients are recycled to the soil as an organic fertilizer (compost and vermicompost), thereby closing the organic matter cycle (Singh et al., 2013). According to Doan et al. (2013), both compost and vermicompost modified soil chemical properties, leading to higher carbon and nitrogen, higher pH and cationic exchange capacity but lower available P, NH_4^+ and NO_3 than mineral fertilizer; vermicompost (Lim et al., 2015b) is known to positively affect soil structure as well as increasing its microbial population and activity. Due to the characteristics possessed by the organic fertilizers, Quiros et al. (2014) concluded that the organic fertilizers were suitable substitutes for mineral fertilizer. A study conducted by Cabanillas et al. (2013) showed that basil plant produced better growth when vermicompost was used as compared to urea. Furthermore, the use of organic fertilizer reduced the quantity of organic fraction that would end up in landfills; and optimized the nutrients that were already in use without requiring the extraction of more nutrients by not disrupting the natural cycle (Quiros et al., 2014).

Vermicomposting, like composting process, is also an organic waste decomposition process but with an addition of earthworms to aid and hasten the waste stabilization process (Lim et al., 2015b); therefore, suitable organic waste or feedstock for earthworms is crucial to ensure a successful and efficient vermicomposting process (Yadav and Garg et al., 2011a). Earthworms can consume most organic materials that have pH in the range from 5 to 8, moisture content between 40 and 55% and initial C/N ratio around 30. However, not all organic waste fall within these parameters; therefore, to make the organic waste more suitable for vermicomposting, the waste should be: 1) amended with bulking agents/organic waste (or amendments) or 2) undergone some form of pre-treatment process. During vermicomposting process, bulking agents or amendments are used to make the organic waste more palatable for the earthworms. For example, cow dung is commonly used as an amendment in vermicomposting process because it is the easiest animal waste for growing the earthworms (Edwards et al., 2004). Some organic waste could be vermicomposted without using bulking materials, but some form of pre-treatment process should be introduced prior to vermicomposting process. For example, dried cow dung is commonly used as an amendment, but fresh cow dung is unfavorable for the growth of earthworms (Edwards et al, 2004). Fresh organic waste materials cannot be applied to soil until they have been sufficiently bio stabilized, because application of immature organic materials to soil may affect plant growth due to nitrogen starvation and production of toxic metabolites (Zucconi et al., 1981).

Therefore, in most vermicomposting studies, it is a common practice to pre-treat the organic waste by at least turning the waste manually to eliminate the volatile gases which are toxic to the earthworms (Lim et al., 2014) and reduce high moisture content in some organic waste (Yang et al., 2014). Like the compost, the presence of heavy metals in the vermicompost poses a serious threat to human and environment owing to its agricultural application. Singh and Kalamdhad (2013a) found that vermicomposting process was effective in reducing most of the bioavailable fractions of heavy metals. Singh and Kalamdhad (2013c) confirmed that the leachable concentration of heavy metals in the vermicompost was under the threshold limit. Moreover, earthworms were able to accumulate heavy metals in the organic waste via skin absorption or in their intestine (Lim et al., 2015b). Suthar et al. (2014) found that some available fractions of heavy metals were removed by the earthworms through gut/skin absorption. Heavy metal content found in the worm tissues confirmed the theory that earthworms had the capability to regulate metals.

4.2 Materials and Methods.

4.2.1 Waste treatment: a case of study in the Marche Region.

The company identified in the Marche region with problems associated with the odorous impact was a company (the name of the company in question will not be specified for privacy reasons) that deals with the treatment of special non-hazardous waste (vegetable waste, cellulose and paper) to produce compost. The activity currently pursued is attributable to agricultural activities as the recovery of plant material is carried out, even starting from waste, returning a soil improver in line with the requirements of the fertilizer regulations. The main wastes used to produce quality compost are vegetable waste from agricultural crops, vegetable waste deriving from agro-industrial activities, wood-cellulosic waste deriving from the maintenance of ornamental greenery, fiber, and paper sludge. The waste derives from agro-industrial processes with physical or thermal treatments without the use of denaturing substances. The production process of the green composted soil conditioner ACC (Active Composting Composite) consists of the aerobic biological transformation of the matrices which evolves through a thermophilic stage and leads to the stabilization and humification of the organic substance. The stages of the process are divided into a first phase of storage and pre-treatment and a phase of maturation. The process is carried out in such a way as to ensure control of the chemical-physical characteristics of the starting organic matrices, control of the process temperature and a supply of oxygen sufficient to maintain the aerobic conditions of the mass. The waste is stored in a confined environment equipped with a drainage and process wastewater collection system and then shredded. Subsequently the waste is subjected to the maturation phase (about 30 days) by bio-oxidation at a temperature of about 55 °C. In this company, the classic abatement of odors takes places trough irrigation and nebulization of piles.

4.2.2 Innovative odors emissions abatement system.

The innovative emissions abatement system consisted in the biological waste treatment technologies such as ***vermicomposting;*** this innovative technique allowed to reduce odors emissions thanks to a reduction of emissions of **organic substances** and **ammonia.**

4.2.3 Earthworm species used for vermiconversion.

Composting earthworms, i.e., ***E. fetida*** of different age groups were obtained from stock culture; *Eisenia fetida*, is also known as "*Californian red earthworm*", red because of the color of the skin, Californian because in this country its breeding took place for the first time. E. fetida a composting worm was used in the experiments due to its well established potential for vermicomposting of compostable organic materials such as agricultural. It is among the most used species for breeding and the production of worm compost, thanks to its high ability to reproduce and its characteristics of low mobility.

Its main features are:

- Length between about 5 and 10 cm;
- Diameter of about 3-5mm;
- Weight about 1g;
- Body divided into cylindrical segments with regeneration capacity;
- On each segment there are 8 short and sturdy bristles which contribute to the locomotion of the animal;
- Production of about 1 g of compost per day;
- Photosensitive: if exposed to sunlight, it dies in a few minutes, due to UV rays;
- Breathing through the epidermis;
- Lives in very humid environments (about 80%);
- Ideal pH range: 6.2 - 7.8;
- Ideal temperature: about 20 ° C (they survive in temperatures from 0 to 41° C);
- Average age: 15-16 years;
- Under ideal conditions, the population can double monthly.

4.2.4 Experimental design.

In this company, we used the ***landfill leachate*** as odors substance to be treated with earthworms; a line with a pump was set up to recirculate the leachate through the containers with the earthworms (fig.1).

Fig.1 Experimental design.

This mixture has been characterized by chemical analysis taking samples in the following time intervals: 0, 1, 7, 10, 15, 21, 28 and 35 days.

In particular, the parameters monitored over time were:

- **pH** that was determined by the APAT CNR-IRSA 2060 with pH meter (*Orion model 710A*).
- **EC** (**Electrical Conductivity**) that was determined by the *Rapport ISTISAN 07/31 ISS. BDA 022 Rev 00 - internal method* with ISE meter (*Orion model 710A*).
- **TOC** (**Total Organic Carbon**) that was determined by the *ISPRA 5135* method and spectrophotometer analysis (λ=435 nm). If the sample contains particles, the manufacturer recommends diluting the sample before analysis. This method involves the following steps for determining the COT: 1) pipette 1.0 ml sample into the digestion cuvette (LCK 386 30-300 mg/l); 2) insert the open digestion cuvette in the *TOC-X5* shaker, pushing it down as far as it will go. Position the fan cover over the cuvette and switch on the instrument; after 5 minutes an acoustic signal will signal the end of the agitation phase. That phase has the function of expelling the total inorganic carbon (TIC). 3) when the sample preparation is complete, open the blue indicator cuvette and immediately screw on the membrane double cap tightly (the barcode label must point towards the indicator cuvette). 4) immediately close the digestion cuvette tightly with the prepared indicator cuvette; hold cuvette

combination vertically and not shake. 5) heat in the thermostat *LT 200* (blue indicator cuvette upwards) for 2 hours at 100° C: the heat favors the oxidation of the TOC to carbon dioxide. The CO_2 passes through a membrane into the indicator cuvette, where it causes a color change to occur, which is evaluated with a spectrophotometer (model *Hach Lange DR 2800*). The instrument provides the concentration of COT present in the sample in mg/l.

- **COD** (**Chemical Oxygen Demand**) that was determined by the *ISPRA 5135* method and spectrophotometer analysis (λ=448 nm). This method is based on the following principle: oxidable substances react with sulphuric acid – potassium dichromate solution in the presence of silver sulphate as a catalyst. Chloride is masked by mercury sulfate. The reduction in the yellow coloration of Cr^{6+} is evaluated. This method involves the following steps for determining the COD: 1) bring the sediment into suspension by inverting s few times; 2) carefully pipette 2.0 ml sample; 3) close cuvette (LCK 314 15-150 mg/l), thoroughly clean the outside; 4) shake and heat in the thermostat *LT 200* for 2 hours at 148° C; 5) remove the hot cuvette and carefully invert twice; 6) allow to cool to room temperature in a cooling rack; 7) finally, clean the outside of cuvette and evaluate with a spectrophotometer (model *Hach Lange DR 2800*); sediment must be completely settled before evaluation is carried out. The instrument provides the concentration of COD present in the sample in mg/l.

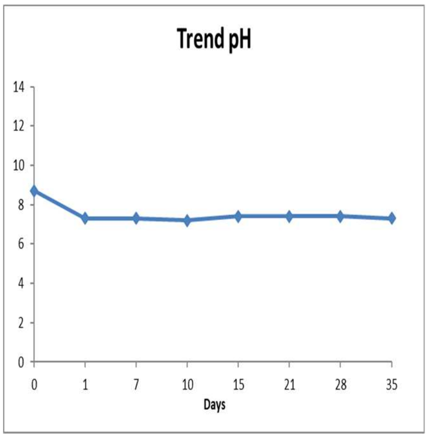
- **Ammonia** (**NH_3**); that was determined by the *APAT CNR-IRSA 4030 A2* method and spectrophotometer analysis (λ=420 nm). According to the principle of the method, the ammonia present in the sample reacts with an alkaline solution of potassium iodo-mercurate (*Nessler's reagent*) to form a colored complex. The absorbance of this complex is then measured with the spectrophotometer. After filtering or centrifuging the sample, take 50 ml of filtrate, add the stabilizing solution (1 drop of EDTA reagent) and mix well; then add 2 ml of Nessler's reagent and mix again. Before proceeding with the measurement, wait about 15 minutes for the complete color development. From the absorbance value, corrected for the blank value, determine the ammonia nitrogen concentration using the calibration curve. If a sample dilution has been performed, multiply the result obtained by the dilution factor.

- **Nitrates** (**NO_3^-**); that was determined by the *APAT CNR-IRSA 4020* method and ion chromatograph analysis. This technique is based on the separation of the analytes by means of an anion exchange column based on their affinity for the stationary phase. The recognition of the analytes is carried out by comparing the retention time of the sample peaks with the retention time of the reference solutions. The concentration is finally determined by comparing the peak area with the calibration curve of the analyte constructed by means of a series of reference solutions at different concentrations. For samples containing suspended particulate, filtration before injection is recommended.

4.3 Result and discussion.

4.3.1 pH.

The leachate samples were subjected to pH measurement with a pH meter (*Orion model 710A*); the results obtained showed a decrease in pH (from 8,7 to 7,3) (fig.2)



Days	pH
0	8,7
1	7,3
7	7,3
10	7,2
15	7,4
21	7,4
28	7,4
35	7,3

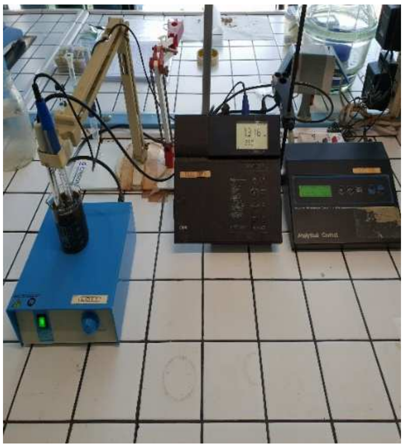
Fig.2 Trend Ph.

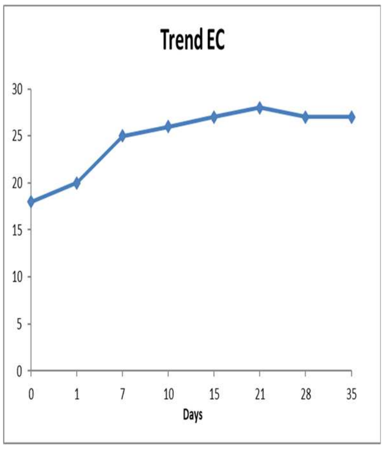
The pH during the experimental set decreased slightly, remaining around neutral values and in any case in the ideal earthworm survival range; the lower pH recorded in the final products might have been due to the production of CO_2 and organic acids by microbial metabolism during decomposition of different organic substrates (Garg et al., 2006).

Similar observations have been reported by other scientists for vermicomposting process. Khwairakpam and Bhargava (2009) reported a decrease in pH during the vermicomposting of sewage sludge. The difference in pH of different waste mixtures can be attributed to difference in physicochemical characteristics of wastes used in the process. Ndegwa and Thompson (2000) have reported that shift in pH values may be due to N and P mineralization and conversion of the organic material into intermediate of organic acids. Pramanik et al. (2007) have postulated that decomposition of organic matter leads to the formation of ammonium (NH^{4+}) and humic acids.

4.3.2 EC (*Electrical conductivity*).

The leachate samples were subjected to EC measurement with an ISE meter (*Orion model 710A*); the results obtained showed an increase in EC of leachate (from 18 mS to 27 mS) (fig.3).





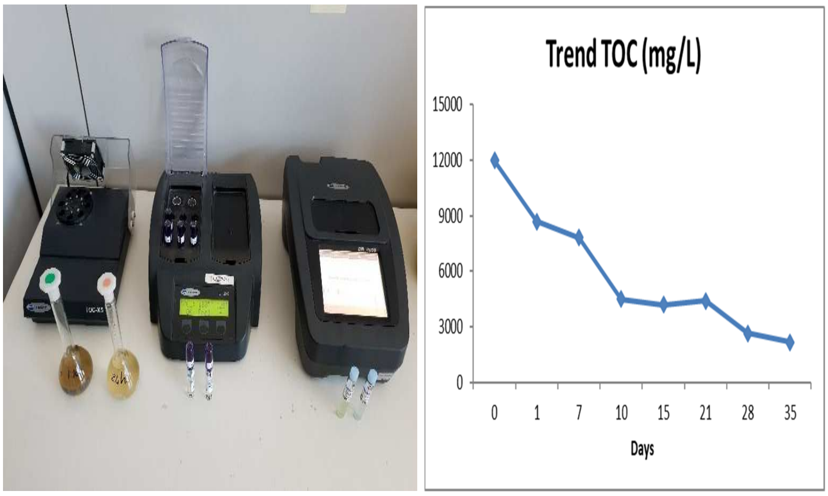
Days	EC (mS/cm)
0	18
1	20
7	25
10	26
15	27
21	28
28	27
35	27

Fig.3 Trend EC.

Electrical conductivity (EC) of solution was higher than initial wastes. The EC reflects the salinity of any material and it is a good indicator of the applicability and utility of a compost or vermicompost for agricultural purposes. This increase in EC might have been due to release of different mineral ions, such as phosphate, ammonium, potassium etc. (Kaviraj and Sharma et al., 2003).

4.3.3 TOC (*Total Organic Carbon*).

The TOC was determined by the *ISPRA 5135* method and spectrophotometer analysis (λ=435 nm); TOC during the experimental set decreased considerably (from 11980 mg/l to 2160 mg/l) (fig.4).



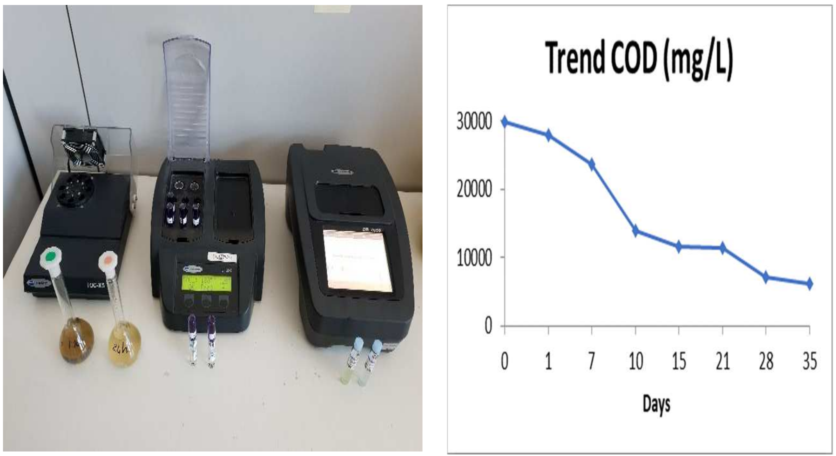
Days	TOC (mg/l)
0	11980
1	8700
7	7800
10	4500
15	4200
21	4400
28	2650
35	2160

Fig.4 Trend TOC.

This decrease in TOC can be attributed to the **oxidation of organic carbon to CO_2** through the interaction between earthworms and microorganisms; indeed, the combined action of earthworms and microorganisms may be responsible for TOC loss from the initial waste in the form of CO_2. Similar observations have been reported by Prakash and Karmegam (2010) during vermicomposting of sugar industry waste. Kaviraj and Sharma (2003) have reported 20–45% reduction of TOC as CO2 during vermicomposting of municipal or industrial wastes. Dominguez and Edwards (2004) have reported that earthworm fragments and homogenizes the ingested material through muscular action of their foregut and also adds mucus and enzymes to ingested material and thereby increases the surface area for microbial action, while microorganisms perform the biochemical degradation of waste material providing some extra-cellular enzymes within the worm's gut. Thus combined action earthworms and microorganisms bring about C loss from the substrates in the form of CO_2.

4.3.4 COD (*Chemical Oxygen Demand*).

The COD was determined by the *ISPRA 5135* method and spectrophotometer analysis (λ=448 nm); also the COD during the experimental set decreased considerably (from 29800 mg/l to 6220 mg/l); this decrease in COD confirmed the **decrease in organic matter present in the sample** (Fig.5).

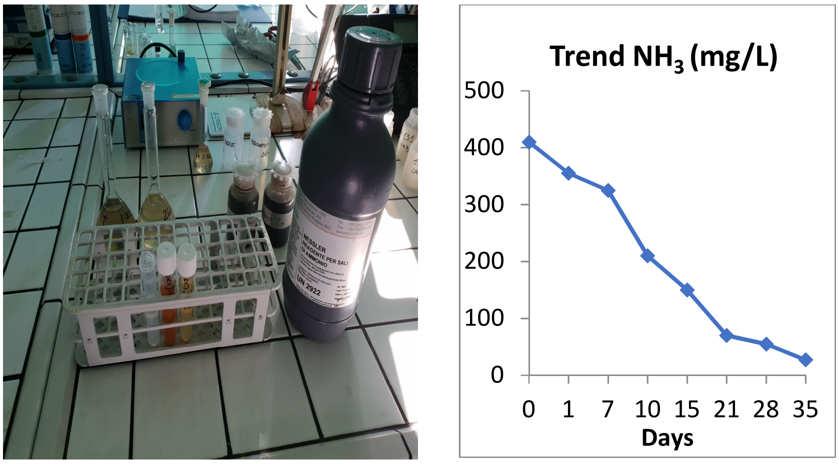


Days	COD (mg/L)
0	29800
1	27900
7	23600
10	14000
15	11600
21	11450
28	7120
35	6220

Fig.5 Trend COD.

4.3.5 Ammonia (NH_3).

Ammonia was determined by the *APAT CNR-IRSA 4030 A2* method and spectrophotometer analysis (λ=420 nm); ammonia (NH_3) during the experimental set decreased considerably (from 410 mg/l to 27 mg/l) (Fig.6).



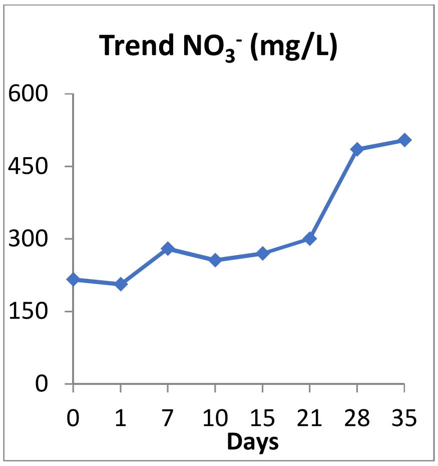
Days	NH_3 (mg/L)
0	410
1	355
7	325
10	210
15	150
21	70
28	55
35	27

Fig.6 Trend NH_3.

This decrease in NH_3 can be attributed to the **nitrification process** by microorganisms present in the soil; this result further supports the idea that the presence of earthworms could accelerate the nitrification process, as corroborated with some studies (Parkin and Berry, 1999; Wang et al., 2011; Costello and Lamberti, 2009; Huang et al., 2016). In general, the skin and gut of earthworms can excrete the nitrogenous substances like their mucus and urine (Whalen et al., 2000), which is one reason for the enriched nitrogen content in the vermicomposting system. Earlier studies have reported that vermicomposting may enrich the N-content of vermicompost due to N additions by earthworms in the form of mucus, enzymes or nitrogenous excretory substances (Tripathi and Bhardwaj, 2004) and as a consequence of nitrogen transformation mediated by the vermicompost's microbiota through organic matter mineralization and microbial nitrogen-fixing (Bhattacharya and Chattopadhyay, 2004).

4.3.6 Nitrates (NO_3^-).

Nitrates was determined by the *APAT CNR-IRSA 4020* method and ion chromatograph analysis; during the experimental set increased (from 216 mg/l to 504 mg/l): this increase in nitrates confirms the nitrification processes of ammonia by microorganism, process also favored by the interaction with earthworms (Parkin and Berry, 1999; Wang et al., 2011; Costello and Lamberti, 2009; Huang et al., 2016) (Fig.7).



Days	NO_3^- (mg/L)
0	216
1	206
7	280
10	256
15	270
21	300
28	485
35	504

Fig.7 Trend NO_3^-.

4.4 Conclusion.

The results obtained in this study highlighted the potential of earthworms (i.e. Eisenia fetida) in the degradation of vegetable waste; in particular, the experiments carried out on the sample (landfill leachate) showed an increase in the degradation of organic matter and in the nitrification process of ammonia thanks to the presence of earthworms and their interaction with microorganisms present in the soil. The decrease in the concentration of these compounds (organic matter and ammonia) has consequently led to a decrease in odors emissions.

For this reason, in the future, earthworms could be used in the waste disposal sector, with reference to the vegetable waste sector and represent an innovative system for the elimination of odors deriving from this activity.

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