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Sustainable Reduction of the Odor Impact of Painting Wooden Products for Interior Design

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Abstract: The construction and building field represents a key sector for the recent Circular Economy Action Plan (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 consisting of the reduction of odor emissions, which produce negative impacts on the environment and a 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 to develop an innovative process able to combine the use of lower impact paints with a more efficient UV system for the abatement of the emissions.

Keywords: wooden door; VOCs; environmental footprint; environmental sustainability; emission abatement; interior design

1. Introduction

All kinds of products have an environmental impact during their life cycle, from their production to their final disposal. Product design defines more than 80% of the environmental load; therefore, sustainable choices must be made in this phase [1]. It is evident that product sustainability is a priority for 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 [2]. 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 [2]. The interior design market is strongly related to this sector since each building needs to be furnished [3]. In this regard, the wood painting shows many criticalities for its significant contribution to poor air quality and electricity consumption [3–6]. Doors are typical wood components inside 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 the environment, human health and personal welfare [7,8]. VOCs represent an important category, since they may also be toxic at low concentrations, causing severe effects when inhaled. For these reasons, their detection is important for the assessment of indoor air quality [9,10]. These pollutants, when emitted into the atmosphere, participate in the photochemical smog phenomena [11]. A further significant impact related to VOCs is odor emission, which often causes a strong and persistent annoyance for the population [12]. In more detail, odor is the property of a substance, or rather of a mixture of substances, capable of triggering the sensation of smell [13–16]. This aspect is the subject of increasing attention for the public administration and could be translated into consent decrease and economic loss for the companies responsible. Indeed, in communities exposed to odor emissions, even though there may be no immediate apparent diseases or infirmities, there is not an atmosphere of complete mental, social, or physical wellbeing [17]. Odor emissions are considered air pollutants that require immediate attention [18–21]. The World Health Organization has defined air pollution as the environmental risk with the highest mortality among developed countries, causing more than 150,000 deaths per year [22]. This has pushed the European Commission to issue directives focused on 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 [23–25]. As a consequence 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 [26,27]. The control of VOC (and odor) emissions can be carried out by different approaches, depending on the possible separation or destruction [16,28–30]. 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 towards odor emission abatement include: adsorption (by activated carbon, activated alumina, silica gels and zeolites), absorption, thermal oxidation, catalytic oxidation, photocatalysis, and membrane use [28,31,32]. Biological treatment systems mainly include biofilters and bioscrubbers/biotrickling [28,33,34]. Thermal treatment is one of the most common approaches; it involves the use of high temperatures (900–1000 °C) to oxidate VOCs to CO_2 and H_2O and it can be applied to any exhaust air [28]. The combustion system can be completely powered by VOCs. However, if the pollutant concentration is too low (a 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 (and are 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, innovative paints such as UV-based inks show many advantages: the reduction of solvent content (i.e., water-based paints, which can be dried by polymerization, ensuring a higher efficiency of the dye used) and the reduction of environmental impacts thanks to the lower solvent content and the consequently lower VOC release. In this context, the present paper aimed to evaluate two systems for 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 paired with a UV system for the abatement of emissions. The scientific literature reports many sustainability assessments in the building construction field; nevertheless, the interior design sector is often neglected [35–37]. Furthermore, most research is based on lab scale or literature data, and is not yet optimized for real world implementation. It often excludes the study of emissions detected during the production process [38,39]. The present paper aimed to help fill this gap in the literature thanks to the cooperation of a company which allowed us to consider a full-scale manufacturing chain of wooden 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 using the life cycle assessment (LCA) tool.

2. Materials and Methods

2.1. Case Study Description

The subject of this study is an Italian company specialized in wood manufacturing, mainly in door production. Considering the sustainability target and the strong interest for 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 that is able to completely substitute the current approach (a post-combustor). In more detail, the abatement system consists of UV painting and drying (Cefla UV2000); this technique uses paints with a lower content of VOCs and it is highly efficient at reducing odor emissions. The UV system allows for the polymerization and drying of the paints in a short time thanks to the photochemical reactions. The high-speed reaction makes the incorporation of VOCs during the reticulation possible, preventing the evaporation phenomena and the consequent environmental impact.

2.2. Emission Sampling

The emissions of the door production lines, the objective 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 European 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. Sampling took place through a grid to evaluate the distribution of the measures (the recorded parameters must be pressure difference, $\Delta P > 5$ 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 device included a filter, which was necessary to remove fine particles that could clog the burner. The system design ensured the minimum residence time (less than 60 s) 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 a purity of 99.998% avoided possible interferences during the analysis. The instrument allowed continuous measurement (every 12 s) of total organic carbon (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.

2.3. Environmental Sustainability Analysis

The assessment of the sustainability, using the LCA approach, allowed us to evaluate the environmental load of the door production processes, estimating the gain resulting from the use of innovative paint combined with a UV system for VOC abatement. In more detail, the analysis focused on the environmental impact due to the different energy consumptions required to verify the real advantage of the innovative technique. The study was carried out following the recommendation of International Organization for Standardization (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. The method selected was Environmental Footprint (EF) 3.0. Figure 1 describes the system boundaries considered for the assessment. In more 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 traditional painting and the following VOC abatement by a post-combustor. Scenario 2 includes the use of the UV painting and drying system, without further emission treatments. Scenario 3 represents an additional improvement on Scenario 2, thanks to the substitution of the average grid mix with the renewable photovoltaic technology for 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 to be 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 this company facility, this choice did not affect the effectiveness of the present study.

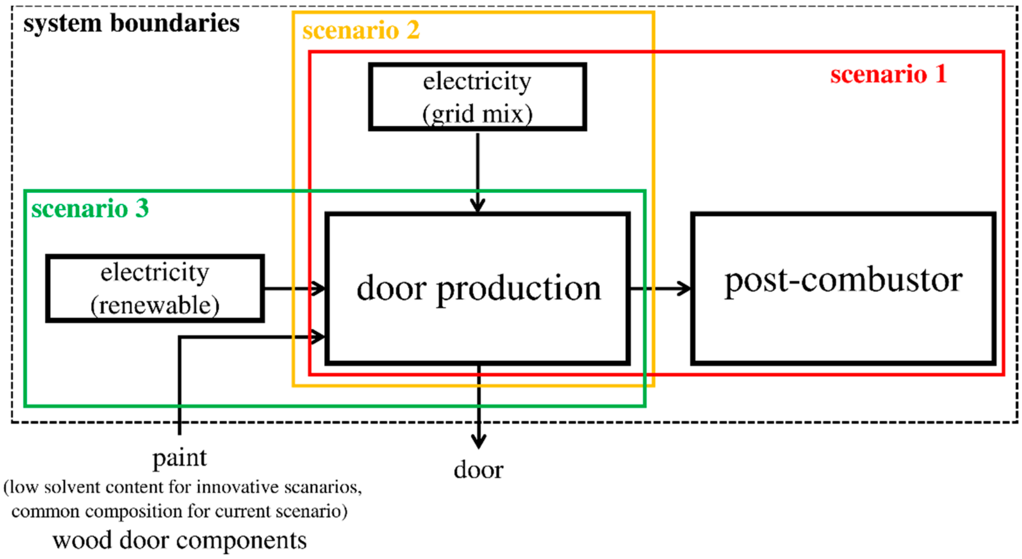

Figure 1. System boundaries considered for the LCA.

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 the post-combustor (Table 1). The variability of electricity consumption was due to the different models of door included in the assessment, with the aim of obtaining more consistent results. The highest efficiency of dye in the innovative paint allows a lower variability of electricity consumption, irrespective of the door model. For the electricity impact assessment, an average European grid mix was selected (in Scenarios 1 and 2) and a European mix of photovoltaic technologies was selected in Scenario 3. In regards to the methane consumption, we considered an operative time of the post-combustor of 12 h. Table 1 reports an average amount of methane supplied; nevertheless, this could increase up to 900 m^3 in the absence of VOCs (e.g., during the daily steps of ignition, cooling and work breaks), and it could reach zero if the quantity of VOCs is enough to power the combustor (this condition was excluded because it is extremely rare).

Table 1. Process consumptions considered for the LCA (functional unit: 10 t 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. Results

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 us 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 (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, which was 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 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 Regulations.

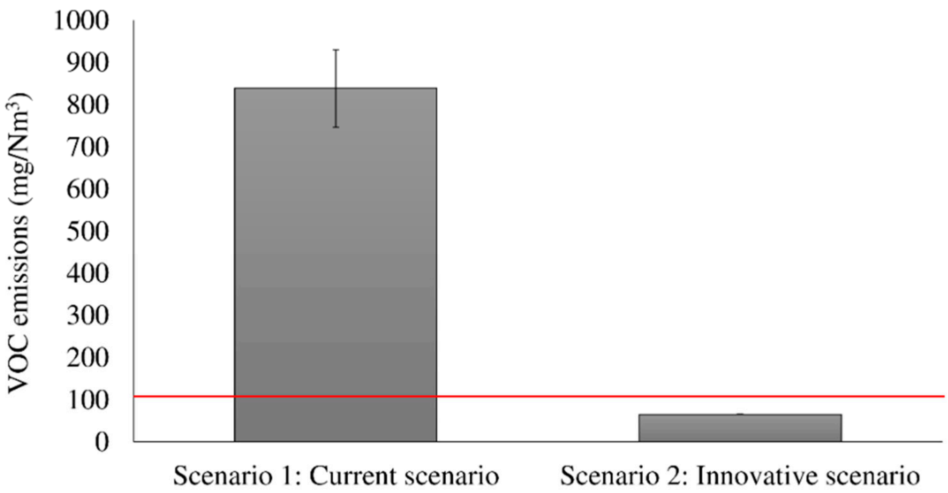

Figure 2. Emissions from door production chain: current vs. UV abatement systems. Red line represents the Italian legal limit for volatile organic compound (VOC) emissions.

3.2. *Environmental Sustainability Analysis*

The promising results of the innovative approach, observed in terms of a reduction in emissions, were confirmed by the assessment of the impacts of the process 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 that was on average five 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 methane consumption caused about 50% of the impact of Scenario 1. The innovative treatment also acted on the reduction of emission variabilities; indeed, the highest dye efficiency of water-based paints decreased the energy request for painting, irrespective of the door model. In regard to the post-combustor impact, the variability of the results was connected to the VOC flows to treat, considering both the daily working operation and the possible monthly production changes in 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 (Figure 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 consumption of the raw materials.

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 the door production chain from Scenario 1 to Scenario 2 considering the normalized and weighted results. The percentage grew up to 95% for the use of renewable energy. This achievement was mainly connected to the positive effect of the innovative approach on the categories of ionizing radiation, resource use, energy carriers and climate change, responsible for 40%, 40% and 14% of the impact of Scenario 1, respectively. The effect on ionizing radiation was mainly due to the electricity demand of the door production process; indeed, the European grid mix selected for the analysis includes about

26% of energy production from nuclear sources which cause, when combined with the mineral oil and gas extraction, the release of radionuclides [40,41].

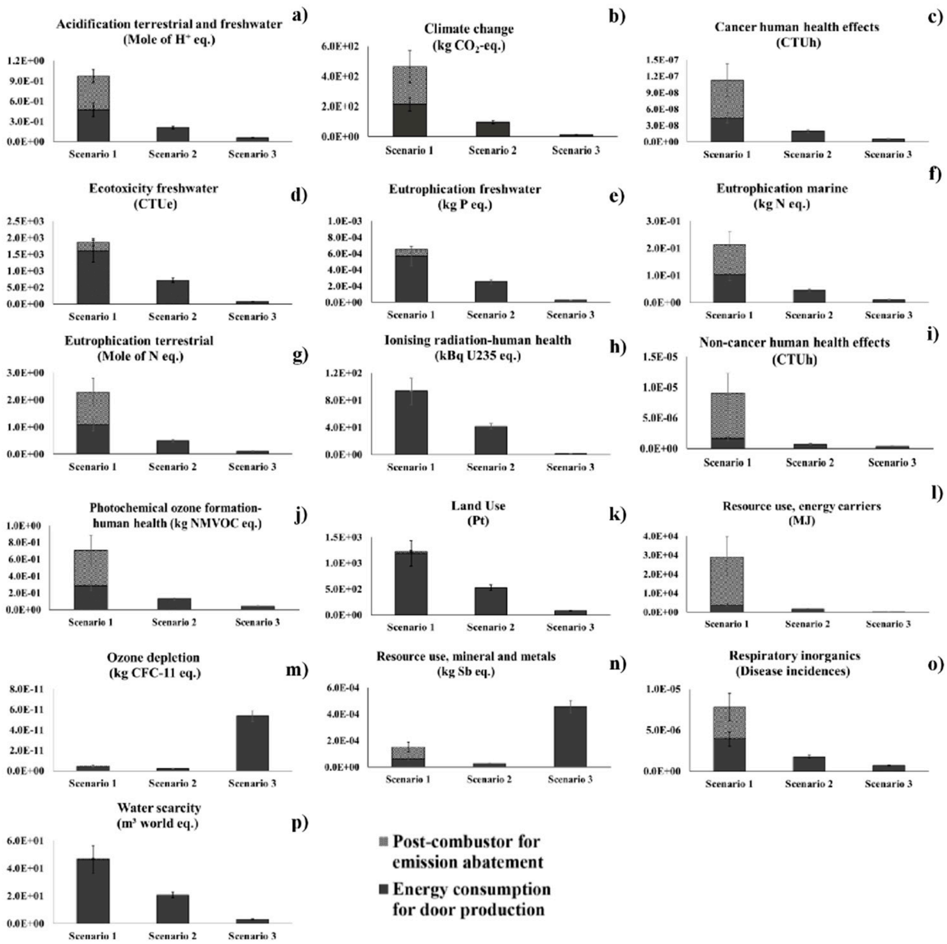

Figure 3. Results of LCA: classification and characterization steps (Scenario 1: current scenario; Scenario 2: innovative scenario; Scenario 3: innovative scenario combined with renewable energy use). Functional unit: 10 tons of wood products. Each letter (**a**–**p**) represents an impact category discussed in the manuscript.

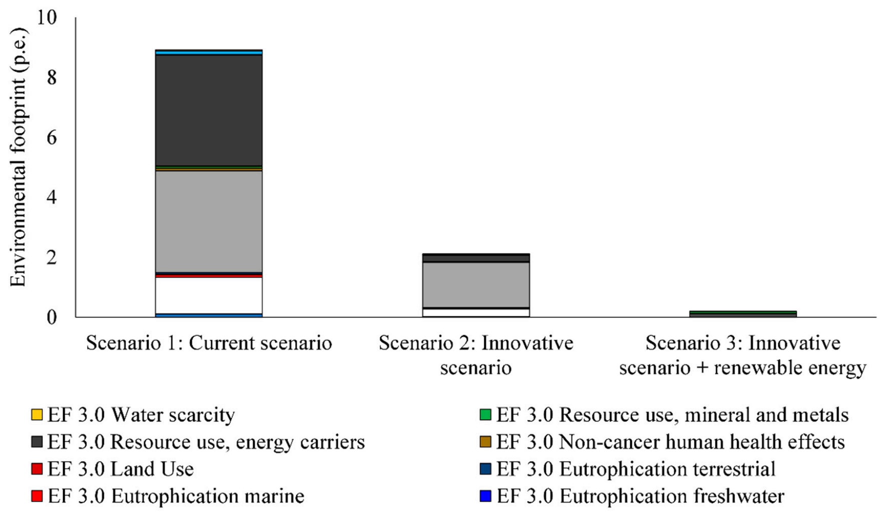

Figure 4. Results of LCA: environmental footprint, expressed as person equivalent (p.e.). Functional unit: 10 tons of wood products.

4. Discussion

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 for the production of wooden doors for interior design. The new approach aimed to substitute the current high impact manufacturing with an innovative system able to combine low solvent paints with a UV system for the abatement of emissions. The results were satisfactory, with resulting VOC emissions well below the regulation limit. This achievement was combined with a significant decrease in energy consumption, which translated into an environmental gain higher than 75%, which was 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 for the collection of representative data. Furthermore, it demonstrated the real interest of the company to move towards the reduction of their environmental impact, which is often translated into an economic and social gain.

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