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Enhancing Sustainability in Italian Water Supply Pipes through Life Cycle Analysis

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Abstract: The primary concern regarding the sustainability of the urban water cycle remains the performance of water supply systems. This, in turn, is determined by the functionality and sustainability of the system components, such as the pipe networks, pumps, and other appurtenances, which must be analyzed from an environmental perspective. The aim of the present study is to analyze the sustainability of two different types of water supply pipe materials that are commonly used, polyvinyl chloride and high-density polyethylene, using a comparative Life Cycle Analysis methodology. The functional unit was established in accordance with the water supply system that serves an Italian metropolitan city with a dimension of 9240 km, as one meter of water supply infrastructure, with 40 years as a life span. A cradle-to-gate analysis was conducted, starting from the production phase of the water pipelines to the maintenance phase, excluding the end of life and disposal phases. The chosen methodology was CML, justified by the fact that the results are more understandable and reproducible. Results comparison revealed a higher environmental impact during the production phase, while the maintenance phase had a very low impact. Notably, PVC pipe in comparison with HDPE material had a higher impact, except in two categories of impact: abiotic depletion and photochemical oxidation. The study contributes to the future development of alternative approaches for sustainable and eco-efficient water supply infrastructure designs and materials.

Keywords: environmental impacts; eco-friendly; life cycle analysis (LCA); pipe material; sustainability; water supply system

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1. Introduction

As the Brundtland Commission concluded that the fundamental concepts in policy generation are "sustainability" and "sustainable development", the new common goal has become "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [1,2].

In this context, water sustainability has become one of the most discussed topics worldwide in the last decade. Sectors involving water extraction from aquifers and water supply and sanitation (WSS) are facing increasing pressures, especially due to the impacts generated by the materials involved in terms of climate change, environmental pollution, ozone depletion, marine ecotoxicity, and waste accumulation [3–6]. When discussing water supply systems, the risks related to managing the system are primarily examined from the perspective of water consumers [7]. Water network operators are obligated to uphold services at an elevated operational standard, ensuring full adherence to safety and availability regulations concerning the cleanliness, purity, and taste of water. Additionally, they strive to promote environmental sustainability within waterworks infrastructure [8]. Specifically, there is a growing emphasis on the utilization of advanced technologies and analytical tools as indispensable tools for sustainability. These tools enhance our comprehension, facilitate efficient management, and promote judicious use of water resources [9].

After consulting studies on pipe utility, Fagan et al. [10] concluded that pipes have multiple uses, not limited to the construction industry, for erecting water supply and drainage systems for modern cities and housing, which are designed in accordance with general principles that are widely recognized and clearly defined in related legislation [11]. The most used are metal pipes; nevertheless, they are susceptible to damage due to the electrochemical reaction known as corrosion and present a potential risk of causing massive environmental and economic problems [4,12]. According to the EPA, corrosion is a part of the 15 mandatory water quality standards for drinking water contaminants [13]. The effects of the presence of corrosion are given by the metallic taste and the visible effects on the corroded pipes/bodies. In order to reduce these risks, non-metallic pipes, such as high-density polyethylene (HDPE) pipes and concrete pipes, have been used in recent years.

According to Hajibabaei et al. [14], the selection of the pipe material and the pipeline installation methodology are the main concerns in terms of impact assessment [15]. The most applied methodology to determine the environmental impact through an entire life cycle is Life Cycle Assessment (LCA). LCA is normally used to verify and ascertain the environmental impact of any activity and aims to examine all the effects produced on the environment [12,14,16].

Currently, the LCA methodology is used in many areas, such as eco-sustainable design, eco-labelling, waste management and other services, and the choice of production flows. This allow companies that use it to obtain the environmental impact of a product or service and be able to count on a competitive advantage derived from a market that is increasingly attentive and sensitive to eco-sustainability issues.

To evaluate the environmental impacts of a product, a service, or a process, the ISO standards of the 14040–14044:2006 series are available, which regulate the international Life Cycle Assessment (LCA) methodology [2,17–20]. This methodology allows the evaluation of energy and environmental loads along the entire life cycle. When speaking of "life cycle" analysis, we are referring to two aspects: the first is the verification of how much an entire system affects the environment, and the second lies in the analysis of the individual items of the cycle to improve the relative impact and identify critical issues in which to intervene.

In this study, life cycle analysis was developed for pipelines in the water supply sector, comparing various types of pipelines used within the Metropolitan City of Bologna aqueduct network, managed by an Italian multi-utility company. Studies conducted by the Italian multi-utility show that the pipeline materials present throughout the analyzed aqueduct network include polyvinyl chloride (PVC), high-density polyethylene (HDPE), cast-iron, steel, and cement/asbestos. Notably, PVC and cast-iron exhibit superior technical and mechanical performance. HDPE demonstrates the highest consistency within the networks, while steel boasts of a significant percentage of usage within the specific aqueduct network under analysis. Conversely, cement/asbestos pipelines are no longer considered, since the usage of such pipelines in recent years has been negligible. The use of polymeric pipes in water supply is gradually replacing cast iron and steel pipes. However, data on the environmental impacts of the polymeric pipes for water supply pipes in the Italian Metropolitan City of Bologna are scarce.

In specific, the study has as its objective assessing the environmental impact of two commonly used plastic pipes (PVC and HDPE) for water supply in the Metropolitan City of Bologna, using an LCA tool.

2. Materials and Methods

This study presents a Life Cycle Assessment of polyvinyl chloride (PVC) and high-density polyethylene (HDPE) pipes in the water supply system of an Italian metropolitan city. The environmental impact was assessed utilizing LCA methodology [18], a widely used approach for evaluating water supply systems [17,21,22]. LCA comprises four steps, presented in Figure 1.

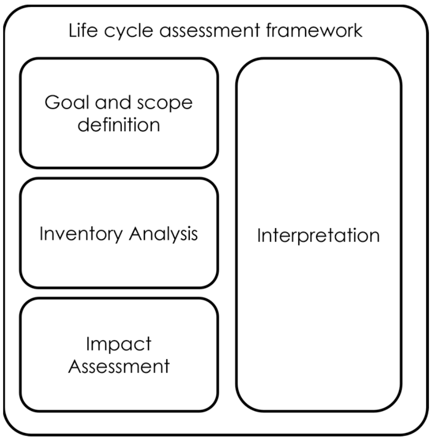

Figure 1. ISO framework for LCA ISO 14040.

This study employed SimaPro 9.2 software alongside the Ecoinvent v.3.8 [23,24] and Industrial Data 2.0 databases. This approach facilitated systematic and transparent modeling and analysis of diverse life cycles to assess the environmental impact of processes throughout selected life cycle stages, pinpointing critical areas (hotspots) across the entire chain [22,25]. SimaPro and Ecoinvent are commonly used for LCA studies due to their extensive availability of reliable data, user-friendly interfaces, and compatibility with each other. Ecoinvent provides a comprehensive and transparent database of environmental data, rigorously validated by experts. SimaPro, on the other hand, offers an intuitive platform for conducting LCA analysis, making the process more accessible and streamlined. Together, they ensure consistency, comparability, and accuracy in LCA results, making them preferred tools for researchers and practitioners in the field of environmental impact assessment. In addition, the CML-IA calculation method used to analyze various impact categories is a validated method employed by all LCA software.

2.1. Goal and Scope Definition

The objective of this LCA study was to assess the sustainability of two types of water pipes of different materials used for the water supply system in the Metropolitan City of Bologna to determine the type of plastic pipeline with the lowest environmental impact. The materials investigated were PVC pipe and HDPE pipe. Two different pipe diameters (90 mm and 125 mm) for water supply infrastructure were assessed. The specific goal was established to assess the environmental impacts resulting from the production, transportation, installation, and maintenance phases that constitute the life cycle of a water supply pipeline.

A functional unit (FU) serves as the criterion for comparing distinct phases by establishing relationships between inputs and outputs [18]. In an LCA for water supply infrastructure, inputs are used as the FU [21]. For this research, the choice of FU is one meter of water supply infrastructure with a life span of 40 years. The life span of the water pipelines at 40 years was selected in accordance with the minimum Italian legislative criteria and the guidelines of the multi-utility water company. This value ensures a safe pipe life span, although in practical cases, the pipes may last longer than the selected life span. A cradle-to-gate comparative analysis drove the assessment, starting from the pipelines' production to their maintenance phase, excluding the end-of-life and disposal stages.

2.2. Boundaries

The inputs are the materials, energy, and resources that enter the unit process, while the outputs are the products, waste, and emissions generated due to the process [23].

The LCA was conducted using a cradle-to-gate method and compared the environmental impacts of pipes made of different plastic materials (PVC and HDPE) and diameters (90 mm and 125 mm). The LCA considered the production, the transport, the installation, and the maintenance of the pipes in the assessment (Figure 2).

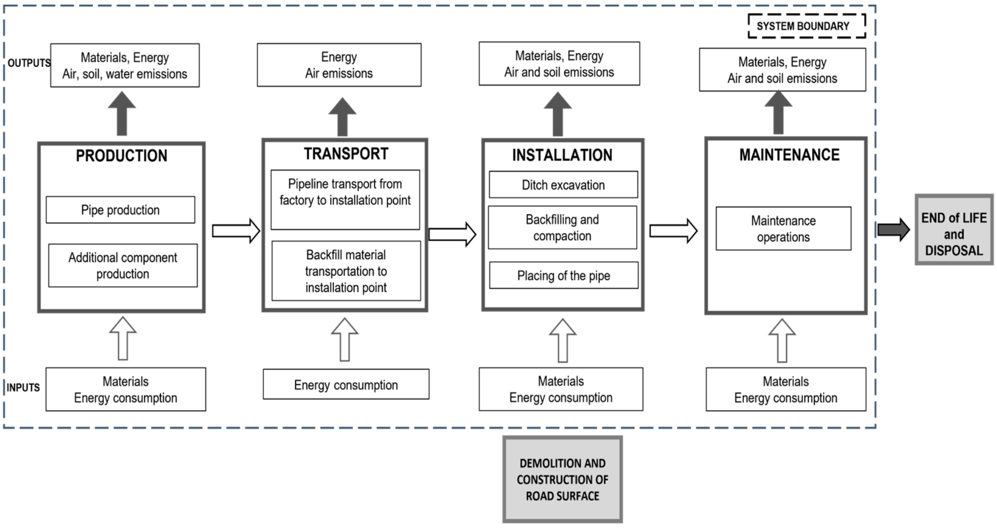

Figure 2. System boundary.

The life cycle typically commences with the extraction of raw materials, followed by their transportation to the pipe production factory. Subsequently, the manufactured pipelines are conveyed to the construction site for installation. This process encompasses the initial stages of material extraction and production, through to the final deployment of the pipelines. During the installation, a trench is excavated to accommodate the pipe, and the trench is backfilled after the pipe is installed [26,27]. Then, the maintenance operations for the pipeline are considered.

2.3. Life Cycle Inventory (LCI) Analysis

The primary inventory analysis was conducted utilizing the data provided by the waterworks company. To obtain product-specific data, the material quantities were estimated using precise measurements of dimensions or weights, ensuring accuracy in the assessment. Furthermore, process-specific data were meticulously gathered by performing a comprehensive time study analysis of each phase involved. Secondly, the collected data underwent rigorous scrutiny and evaluation to build the LCA model, ensuring its reliability and robustness. Finally, both primary data gathered directly from observations and measurements and secondary data obtained from reliable sources were synergically integrated to refine and enrich the study's modeling process. Background data was taken from the Ecoinvent v 3.08 and Industrial Data 2.0 databases, as well from the relevant literature, such as the guidelines followed by the multi-utility water company and [14,28].

The inventory of phases examined in this LCA study, as defined in SimaPro software, is described in the following subsections. Table 1 summarizes the list of items included in or excluded from the LCA inventory based on the LCA phases considered.

Table 1. Overview of items included and excluded in the analyzed phases of LCA.

LCA Phase	Included in the Analysis	Excluded from the Analysis
Production	Raw materials, pipe manufacturing, additional components for pipes	Production, maintenance, and end-of-life of production equipment
Transportation	Transportation distance, vehicle type, fuel consumption	Production, maintenance, and end-of-life of vehicles, transportation of raw material to the factory
Installation	Equipment for excavation and place of the pipes, materials required in trenches	Production and maintenance of installation machinery, pipeline dewatering, hydrostatic testing of the pipeline
Maintenance	Maintenance operations	Production and maintenance of equipment used in this phase

2.3.1. Production

The production of a typical HDPE pipe involves the use of HDPE material derived from the processing of granular high-density polyethylene, which is processed through the following two industrial processes [28]:

- Extrusion: industrial process for the creation of so-called 2D elements (duct);
- Injection molding: industrial process for forming elements defined as 3D (bends, fitting elements).

Similar production processes are followed for the manufacture of PVC pipe, starting from the processing of granular polyvinyl chloride.

The data on the normal pressure and diameter of pipes to be used were provided in the guidelines followed by the company that operates the waterworks.

2.3.2. Transport

The amount of environmental impact incurred during transportation is intricately tied to several factors, including the distance traveled, the specific type of vehicle employed, and the vehicle fuel consumption. This relationship underscores the importance of considering various variables when evaluating the environmental implications of transportation processes. The data about the transportation was provided by the waterworks company. The transportation distance from the pipe production factory to the installation site was considered equal to 215 km for HDPE pipelines and 175 km for the PVC pipeline.

On the other hand, the transport distance of backfill materials (sand and gravel) was assumed to be constant at 20 km.

2.3.3. Installation

The installation phase consists of trench excavation, sand bedding, laying of the pipe, backfilling, and compaction of the surface course. The dimensions of the trench are presented in Figure 3. In all cases, the trench was considered to be vertical. The specifications of the trench and thickness of the bed were indicated by the waterworks company guidelines and are shown in Figure 3. The depth of pipe was taken as 1 m from the ground surface to the top of the pipe. The pipe depth is based on the guidelines provided by the multi-utility company, and it is applicable throughout the Emilia-Romagna region in Italy. The pipes were assumed to be laid under unpaved road. Gravel was used for bedding, whereas sand was used for backfilling.

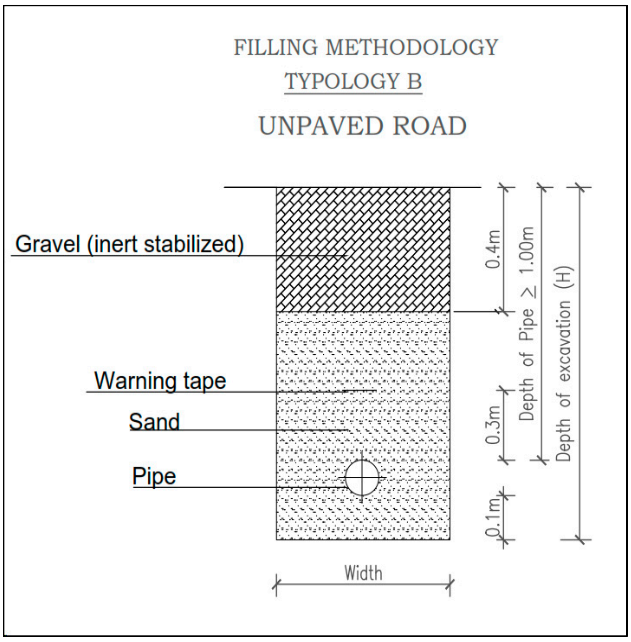

Figure 3. Dimensions and specifications of the trench.

A hydraulic excavator and compactor were considered for excavation, backfilling placement, and compaction of the surface course. The operating hours of the machines were taken from the literature [13,28].

2.3.4. Maintenance

The last phase of the LCA is represented by extraordinary maintenance of the water supply pipeline in the event of a burst. The maintenance activities are designed to restore to optimal operating conditions a water supply pipeline affected by a point break. The guidelines supplied by the company that operates the waterworks provide pipe material rupture rates over the 40-year life span and maintenance activities.

For a 1 km long pipeline that has a burst, the maintenance activities to be performed consist of replacing 1.5 m length of pipeline near the breakpoint. Therefore, the maintenance phase involves production of a new part of the pipeline, transportation to the site, excavation near the breaking point, replacement and installation of the deteriorated part, backfilling with new material, and disposal of the excavated material. However, in this study, the disposal of excavated material is neglected because the environmental impact is assumed to be insignificant.

2.4. Life Cycle Impact Assessment

The significance of the potential environmental impacts is evaluated by utilizing the comprehensive data obtained from Life Cycle Inventory (LCI). The analysis involves relating specific impacts with the inventory data, adhering to the guidelines outlined in ISO 14040:2006 [29]. Through this methodical approach, the LCI results are effectively translated into the environmental impacts from each scenario considered, thus providing valuable insights into the environmental ramifications of the assessed activities.

In this study, the CML-IA 2 baseline v 3.08/EU25 method was used, and mid-point impact categories investigated [30], focusing on the following seven (7) impact categories: Abiotic Depletion (ADP), Global Warming Potential (GWP100a), Ozone Layer Depletion Potential (ODP), Human Toxicity Potential (HTP), Photochemical Oxidation (PO), Acidification Potential (AP), and Eutrophication Potential (EP). These impact categories were selected after an extensive literature review and based on their application in environmental impact assessments of water supply pipe systems [12,14,25,28,30]. In addition, global warming potential, abiotic depletion, and human toxicity are used to highlight impact categories that relate to climate change.

3. Results

The findings of the study are presented in two parts. The first part focuses on the mid-point impact assessment, concentrating on the environmental impacts of comparing two common water pipe materials (namely PVC and HDPE with 90 and 125 mm diameters) to identify sustainable solutions among these alternatives. The second part shows the environmental impact associated with water pipe materials for the analyzed stages of the life cycle assessment.

Table 2 displays the impact assessment results for each impact category as well as for the CML-IA 2 mid-point level. Tables 3 and 4 provide insight into the relative contribution of each stage to the overall impacts.

Table 2. Impact assessment results for the various water pipe materials.

Impact Category	Units	Water Pipe Material			
		HDPE		PVC	
		Ø 90	Ø 125	Ø 90	Ø 125
Abiotic depletion	kg Sb eq	1.38×10^{-5}	1.47×10^{-5}	1.15×10^{-4}	1.74×10^{-4}
Global warming (GWP100a)	kg CO_2 eq	10.335	14.485	13.185	17.790
Ozone layer depletion (ODP)	kg CFC-11 eq	1.15×10^{-6}	1.24×10^{-6}	4.06×10^{-6}	5.85×10^{-6}

Table 2. *Cont.*

Impact Category	Units	Water Pipe Material			
		HDPE		PVC	
		Ø 90	Ø 125	Ø 90	Ø 125
Human toxicity	kg 1.4-DB eq	2.482	3.254	7.752	11.377
Photochemical oxidation	kg C_2H_4 eq	2.55×10^{-3}	3.94×10^{-3}	2.71×10^{-3}	3.71×10^{-3}
Acidification	kg SO_2 eq	0.034	0.046	0.053	0.072
Eutrophication	kg PO_4- eq	9.19×10^{-3}	0.013	0.016	0.022

Note: Values refer to functional unit of 1 m of water supply infrastructure.

Table 3. SimaPro results—normalized (dimensionless) values of impact of HDPE 90 mm diameter water pipe.

Impact Category	LCA Phase				
	Transportation	Production	Installation	Maintenance	Total
Abiotic depletion	1.18×10^{-13}	2.66×10^{-14}	1.79×10^{-14}	1.12×10^{-17}	1.62×10^{-13}
Global warming (GWP100a)	5.58×10^{-13}	9.56×10^{-13}	5.43×10^{-13}	1.28×10^{-16}	2.06×10^{-12}
Ozone layer depletion	5.83×10^{-15}	1.83×10^{-15}	5.17×10^{-15}	8.81×10^{-19}	1.28×10^{-14}
Human toxicity	1.42×10^{-13}	1.24×10^{-13}	5.36×10^{-14}	2.04×10^{-17}	3.2×10^{-13}
Photochemical oxidation	3.93×10^{-14}	1.82×10^{-13}	7.9×10^{-14}	1.76×10^{-17}	3×10^{-13}
Acidification	2.35×10^{-13}	4.7×10^{-13}	5.12×10^{-13}	7.79×10^{-17}	1.22×10^{-12}
Eutrophication	1.05×10^{-13}	3.36×10^{-13}	2.55×10^{-13}	4.32×10^{-17}	6.97×10^{-13}

Note: Values refer to functional unit of 1 m of water supply infrastructure.

Table 4. SimaPro results—normalized (dimensionless) values of impact of PVC 90 mm diameter water pipe.

Impact Category	LCA Phase				
	Transportation	Production	Installation	Maintenance	Total
Abiotic depletion	1.35×10^{-12}	1.01×10^{-13}	1.23×10^{-12}	1.79×10^{-14}	1.35×10^{-12}
Global warming (GWP100a)	2.62×10^{-12}	4.79×10^{-13}	1.6×10^{-12}	5.43×10^{-13}	2.62×10^{-12}
Ozone layer depletion	4.55×10^{-14}	5.01×10^{-15}	3.53×10^{-14}	5.17×10^{-15}	4.55×10^{-14}
Human toxicity	1×10^{-12}	1.22×10^{-13}	8.24×10^{-13}	5.36×10^{-14}	1×10^{-12}
Photochemical oxidation	3.2×10^{-13}	3.38×10^{-14}	2.07×10^{-13}	7.9×10^{-14}	3.2×10^{-13}
Acidification	1.89×10^{-12}	2.01×10^{-13}	1.18×10^{-12}	5.12×10^{-13}	1.89×10^{-12}
Eutrophication	1.19×10^{-12}	9.02×10^{-14}	8.47×10^{-13}	2.55×10^{-13}	1.19×10^{-12}

Note: Values refer to functional unit of 1 m of water supply infrastructure.

Characterization

The potential environmental impacts associated with each plastic water pipeline considered are shown in Figures 4 and 5. The results show that the HDPE pipe was the most environmentally friendly alternative for all the seven impact categories for the 90 mm diameter pipe, and in six out of seven impact categories for the 125 mm diameter pipe (except photochemical oxidation).

A comparative analysis reveals that PVC pipes exhibit the highest level of environmental impact among the considered materials. Table 2 shows that 17.8 kg CO_2 eq is released in the GWP categories of 125 mm diameter PVC pipe compared to 14.5 kg CO_2 eq of 125 mm diameter HDPE pipe. The greatest evidence of impacts can be seen between HDPE and PVC pipes in the categories of ADP (impact of PVC is 91% greater than that the HDPE pipe) and ozone layer depletion (impact of PVC pipe is 78% greater than that of HDPE).

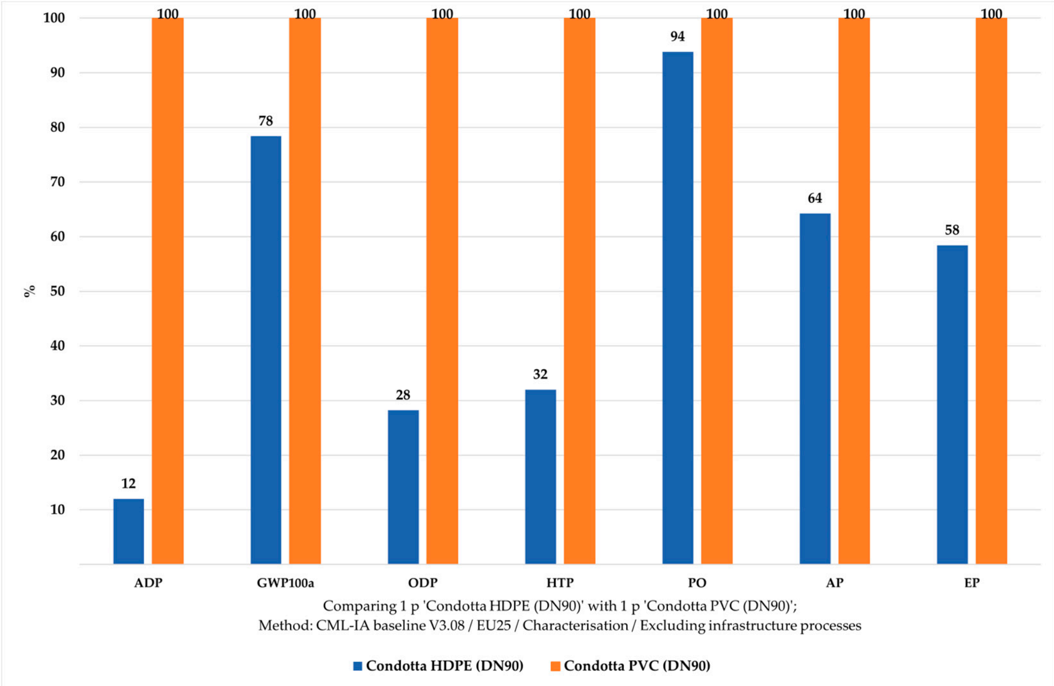

Figure 4. Comparison of impact results for HDPE and PVC with 90 mm diameter.

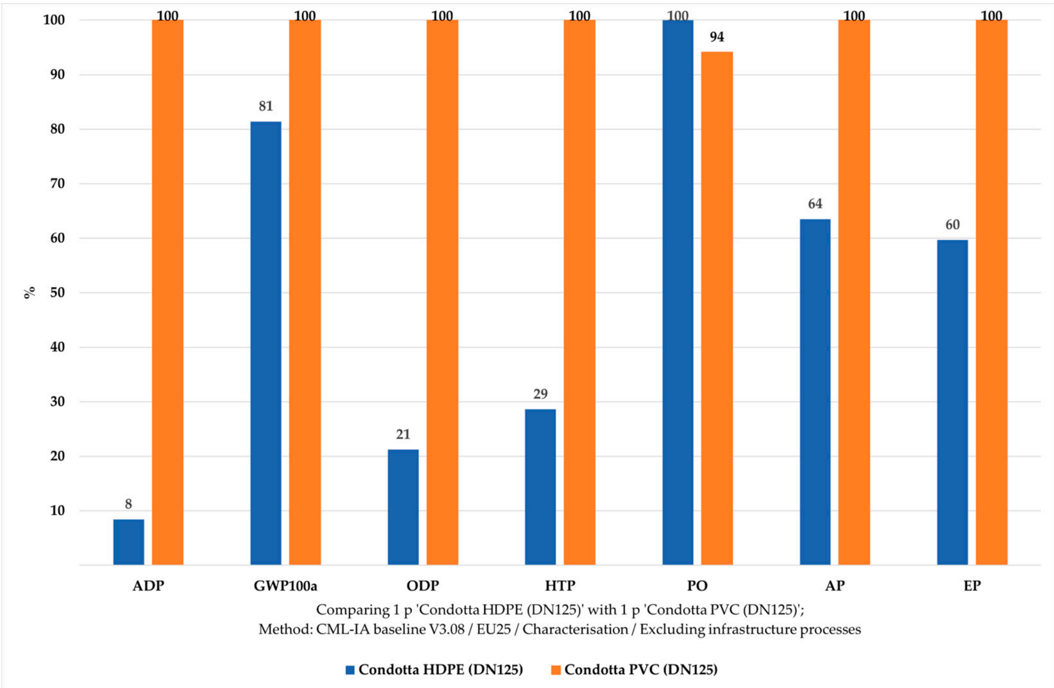

Figure 5. Comparison of impact results for HDPE and PVC with 125 mm diameter.

The 125 mm diameter pipes have higher environmental impacts than the 90 mm diameter pipes for both HDPE and PVC. The impact of the 125 mm diameter HDPE pipes was 6–35% higher than the 90 mm diameter pipe. Similarly, the 125 mm diameter PVC had an impact 26–34% higher than the 90 mm diameter.

Figure 6 illustrates the contribution of each life cycle stage to the environmental impact categories for the 90 mm diameter HDPE pipe. The same trend of results was obtained for the 125 mm diameter HDPE pipelines.

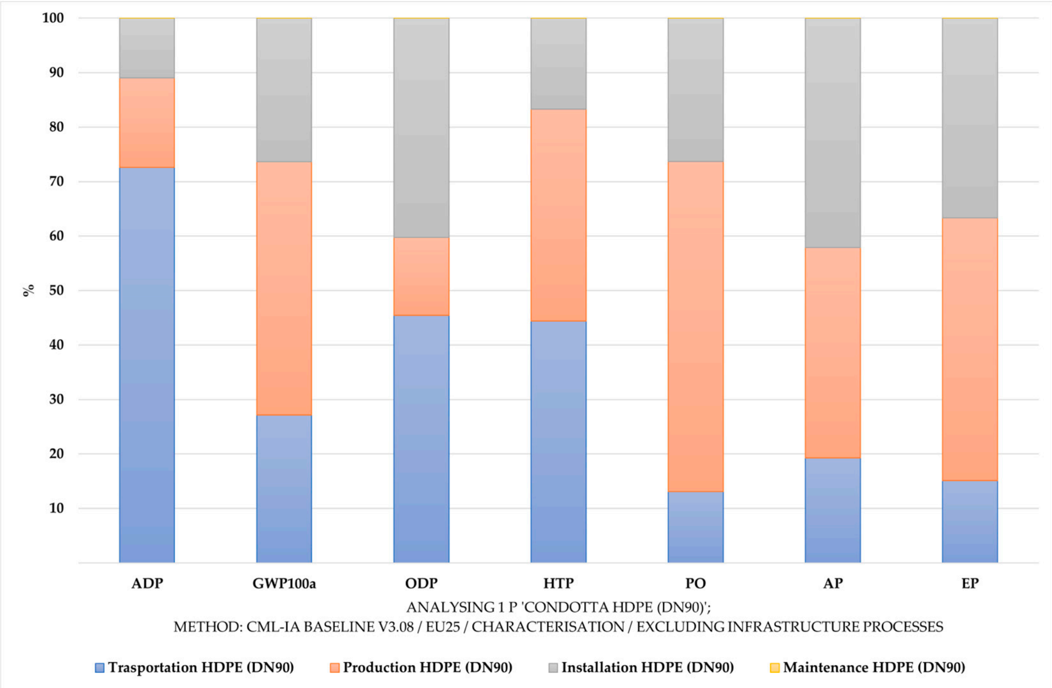

Figure 6. LCA phase contribution for HDPE 90 mm diameter pipe.

Figure 6 also indicates that the production phase is the largest life cycle impact stage in all categories except for abiotic depletion and ozone layer depletion. The production phase of the 90 mm diameter HDPE pipe contributes 16–61% for all impact categories. The installation phase of the 90 mm diameter HDPE pipe contributes 11–42% of all the impact categories. The transportation phase contributes 13–72% of all the impact categories. The contribution from the maintenance phase is insignificant, with less than 1%.

The phases of production and transportation are the main contributors, respectively responsible for over 73% of the impact in four out of seven impact categories (i.e., ADP, GWP100a, HTP, PO) and more than 57% in three out of seven impact categories (i.e., ODP, AP, EP).

Moreover, the LCA results of each impact category for the 90 mm diameter HDPE pipe are presented in Table 3. To provide clarity, the results for each category are normalized based on the scenario with the highest impact in that category. This normalization process ensures a clear and comparable understanding of the relative environmental implications across different scenarios [31].

Life cycle analysis of PVC pipelines shows a common trend for HDPE pipelines in the distribution of impacts with respect to the various stages considered.

Figure 7 indicates that the production phase is the largest life cycle impact stage in all categories. The production phase of PVC 90 mm diameter pipe contributes between 61 and 91% in all impact categories. The installation phase contributes 1–27% of all the impact categories, whereas the transportation phase contributes 7–18% of all the impact categories. The maintenance phase has an insignificant contribution of less than 1%.

Moreover, the LCA results of 90 mm diameter PVC water pipe for each impact category are presented in Table 4. To provide clarity, the results for each impact category are normalized based on the scenario with the highest impact in that category.

An uncertainty analysis was performed utilizing the Monte Carlo simulation technique, incorporating a 95% confidence interval.

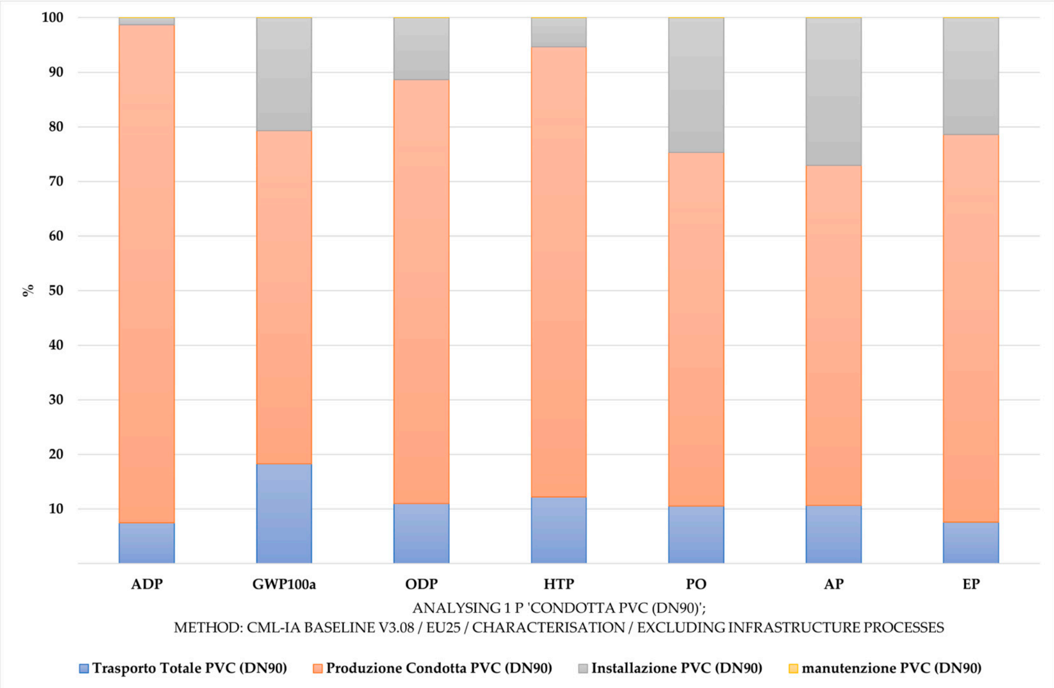

Figure 7. LCA phase contribution for PVC 90 mm diameter pipe.

4. Discussion

The high-density polyethylene pipes were the least impactful throughout their life cycle. PVC pipes have higher environmental impacts in all categories. Recio et al. [32] reported that the energy consumption (1055 kWh) and CO_2 emissions (454 kg) for producing 125 mm diameter HDPE pipe were 1.3% and 0.4% more than for PVC pipe. The production of PVC pipe has been noted by Alsabri and Al-Ghamdi [33] to consume more energy and contribute more to global warming than polyethylene pipe. This may be attributed to the use of chlorine in the manufacture of PVC. High energy consumption during the manufacturing of chlorine results in CO_2 and SO_2 emissions, which contributes to the high GWP100a and AP [34]. Similarly, in the production of PVC in China, Ye et al. [35] cited chlorine as the greatest contributor to human, terrestrial, and marine ecotoxicity.

Sanjuan-Delmas et al. [28] compared the environmental impacts of 90 mm diameter HDPE, PVC, ductile iron, and glass fiber-reinforced polyester pipes. They found similar environmental impacts for PVC and HDPE pipes, but PVC pipes were up to 10% less impactful in terms of ADP, AP and PO. Hajibabaei et al. [14] found PVC pipe to have a lower environmental impact on resources than HDPE pipe of the same size.

As in the previous studies regarding the life cycle impact assessment of pipelines used in water supplies systems [14,36], we observed that the impacts are generated by the primary material. The potential environmental impact of abiotic depletion, global warming, ozone layer depletion, photochemical oxidation, acidification, and eutrophication are more significant in the case of PVC pipe in comparison with HDPE. This finding underscores the significant role of PVC in contributing to environmental effects across various parameters and emphasizes the importance of exploring alternative materials to mitigate such impacts.

The current study revealed that the 125 mm diameter pipes had up to 35% higher environmental impact than the 90 mm diameter pipes for both HDPE and PVC. The production, transport, and installation of the pipes could be responsible for this observation. The weight of the pipe influences the amount of energy required for transport. In addition, the environmental impact of installing 90 mm diameter pipes (irrespective of material) is expected to be lower than the 125 mm diameter pipes. This is because the width and depth of the trenches for the 125 mm diameter pipes are more than that for the 90 mm diameter pipes. This increases the amount of energy and materials required for the production, transportation, and installation of the bigger diameter pipes [28]. In terms of the phases that contribute to the environmental impact, the results revealed that the production phase contributes to all impact categories except for photochemical oxidation, followed by the installation and transportation phase. This trend applies to both types of materials analyzed in the study.

The greatest contributor to the installation phase is the energy consumption for excavation, transport of backfilling material, backfilling, and compaction. To reduce the environmental impact, efficient trenching methods should be explored. For instance, the use of trenchless methods of pipe installation has been found to be less impactful than other traditional methods [14], such as open cut trenching, as was used in the current study area.

To address the environmental impact of end-of-life pipes, material recycling is gaining global attention. Ait-Touchente et al. [37] reviewed the literature on recent advances in PVC recycling. Their review shows that PVC recycling has greater environmental benefits and could significantly reduce greenhouse gas emissions. Similarly, the results of a study by Ye et al. [35] show that the production of recycled PVC has less impact than virgin PVC in all the impact categories. According to data from the Ecoinvent database, recycled HDPE granules are indeed less impactful compared to virgin ones in the categories AD, GWP100a, ODP, PO, and AP. However current Italian regulations do not permit the full utilization of recycled plastic materials for water supply pipelines, only as an addition to virgin material (see BS EN ISO 1452-1:2009 and BS EN 12201-1:2011) [38,39].

5. Conclusions

The environmental impacts of water supply infrastructure materials and their assessment through Life Cycle Analysis (LCA) are crucial topics for advancing sustainability in urban planning and construction practices. Addressing these issues contributes to the broader goals of reducing environmental footprints and promoting sustainable development in the context of global challenges. In this study, LCA methodology was used to assess the environmental impacts of 90 mm and 125 mm diameter PVC and HDPE pipes for the water supply system in an Italian metropolitan city.

A cradle-to-gate method was used to identify the most sustainable option from an environmental perspective. A functional unit of 1 m of water supply pipe was considered for a life span of 40 years. The LCA phases considered were production, transportation, installation, and maintenance of the pipes. The end-of-life and disposal stages of the pipe were excluded. The seven (7) impact categories assessed were Abiotic Depletion (ADP), Global Warming Potential (GWP100a), Ozone Layer Depletion Potential (ODP), Human Toxicity Potential (HTP), Photochemical Oxidation (PO), Acidification Potential (AP), and Eutrophication Potential (EP).

Considering both pipe diameters, the high-density polyethylene pipes are the least impactful throughout their life cycle. The PVC pipes had higher environmental impacts. In terms of the LCA phases, the production stage of the pipes had the largest environmental impact (61% of all seven impact categories). The transportation and installation phases showed similar impact contributions. Maintenance of the pipes had insignificant environmental impact. When the diameter of the pipe increased from 90 mm diameter to 125 mm diameter, the environmental impacts increased by about one-third for both materials.

The contribution of the 125 mm diameter PVC pipe to GWP was 17.8 kg CO_2 eq compared to 14.5 kg CO_2 eq for HDPE pipe. Considering the 90 mm diameter pipes, the values for the 125 mm diameter pipes were reduced by 26% for the PVC pipe and 29% for the HDPE pipe. HDPE pipes are environmentally sustainable options to replace PVC pipes for the water supply in this Italian metropolitan city.

The development of a tool based on LCA methodology for calculating the environmental impact assessment of water pipes, along with the incorporation of sustainable indices in public procurement processes for purchasing water supply pipes, derived from global warming potential results, are useful in developing alternative approaches for sustainable and eco-efficient water supply infrastructure design and materials.

The environmental impact of the use, end-of-life, and disposal phases of the pipes was not assessed in this study, even though it could be significant. This could change the impacts related to the various phases of the life cycle. However, the exclusion of end-of-life and disposal phases was made because the multi-utility company does not manage the end of life of the pipelines. Future research should extend this study to include the use, end-of-life, and disposal phases of the pipes.

Moreover, further research should be conducted to assess the sustainability of PVC and HDPE manufacturing processes as well as the lifetime of the pipes. The lifespan of the pipe affects the environmental impact of its application. From an economic perspective, an analysis of the manufacturing process chain could be performed, using suitable economic indicators. In terms of social sustainability, it is imperative to consider the multifaced impact of industry on the local community. This encompasses not only the direct effects on industry operators but also the broader implications of organization policies, community engagement initiatives, customer satisfaction metrics, and options for product take-back programs. By employing a range of social indicators, stakeholders can comprehensively evaluate the social footprint of industry activities, identify areas for improvement, and implement strategies to foster positive social outcomes and community well-being. Finally, the use of organic bioplastic pipes could be explored.

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