COMPARATIVE LIFE CYCLE ASSESSMENT OF PVC AND FRP PIPES THROUGH A GATE-TO- GATE APPROACH

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DEPARTMENT OF EARTH AND ENVIRONMENTAL SCIENCE

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A thesis submitted in fulfilment of the requirements for the award of
the Masters in Science (Environmental Sciences)

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Dedication

To my beloved father, whose unwavering support and boundless love shaped the person I am today. Your guidance and wisdom continue to inspire me in every endeavor. Though you are no longer with us, your spirit lives on in my work and in my heart. This thesis is dedicated to you, as a testament to your enduring influence in my life.

Muneeb Abrar

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ABSTRACT

The demand for water infrastructure systems has been steadily increasing. Over the past few decades, we have seen dramatic increases in urbanization that has substantially added to an already-enhanced need for improvement of wastewater infrastructure systems. Traditionally studies on sewer system design have been focusing on maximizing the economic advantages, while limited work has been done on the analysis of environmental impacts of sewer systems made of different piping materials. In the near future, the best environmental management practices will depend on the design and implementation of creative pipes with lower installation, long-term operation, and maintenance costs. Using SimaPro 7.1.8 LCA software, the life cycle assessments (LCAs) of two different water pipe materials— Polyvinyl Chloride (PVC) and Fiber Reinforced Polymer (FRP)—as well as their environmental implications are examined in this work. In our investigation, 13 kg pipe having a diameter of 4 inches and a length of 5 meters was designated as the functional unit. When comparing pipe materials, environmental effects such as Aquatic Eco toxicity, Aquatic acidification, Aquatic Eutrophication, Respiratory inorganics, Global Warming Potential, Ozone layer depletion, Respiratory organics, Non-carcinogens, Carcinogens and Ionizing radiation were measured. The findings indicate that out of all the phases involved in pipe manufacturing, the production phase has the greatest impact on the environment. Fossil fuel is the area most affected by pipe systems, and out of two, PVC has the greatest impact and FRP has the least impact on the majority of these areas.

Keywords: Life Cycle Assessment, Polyvinyl Chloride (PVC), Fiber Reinforced Polymer (FRP), LCI, Environmental impacts, BEES, IMPACT 2000+

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LIST OF ABBREVIATIONS

Abbreviation	**Full Form**
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
PVC	Polyvinyl Chloride
FRP	Fiber Reinforced Polymer
FU	Functional Unit
GWP	Global warming potential
AT	Aquatic toxicity
AA	Atmospheric acidification
EU	Eutrophication
OLD	Ozone layer depletion
ISO	International Organization for Standardization
GHG	Greenhouse gases

1. INTRODUCTION

1.1 Background:

The Life Cycle Assessment (LCA) is a standardized approach (ISO, 2006) that evaluates a product, service, or activity's environmental performance over the course of its lifespan (Loubet, Roux, Loiseau, & Bellon-Maurel, 2014). The International Organization for Standardization (ISO) has given this data. As per loubet, Roux Loiseau, & Bellon-Maurel (2014), the Life Cycle Assessment (LCA) is a standardized approach that evaluates the environmental Performance of a service, good or activity across its whole life cycle, as per the International Organization for Standardization (ISO, 2006).

The ISO Environmental Management Standards, such as ISO 14040 (2006) and ISO 14044 (2006), specify the Life Cycle Assessment (LCA) methods. In an effort to better understand how their activities and products affected the environment, industries first created life cycle assessment (LCA) in the 1960s. Over time, the scope of life cycle assessments (LCAs) grew to encompass not only energy consumption but also other environmental aspects like as pollution, resource depletion, and greenhouse gas emissions. LCA frameworks were first used to study wastewater systems in the 1990s as part of a larger trend towards sustainable water management. It was acknowledged that the energy use and emissions from urban water and wastewater systems have a substantial impact on the environment.

To ensure high water quality, infrastructures must be managed efficiently within the urban water cycle framework. The World Bank (2014) estimates that 53% of people on Earth now reside in cities, a number that is expected to increase to 70% by 2050 (UN 2012). As a result, there will be an increase in the construction of new infrastructure related to water and an expansion of existing infrastructure. The condition of much of the world's pipe infrastructure is poor and only grows worse with time. The majority of the pipes in the water and wastewater system have achieved or exceeded their anticipated 50–100 year lifespan, which is the cause of its unstable condition. According to a 2007 survey by the American Water Works Association (AWWA), there are 16% on average "unaccounted for" or "unbilled" water leaks, with some leaks exceeding 50% (Tafuri & Selvakumar, 2002). The environment, public health, and water rates in the US are all significantly harmed by water leaks.

Many metropolitan water infrastructure systems in North America, such as subterranean water and wastewater piping networks, are nearing the end of their useful lives, which range from 50 to 75 years (Younis and Knight, 2010). It is challenging to meet the increasing demand for new urban water infrastructure, particularly in light of the current budgetary and environmental constraints. Reactive asset management, which only performed rehabilitation or repair after a pipe failed, was the strategy utilized in the past to address issues brought on by ageing sewer pipes. Conventional infrastructure management ignored the long-term socio-economic ramifications and the effects on the environment in favor of maximizing financial gains (Mirza, 2007). Unfortunately, because this kind of strategy only took short-term costs into account, it was determined to be unsustainable.

The selection of pipe material in a water distribution network is dictated by the design criteria, which are derived from geological, hydraulic, static, and economic assessments. The cost/effectiveness ratio is a crucial factor in this process. The use of cost comparison criteria has been made mandatory by new regulatory rules stricter with regard to the life cycle of materials and the effects they have on the environment. This type of evaluation requires a framework, such as life cycle assessment (LCA) that compares different material types based on the environmental consequences of their life cycles.

The quality of a plumbing system's component elements and installation affect its longevity and functionality. The way a material interacts with construction and control activities determines its life cycle performance, rather than the material itself. Because materials can affect biological growth and can result in sags, leaks, and roots depending on the type of installation work, they are important for both the durability and deterioration of pipe construction. As a result, maintenance takes on greater significance when construction errors occur.

An effective tool for assessing the environmental impact associated with mass and energy fluxes into and out of the product under analysis is the life cycle assessment (LCA) approach. It was first established in its current form by ISO 14040/2006 standards. The validity and significance of life cycle analysis are combined, since it is well recognized that lowering environmental expenses before and after production allows the mitigation of environmental consequences (Stavropoulos, Giannoulis, Foteinopoulos, Papa charalampopoulos, &2016; Chryssolouris).

Consequently, appropriate material types and high-quality installation work should be considered for a thorough upgrade of the water and wastewater infrastructure (A Petit-Boix et al, 2014). Enhancing life-cycle performance has several benefits, including lower installation costs, reduced water leakage, resistance to corrosion, and reduced maintenance during the life of a pipe infrastructure system. It is now the solution to many issues with water and wastewater infrastructure. Two distinct pipe materials PVC and FRP have been examined for a sewer system in this study.

Table 1: Characteristics of PVC & FRP piping materials

Material	**Application**	**Key Advantages**	**Key Disadvantages**
PVC	Low pressure on pipes up to 36 inches in diameter	Not corroded, lightweight	Appropriate only for low pressure and small pipe sizes
FRP	Sizes up to 72 inches are available in moderate pressure.	Not corroded, lightweight	Expensive

PVC pipes are widely used in the plumbing, drainage, irrigation, power, and telecommunications sectors, as well as in the ductwork of heating and cooling systems in both residential and commercial settings. Utility companies provide drinking water to homes and businesses using a network of subsurface PVC pipes with thicker walls and greater diameters. Because pipeline is lightweight and mobile, it is simple to lay across long distances. Because it is mass produced using a relatively simple process, it is reasonably priced. It can withstand a great deal of abuse and is robust and long-lasting. Because PVC has a low carbon content during production, it emits less hazardous gases.

FRP is a perfect composite for liquid applications since it resists rust and weather. Applications for fiberglass reinforced plastic (FRP) pipes in industrial products include the processing and transportation of corrosive materials and goods in corrosive conditions. FRP pipes are utilized for a wide range of applications, including the handling of flammable materials in retail outlets and water and sewage pipelines in the municipal and industrial sectors. Furthermore, FRP has antibacterial properties, preventing microbial growth in these pipes. These are also lightweight, which makes transportation and installation easy.

Despite the widespread knowledge that sewage systems may have an influence on the environment at any point during their life cycle, including manufacture, transportation, installation, and use, very few studies have examined the environmental impact of wastewater systems from a life cycle assessment (LCA) perspective. Anders and Anders (1997) assert that because the installation phase of a sewer system necessitates the removal of materials, excavation, and energy consumption, it is crucial. On the other hand, Duet al. (2013) noted that the manufacturing stage of pipes accounts for 92–99% of the potential for global warming, with relatively minimal contributions from installation and transportation. Moreover, according to Strutt, Wilson, Shorney-Darby, Shaw, and Byers (2008), the production and installation stage's CO2 emissions will not be included if the pumping energy is taken out.

Improving life-cycle performance is currently the answer to many issues with water and wastewater infrastructure. Numerous benefits result from this, including reduced installation costs, less water leakage, resistance to corrosion, and less maintenance needed during the life of a pipe infrastructure system (E Vahidi et al, 2016). For a water networking system, four distinct pipe materials like ductile iron, concrete, PVC, and fiber-reinforced polymer have often been taken into consideration. Due to their technological advantages in the pipe transportation, installation, and service stages, PVC and FRP materials may be regarded as the more affordable alternatives to conventional ductile iron and concrete materials (Turner, 2007).But in order to build and maintain water pipe networks, more ecologically friendly biomass materials must be developed in light of growing worries about climate change (Faria and Guedes, 2010).

1.1 Research Gap:

Traditionally on sewage system design have often concentrated on optimizing the financial benefits (Mirza, 2007), while the environmental impacts and long-term socio-economic consequences are largely ignored. For instance, it has been noted that PVC and FRP materials offer affordable substitutes for standard materials, and that there are frequently financial benefits connected with their use, installation, and transportation phases (Bank, 2006; Turner, 2007; Hollaway, 2010). It is critical to take into account the environmental consequences of these materials as worries about their effects on the environment, climate change, and the depletion of natural resources grow (Turner, 2007; Faria & Guedes, 2010). This study's primary objectives are to measure the environmental effects of FRP and PVC pipe materials in sewer systems and to provide guidance for pipe material selection that optimizes environmental performance throughout the life cycle.

1.2 Problem statement:

Water networking system contribute to the degradation of natural environment and deterioration of human health at different stages of its life cycle, in this regard every stage of its life cycle requires evaluation. Therefore, this study finds out environmental impacts at manufacturing stage of two different type of pipe material.

1.3 Study Objectives:

The present study aims:

- To conduct the material specific LCA of two water pipe types at manufacturing stage.
- To compare the LC of two pipe types with respect to environmental impacts.

1.4 Significance of study:

- This research offers recommendations to decision makers for choosing water supply systems that will improve life cycle performance.
- Study will also bring the most ‘popular’ piping materials in the water system industry out of two selected ones and examine their advantages and disadvantages in comparison to one another more closely.

2. LITERATURE REVIEW

Previous researches has examined the possible environmental impacts of choosing pipe materials for water distribution systems. For instance, (Dennison et al.1999) examined the relative contributions of energy, materials, and manufacturing to the material-dependent global warming potential (GWP) without comparing the two materials as a whole. The total CO2 emissions from the production and use of a fictitious 20.3 cm (8 in.), 500-foot pipe over a 50-year lifespan were rated for four different pipe materials by (Piratla et al., 2012). Over the course of the pipe's lifetime, polyvinyl chloride (PVC) produced the least amount of equivalent CO2 emissions. (Herstein and Filion 2011) extended water distribution system planning beyond the consideration of economic objectives alone by introducing a multi-objective optimization approach and a unique environmental index. For the most part, environmental and economic goals were met together since pumping energies tended to dominate their environmental index (Herstein et al. 2011).

As per Statistics Canada (2011), the construction sector in Canada accounts for approximately 4 to 6% of the country's GDP, which has experienced a growth of 42.7% during the past ten years. Conversely, between 1990 and 2010, the building sector's energy consumption and greenhouse gas emissions rose from 8.9% to 11.7% (Nyboer & Kamiya, 2012). In order to meet the expanding demand of Canada's population, research into sustainable and green construction approaches is therefore desperately needed. Around the world, a lot of research projects are being conducted to create new techniques, paradigms, and instruments for assessing how "green" infrastructure is. Investigations of sewer networks, a crucial subterranean infrastructure, should take the economy and ecology into account.

This chapter's goal is to give background knowledge on the many facets of the research. A thorough literature analysis covering issues including the function of sewer systems in urban areas, types of sewer systems, and their materials and construction is presented in order to fully understand the multidisciplinary character of this research. In keeping with this, a brief overview of the development of these subterranean networks is given. Later parts cover topics related to emergency preparedness, multiple-criteria decision making (MCDM), and lifecycle approaches.

According to study, externalized costs like greenhouse gas emissions have a major impact on the total cost of building and operating a water distribution system. In order to be used in two ways, (1) constructing actual pipe networks and (2) reevaluating the standards used to choose the best pipe diameters, material-dependent GWPs were arranged as functions of pipe diameter. To improve the economics of pipe system alternatives in a southeast Tucson, Arizona, high growth planning area, LCA estimations of GWP were monetized.

Thanks to advancements in life cycle analysis (LCA) techniques, the examination of environmental effects resulting from water distribution and wastewater collecting systems has become more pertinent. Previous research has examined the possible environmental impacts of choosing pipe materials for water distribution systems. For instance, Dennison et al. (1999) did not evaluate the two materials holistically; rather, they examined the fractional contributions of manufacturing, materials, and energy to material-dependent global warming potential (GWP). Piratla et al. (2012) ranked overall CO2 emissions from the manufacture and use of a hypothetical, 20.3 cm (8 in.), 500 ft pipe over a 50-year lifetime for four different pipe materials. Molecular oriented polyvinyl chloride (PVC) provided the lowest equivalent CO2 emissions over the lifetime of the pipe. Herstein et al. (2009) and Herstein and Filion (2011) introduced a multi objective optimization technique and a unique environmental index to extend water distribution system planning beyond the consideration of economic objectives alone. Because their environmental index tended to be dominated by pumping energies, environmental and economic objectives were jointly satisfied for the most part (Herstein et al. 2011). Recio et al. (2005) examined the life cycle energy consumption and associated greenhouse gas (GHG) emission associated with concrete pipes, polyvinyl chloride (PVC), high density polyethylene (HDPE), polypropylene, and ductile iron. That study indicated that externalized costs such as GHG emissions contribute significantly to the overall cost of water distribution system construction and use.

On the other hand, few research using LCA for pipe system analysis were discovered. Water supply pipe systems are crucial components of municipal infrastructure, and the best water pipe systems can be chosen using LCA results to minimize environmental effect. According to Lippitt and Boyles (2001), life cycle assessment (LCA) considers all phases of a water pipe's life cycle that may impact the environment or the economy, including pipe material extraction, maintenance, and disposal. Wastewater from buildings is collected by the pipe network, which occupies a significant amount of underground area in cities, and is then transported to disposal sites. Sewerage pipe systems have a significant environmental impact throughout their life cycle since they are the lifelines of contemporary cities (Halfawy et al., 2008). In the past, choosing pipe materials for the water pipe system design phase was primarily focused on maximizing economic value (Mirza, 2007), with little attention paid to the effects on the environment and society.

Greenhouse gas (GHG) emissions are among the most significant environmental issues. According to a paper by Venkatesh et al. (2009), the production of ductile iron pipes resulted in fifteen times greater greenhouse gas emissions compared to concrete pipes due to the significant energy consumption associated with the zinc coating. PVC or polyethylene (PE) pipelines were the most appropriate materials because of their low cost, strong ductility, and capacity for tiny pipe diameter, even though the fabrication of plastic pipelines resulted in much higher GHG emissions than those of concrete pipes (Venkatesh et al., 2009). Recio et al. (2005) also looked at the energy usage and greenhouse gas emissions of pipes constructed of various materials, including polyethylene, PVC, ductile iron, polypropylene (PP), and concrete.

Anderson & Ochoa (2006) PVC demonstrated, on average, lower energy consumption and emissions during production when compared to concrete and ductile iron pipes in their life cycle assessment (LCA). However, complications with recycling and disposal during its end-of-life phase were recognized as concerns. Van van Velden et al. (2014) study emphasized the effects that PVC's production of chlorine, a crucial component that greatly adds to global warming and the possibility of ozone depletion, has on the environment. Even while PVC has many advantages in terms of performance and durability, there are major environmental costs related to its manufacturing and disposal, so it is important to concentrate on more environmentally friendly alternatives or efficient recycling techniques.

Chlorine-based techniques were found to have a greater influence on PVC pipes throughout the production phase. PE pipes experienced problems with disposal even though they had less of an influence on production. Overall, the research indicated that practical and environmental considerations should be taken into account when deciding between PVC and PE (Al-Hussein et al. 2014). Some of the initial production consequences were lessened by the exceptional durability and recyclability of cast iron pipes. Nevertheless, they used a lot of energy during manufacture, which led to a large amount of carbon emissions (Chi et al. 2016). When compared to certain traditional materials, composite pipes were found to have lower overall impacts due to their lengthy service life and low maintenance requirements.

HDPE had the least overall environmental impact among PVC, HDPE, and DI for water distribution networks, according to a study by Bilec et al. (2010). When economic and environmental concerns are taken into account, PVC turns out to be the most economical option. According to Alvarez et al. (2015), due to its protective coatings, DI performed better in areas with high corrosion potential. Their research on water distribution systems in urban areas revealed that local conditions (soil type, water quality) significantly affected the environmental performance of materials.

Nevertheless, because synthetic resins were used during production, there were still noticeable negative effects on the environment (Vasilenko et al. 2017). The results of the study showed that although metal pipes particularly those made of steel and cast iron had greater effects during the production stage, their long-term environmental advantages came from their durability and recyclability. Despite having less of an impact on manufacturing, plastic pipes had difficulties when it came time to dispose of them.

Although composite pipes performed well in terms of endurance, recycling was a problem (Schneider et al. 2020).

According to the study, the production stage had the biggest influence on the environment, especially when it came to energy use and greenhouse gas emissions. According to Guo et al. (2015), end-of-life recycling had substantial environmental advantages while the usage phase had less of an influence. But in order to build and maintain water pipe networks, more ecologically friendly biomass materials must be developed in light of growing worries about climate change (Faria and Guedes, 2010).

The research on lifecycle assessment (LCA) of water piping materials shows that there isn't a material that is always better; rather, the selection is based on certain operational, financial, and environmental considerations. When it comes to production-related effects, PVC and HDPE usually perform better than ductile iron and concrete, but metals are better in high-pressure systems and can be recycled. In order to make the most sustainable choices for water infrastructure, future life cycle assessments (LCAs) must take into account developments in materials science and recycling technologies that as well as regional considerations and long-term performance.

3. MATERIALS AND METHODS

3.1 Material:

3.1.1 Data Collection

LCA requires certain information at each stage of the analysis (i.e., production). Data for the LCA will be gathered from every resource that was accessible.

3.1.1.1 Primary Data:

- Obtained from two manufacturing sites located within the premises of Rawalpindi and Islamabad namely Accufit plastic (pvt) Ltd (Industrial Area Rawat, Islamabad), Al-Meezan PVC pipe industry (Industrial Area Rawat, Islamabad) by analyzing raw material composition & various energy sources used at product manufacturing.

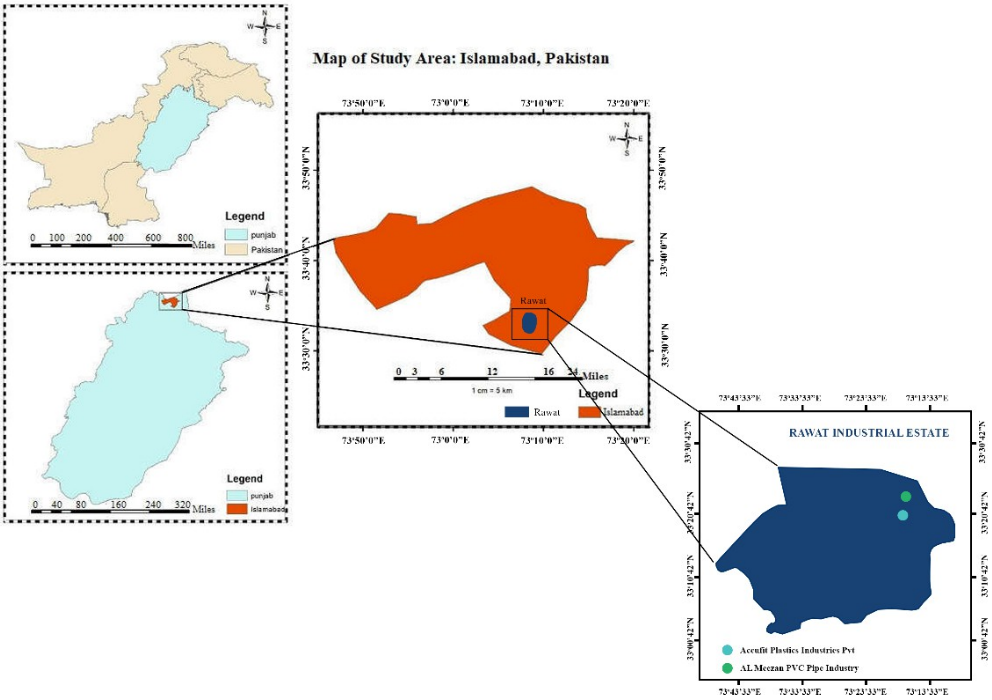

Fig: 3.1 Map location of data collection sites

- Personal communication with private companies

3.1.1.2 Secondary Data:

- From environmental reports
- Archival scientific literature

3.2 LCA Methodology:

Throughout a product's life cycle, including the extraction of raw materials, their transportation, processing, manufacturing, and transportation, life cycle assessment (LCA) can be applied (SAIC, 2006). In this study, we use a Gate-to-Gate technique that focusses only on product manufacturing. This approach makes it possible to evaluate a product's environmental impact based on the materials and energy it uses and generates. ISO 14040 (2006) LCA methodology is used which comprises the following steps:

- Determining the objectives and system limits of analysis through the definition of goals and scope.
- Analysis of the life cycle inventory for the quantification of the collected data such as LCA input sand corresponding outputs.
- Assessment of the LCA results and their impacts on different environmental factors. During this stage effects are categorized according to various environmental impact categories to get indication values that are particular to a given category.
- Interpretation to evaluate and condense the findings from the earlier phases in order to arrive at a significant conclusion.

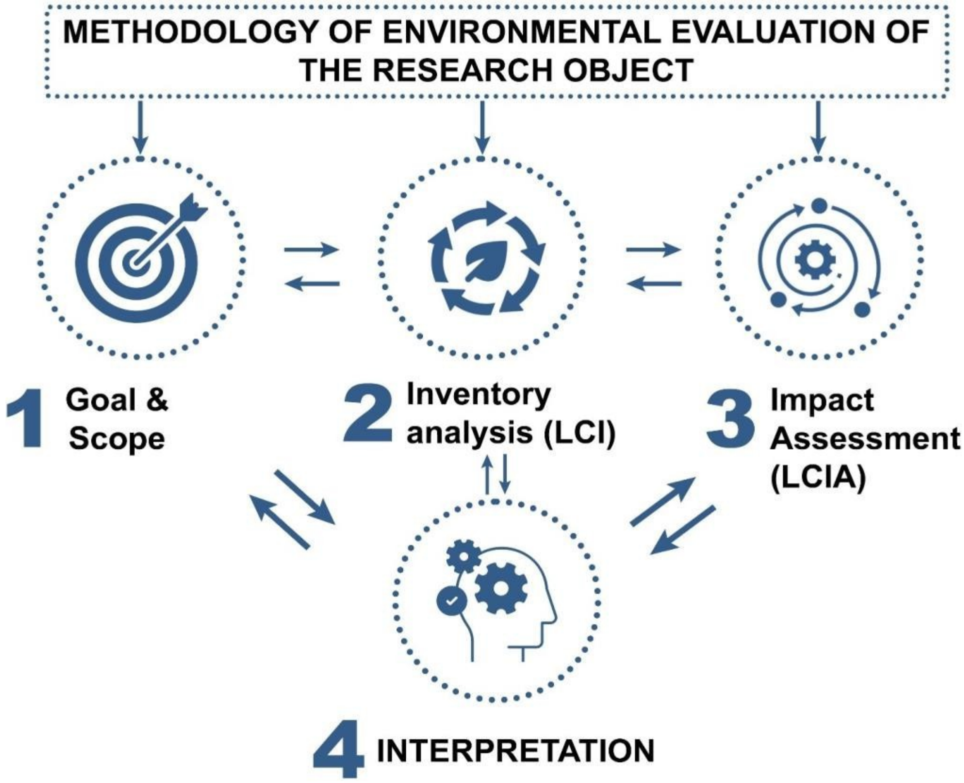

Fig: 3.2 Life Cycle Assessment Methodology

The integrated process used to choose ecologically optimal designs from a pool of physically equivalent configurations is described in this section (Fig. 1). The structural analysis was incorporated into the four phases of life cycle assessment (LCA) (ISO2006) following the establishment of the functional unit (FU) to facilitate the defining of the system boundaries. The life cycle impact assessment, life cycle inventory, aim and scope, and interpretation are these steps.

3.2.1 Functional Unit:

The FU of this analysis is sewer pipe (PVC& FRP) of 13kg mass having a length of 5 linear meter with standard diameter of 110 mm (4 inches), nominal pressure of 0.6MPa and thickness of 3.7-4 mm respectively.

3.2.2 System Boundary:

The life cycle of wastewater pipes consists of four stages: installation, transportation, use and maintenance, and raw material procurement and manufacturing. However, only the manufacturing phase (which comprises the raw material processing and pipe fabrication processes) was looked at because this study employed the Gate-to-Gate approach. As seen in Figure 3, the system limits do not take into consideration the transportation, installation, use/maintenance, disposal, and end-of-life considerations of every material. Moreover, neither the recovery expenses nor the salvage value were established.

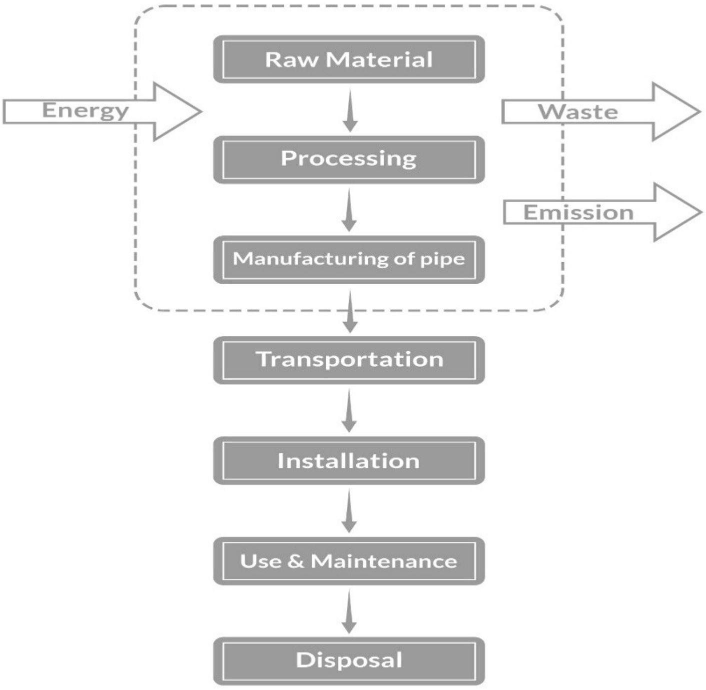

Fig: 3.3 System Boundary of the LCA Study

3.2.3 Life cycle inventory (LCI)

For both PVC and FRP pipe, the LCA Scheme and functional units and boundaries were established, and all input data were gathered in compliance with ISO 14040 (2006) throughout the life cycle inventory stage. Tables 2 and 3 illustrate this. The Simapro program's Ecoinvent database and on-site study provided the information regarding the raw materials and energy fluxes. The information gathered is about the processes used in the production and acquisition of raw materials (plasticisers, pigments, fillers, stabilisers, and resins).

3.2.3.1 LCA inputs for PVC pipe

PN1.0 (Chinese Standards) PVC pipe, with a functional unit mass of 13 kg, was utilized in the Life Cycle Assessment. In this study, the LCA of the PVC pipe is displayed in Fig. 3. LCA of the PVC pipe was conducted taking into account the manufacturing phase, covering raw materials, their processing, and pipe manufacture. All of the raw materials listed in Table 2 must be combined in a large mixer container according to exact proportions and instructions as the first stage in the PVC production process. In this case, a 100 kg capacity mixer is used (mixer size may vary with quantity of production). Ninety degrees Celsius is the temperature at which two bags of PVC resin (each weighing 25 kg), 20 to 25 kg of calcium nitrate (which lowers production costs), 1300 grams of lead (which controls heat), 300 grams of titanium (color pigment), 500 grams of Dimethyl Phthalate Oil (which provides flexibility), and 15 to 25 grams of Triazine Compound (chemical used as a finisher to protect the polymer from UV rays) are placed inside the mixer and blended. After fifteen to twenty minutes, our processing material is prepared. With a diameter of 4 inches and a length of 5 meters, this material is used to create one batch (six pipes), each weighing between 12.5 and 13 kg.

Table 2: Input data for PVC Pipe

Data from the Life Cycle Inventory for the production of 4-inch, five-meter- long PVC pipe			
Input(Material)	**Value**	**Unit**	**mass %**
−PolyVinyl Chloride	7.75	Kg	62.5
Stabiliser			
−Lead (Heat Control)	200	g	3.1
−Dimethyl Phthalate Oil (for flexibility)	65.5	g	1.8
Filler			
−Calcium	4.05	Kg	31.2
Pigment			
−Titanium	40.5	g	1.2
Finisher			
−Triazine Compound (for UV protection)	3.5	g	0.2
***Processing Method: Pipe Extrusion**			

3.2.3.2 PVC pipe Manufacturing

PVC resin and additives are combined and fed into the feed hopper of an extruder to start the production process. An extruder turns the raw material into a continuous tubular melt by using an annular die. The melted pipe is changed into pipe with the needed diameter and wall thickness after it passes through a sizer (the sizer cup is inserted into the extruder based on the required size; in our case, a 4-inch cup is put). The extruded pipe is then cooled with water. Every year, each facility or calibration equipment (which adjusts its dimensions) saves millions of gallons of water thanks to closed-loop cooling mechanisms. After that, the extruded pipe is cooled by going through a water-filled cooling trough. Cooling water uses millions of gallons of water a year per site and is often a closed-loop operation. The PVC pipe industry's increasing adoption of closed-loop water-saving technologies is evidence of its commitment to efficiency and ongoing development. After cooling, the pipe passes via a haul-off to handling equipment where it is chopped or coiled into final lengths. Printing equipment can also be positioned inside the line to precisely mark the extruded pipes. After being removed, pipes are chopped with an electric saw into standard lengths. Next, each pipe's bell-shaped end is fed into a belling machine. Every standard length of pipe used on the production line for municipal potable water systems is subjected to pressure tests. The pipes are loaded onto a truck or rail car and driven to a distributor or building site once they have been fitted into wooden frames and strapped shut. Since practically all of the scrap material is crushed and put back into the extruder, there isn't much waste. This manufacturing process, which is driven by a 40KV electric motor, is known as pipe extrusion. The manufacturing process uses very little electricity and generates almost no emissions.

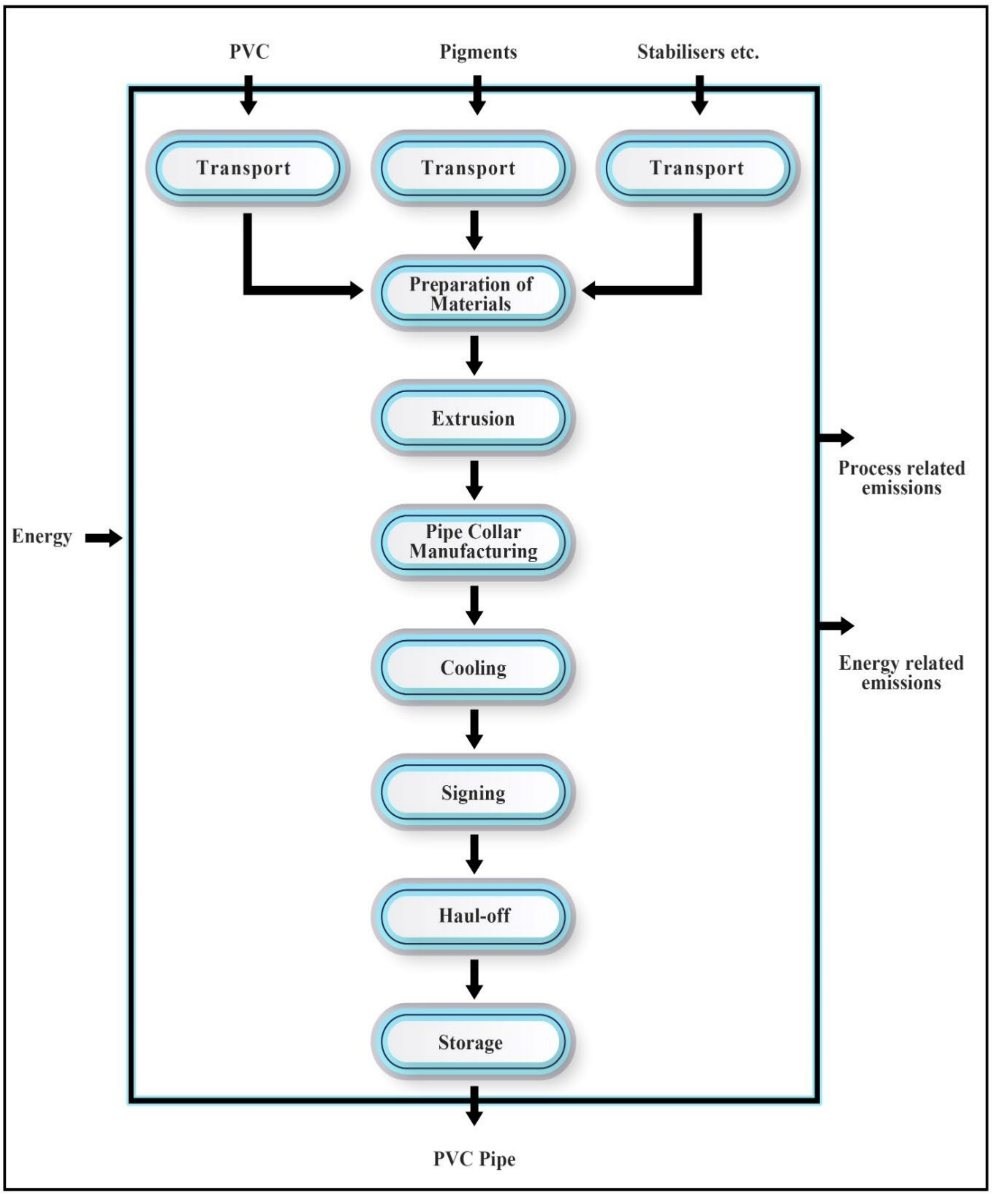

Fig: 3.4 Schematic flow diagram for the production of PVC Pipe

3.2.3.3 LCA inputs for FRP pipe

The process known as the Helical Winding Method is used in the production of FRP pipes. The helical imprint that the pipes bear gives rise to the method's name. The first and most important thing that manufacturers do is set up the mandrel (a piece of prepared equipment with a sheet wrapped around it) which make it simple to release FRP pipe when it is completed. Then, in a large mixer with a capacity of around 100 kg, the resin preparation is done at a high temperature of 90 degrees Celsius, allowing all of the ingredients to melt, mix, and gel together. On a mandrel, the resin mixture which includes bitumen adhesive compound, silica sand, titanium, acrylic acid to prevent corrosion, and epoxy resin for strong adhesion is applied with fiber glass rovings. Table 3 displays the materialistic composition for a single FRP pipe.

Table 3: Input data for FRP Pipe

Data from the Life Cycle Inventory for the production of 4-inch, five-meter-long FRP pipe			
Input(Material)	**Value**	**Unit**	**mass %**
−Glass Fibre	7.25	Kg	68.5
Stabiliser			
−Epoxy Resin (for strong adhesion)	1.25	Kg	10.75
−Acrylic Acid (to prevent corrosion)	130.5	G	1.35
−Bitumen Adhesive compound	65.5	G	0.5
Filler			
−Silica Sand	3	Kg	18.5
Pigment			
−Titanium	40.5	G	0.3
Finisher			
−Triazine Compound (for UV protection)	3.5	G	0.1
***Processing Method: Winding Filament Method**			

3.2.3.4 FRP pipe Manufacturing

The first stage of the manufacturing process involves placing reels of unidirectional fiberglass roving on continuous roving strands. This is done by a computer-controlled winding machine. Fiberglass is sufficiently strong and durable because it contains silicate, polyester, and thermoplastic elements. Using the same wet process as at the visited location, the fibers are impregnated through a resin bath (a trough that holds the substance that was previously prepared in a mixer drum) and helically wound over a spinning mandrel. Depending on the type of pipe, applying two or more layers can be required. Winding operates at a temperature range of 50 to 75 degrees. Currently, the pipes must be left uncovered for one to two hours due to the heated temperature during the winding process. We call this the "curing stage." When the FRP pipe and mandrel have cured, they are separated using a hydraulic machine. Both ends are also chopped to smooth off the ends and provide the pipe the exact measurements it needs. After that, the pipes are put together and packed to meet the needs of different clients.

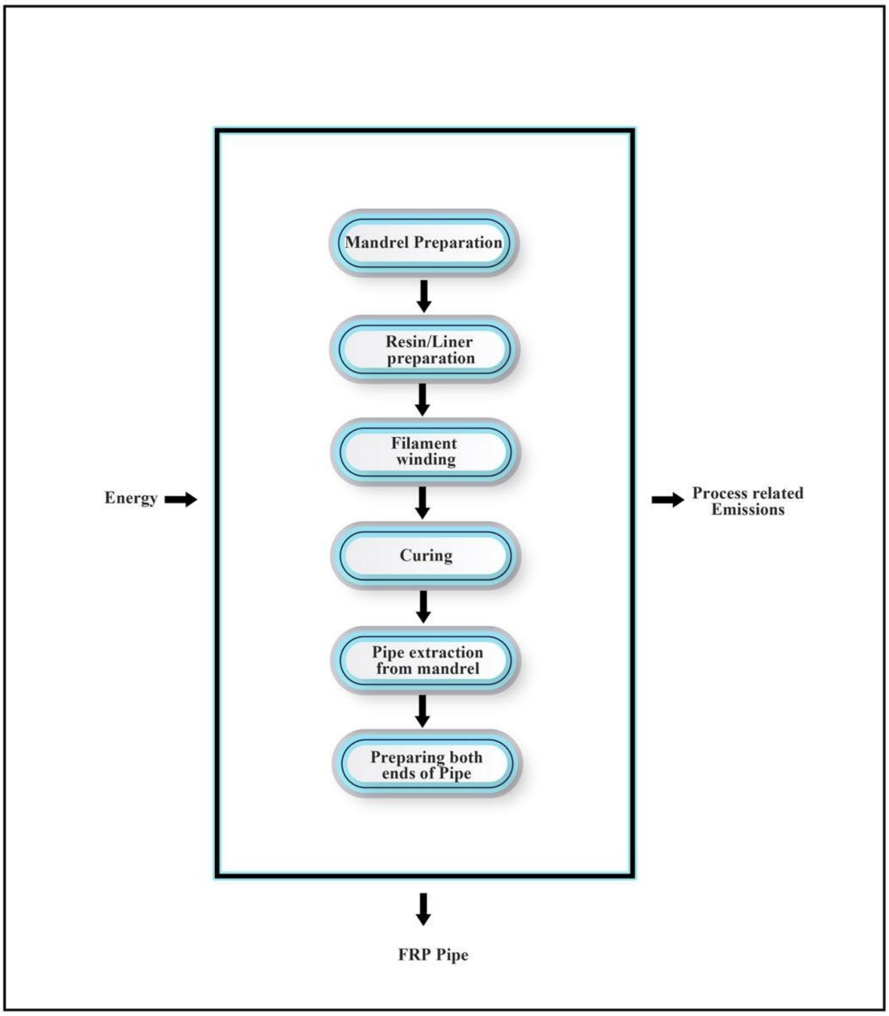

Fig: 3.5 Schematic flow diagram for the production of FRP Pipe

3.2.4 Life Cycle Impact Assessment

The environmental impacts at manufacturing phase were obtained at the life cycle impact assessment stage. Using Simapro (version 7.1.8) software, it was done in accordance with the classification and characterization procedures specified by ISO (2006). LCI results were examined using the BEES index method.

In order to carry out comparative LCA between PVC & FRP, IMPACT 2002+ method is use for impact assessment. All characterization factors of LCA are expressed in units of an equivalent reference substance in the columns of "Unit". The impacts were than compared by using Formula (Reduce. (time) = Value (PVC) / Value (FRP))(Shi, S. Q.,2019) which illustrates that how many times the impact of one is greater than other on environmental categories.

The chosen impact categories were: Global Warming Potential (GWP; kg CO2 equivalents), Ozone layer depletion (ODP; kg CFC-11 equivalents), Aquatic Eutrophication (AE; kg PO4-equivalents), Acidification Potential (AP; kg SO2 equivalents), Respiratory inorganics (RI; kg PM2.5-equivalents), Respiratory organics (RO; kg C2H4-equivalents), Non-carcinogens (NC; kg C2H3Cl- equivalents), and Carcinogens (NC; kg C2H3Cl- equivalents).

4. RESULTS AND DISCUSSIONS

The LCI of PVC and FRP pipe is covered in this part. The Inventory data were analyzed using the IMPACT 2002+ technique and the BEES (Building for Environmental and Economic Sustainability) method. The primary components of IMPACT 2002+ are CML (Guinée et al. 2002), IPCC, Eco-indicator 99 (Goedkoop and Spriensma, 2000, Second Version, Egalitarian Factors), and IMPACT 2002 (Pennington et al. 2005).

4.1 Inventory results

All of the raw materials used and emissions that transpired during the production of PVC and FRP pipes (a functional unit is a pipe weighing 13 kg) are detailed in Tables 4 and 5, respectively. Significant environmental advantages were provided throughout the production phase (Guo et al. 2015). But in order to build and maintain water pipe networks, more ecologically friendly biomass materials must be developed in light of growing worries about climate change (Faria and Guedes, 2010). The consumption that took place during the life cycle (manufacturing stage) of both pipes is listed in the LCI result table. Table 2 is a list of the raw components that were used. The LCI results were especially helpful in the absence of characterization and categorization. The life cycle impact assessment in Section provides a full description of the outcomes.

Table 4: Inventory results of PVC pipe

Substance	Unit (gram)	Total
Aluminium, 24% in bauxite, 11% in crude ore, in ground	g	23.490133
Barite, 15% in crude ore, in ground	g	11.49735025
Calcite, in ground	g	682.7519
Carbon dioxide, in air	g	221.7525825
Chromium, 25.5% in chromite, 11.6% in crude ore, in ground	g	10.27964043
Clay, unspecified, in ground	g	560.46664
Coal, 29.3 MJ per kg, in ground	g	283.3637372
Gas, natural, 30.3 MJ per kg, in ground	g	224.3920885
Iron, 46% in ore, 25% in crude ore, in ground	g	565.83239
Lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in Ground	g	53.81547796

Nickel in groundwater: 1.04% in unrefined ore, 1.98% in silicates	g	29.58831425
Oil, crude, 41 MJ per kg, in ground	g	141.68
Oil, crude, 42.6 MJ per kg, in ground	g	65.65658565
Titanium, in ground	g	40.8
Carbon dioxide, biogenic	g	235.0840463
Carbon monoxide, fossil	g	32.79242918
Methane, fossil	g	74.5314262
Nitrogen oxides	g	58.33512811
NMVOC, non-methane volatile organic compounds, unspecified origin	g	37.29817921
Particulates, > 10 um	g	13.13106188
Sulfur dioxide	g	62.53029586
BOD5, Biological Oxygen Demand	g	27.37282119
Calcium, ion	g	44.71153113
Chloride	g	595.0795608
COD, Chemical Oxygen Demand	g	51.17509017
DOC, Dissolved Organic Carbon	g	14.65494588
Nitrate	g	39.04435508
Silicon	g	121.4993643
Sodium, ion	g	73.54262788
Sulfate	g	69.02042459
TOC, Total Organic Carbon	g	17.83220543

Note: This table does not include substances that weigh less than 10g.

Table 5: Inventory results of FRP pipe

Substance	**Unit (gram)**	**Total**
Carbon dioxide, in air	g	24.2543687
Coal, 18 MJ per kg, in ground	g	178.5258885
Coal, 29.3 MJ per kg, in ground	g	286.9057839
Coal, brown, in ground	g	35.644434
Coal, hard, unspecified, in ground	g	93.5302995
Dolomite, in ground	g	282.0125727
Feldspar, in ground	g	282
Limestone, in ground	g	564.0001039
Oil, crude, 41 MJ per kg, in ground	g	143.451
Oil, crude, 42.6 MJ per kg, in ground	g	13.74701783
Oil, crude, in ground	g	207.81341
Sodium hydroxide	g	846
Titanium, in ground	g	41.31
Carbon dioxide, biogenic	g	23.76883122
Carbon dioxide, fossil	g	645.9356193
Hydrocarbons, unspecified	g	10.75714726
Nitrogen oxides	g	44.13238133
Sulfur oxides	g	21.7247551
Dust, unspecified	g	15.535
Waste, final, inert	g	70.23339624
Waste, inorganic	g	155.1

Note: This table does not include substances that weigh less than 10g.

4.2 BEES index method

The following is a presentation and analysis of the LCA findings of PVC and FRP pipes that were investigated using the BEES index technique.

4.2.1. Analytical findings using the BEES index method

Based on the calculation of BEES environmental impact indices (being expressed by g CO2 eq.) using the SimaPro tool, Figs. 6 and 8 show the overall environmental consequences of PVC and FRP pipes (the mass of 13 kg pipe as a functional unit). Water distribution system design is extended beyond the consideration of economic objectives alone, thanks to the introduction of a unique environmental index and a multi-objective optimization approach by Herstein et al. (2009) and Herstein and Filion (2011). For the most part, environmental and economic goals were met together since pumping energies tended to dominate their environmental index (Herstein et al. 2011). The environmental effect of producing one 13kg PVC pipe (3.56E4g CO2 eq.) and one FRP pipe (7.53E3g CO2 eq.) is shown in Figures 6 and 8, respectively. These numbers imply that the environmental effect of the PVC manufacturing process is 2.80E4g CO2 eq. more than that of the FRP.

4.2.2.1 LCA Results for PVC Pipe

The BEES indices of the raw materials, which include 7.75 kg of polyvinyl chloride, 4.5 kg of calcium, and 0.2 kg of lead (for heat regulation), 0.065 kg of DMP Oil (for flexibility), 0.04 kg of Titanium, and 0.0035 kg of triazine compound (for UV protection) per functional unit—a total of 13 kg— used in the manufacturing of PVC pipe were compared using SimaPro software. The findings are shown in Fig. 6. As shown in the figure, the BEES index of 7.75 kg Polyvinyl Chloride was 1.52E4 g CO2 eq., 4.5 kg Calcium was 1.78E4g CO2 eq., 0.2 kg Lead was 212g CO2 eq., 0.065 kg DMP Oil was 109g CO2 eq., 0.04 kg Titanium was 1.83E3g CO2 eq., 0.015 kg triazine compound was 118g CO2 eq.. Similarly, for vitrified pipes, energy consumption is estimated using data reported in Hammond and Jones et al. (2008). Since polyvinyl chloride, calcium, and DMP have a bigger effect on global warming than other substances, reducing their amounts will further lessen the environmental impact of PVC pipe. PVC was one of five pipe materials that Recio et al. (2005) examined for life cycle energy consumption and associated greenhouse gas (GHG) emissions. His research also reveals that the entire cost of building and operating a water distribution system is heavily influenced by externalized expenses like greenhouse gas emissions.

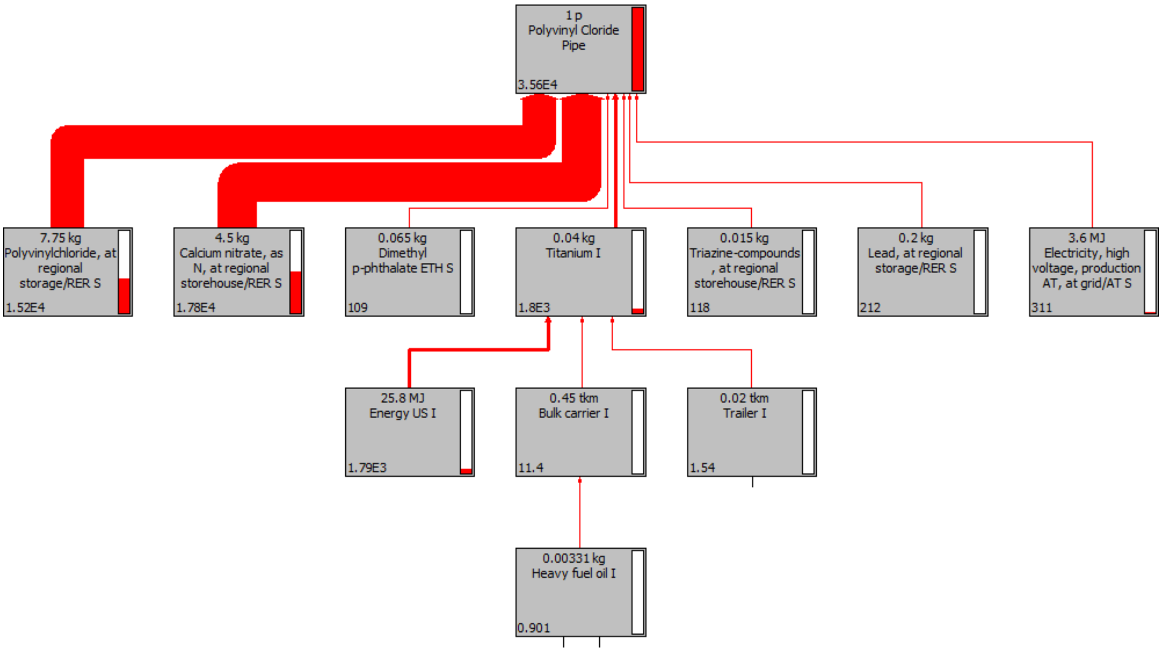

Fig. 4.1. Network of PVC pipe's environmental effect ("1p" stands for one functional unit).

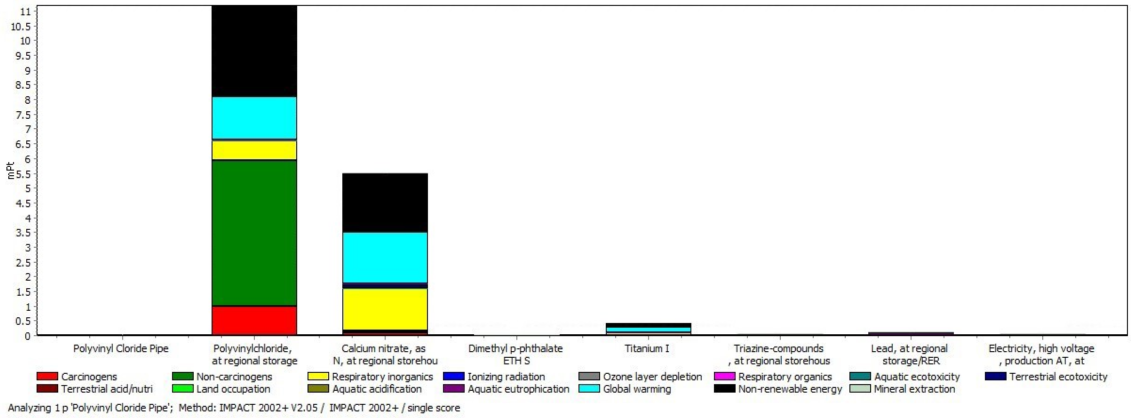

Fig. 4.2. PVC Single Score Environmental Impacts

4.2.2.2 LCA Results for FRP Pipe

As a result, indexes of the raw materials used to make fiber-reinforced polymer (FRP) pipe, which weighed a total of nearly 13 kg, were compared. These raw materials included 7.25 kg of glass fiber, 3 kg of silica sand, 1.25 kg of epoxy resin (for strong adhesion), 0.13 kg of acrylic acid (to prevent corrosion), 0.065 kg of bitumen adhesive compound, 0.04 kg of titanium, and 0.0035 kg of triazine compound (for UV protection).As shown in the figure, the BEES index of 7.05 kg Glass Fibre was 3.6E3g CO2 eq., 1.25 kg Epoxy Resin was 1.38E3g CO2 eq., 0.13 kg Acrylic Acid was 294g CO2 eq., 0.04 kg Titanium was 1.83E3g CO2 eq. The indexes of other raw materials, namely, Silica Sand, Bitumen Adhesive Compound and triazine compound were very small, which could not be displayed/considered. The production phase still showed significant environmental impacts due to the use of synthetic resins (Vasilenko et al. 2017).

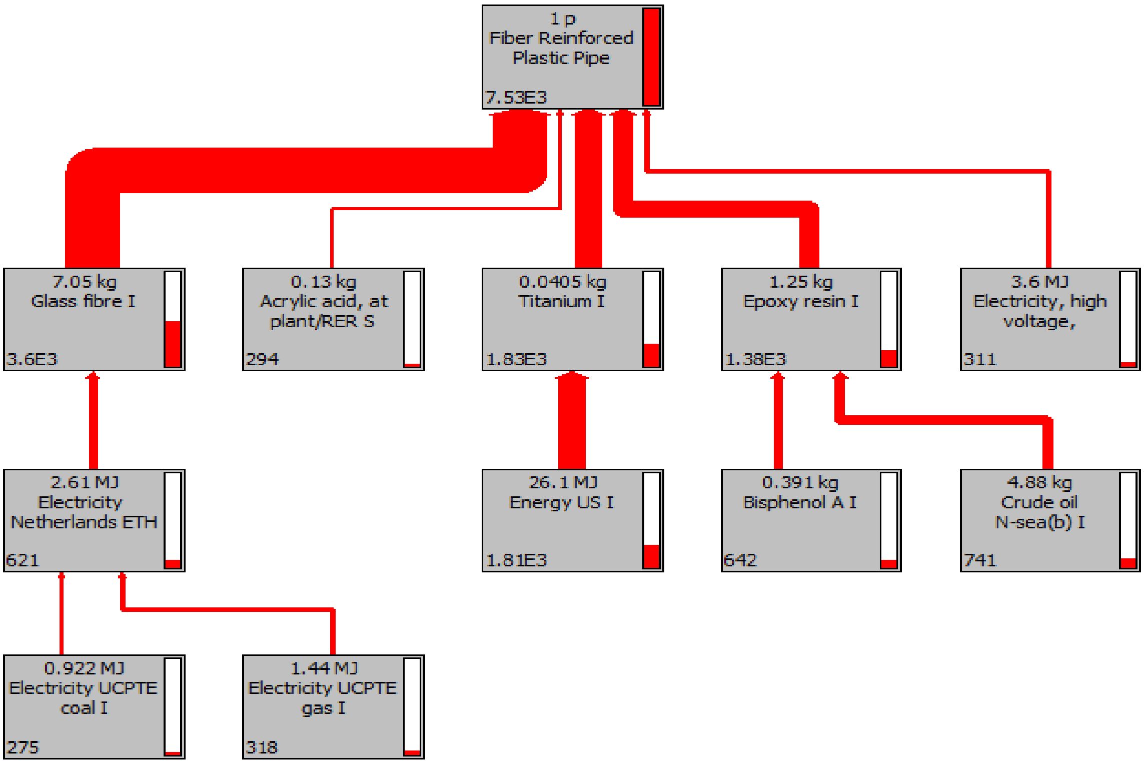

Fig. 4.3. Network of FRP pipe's environmental effect ("1p" stands for one functional unit).

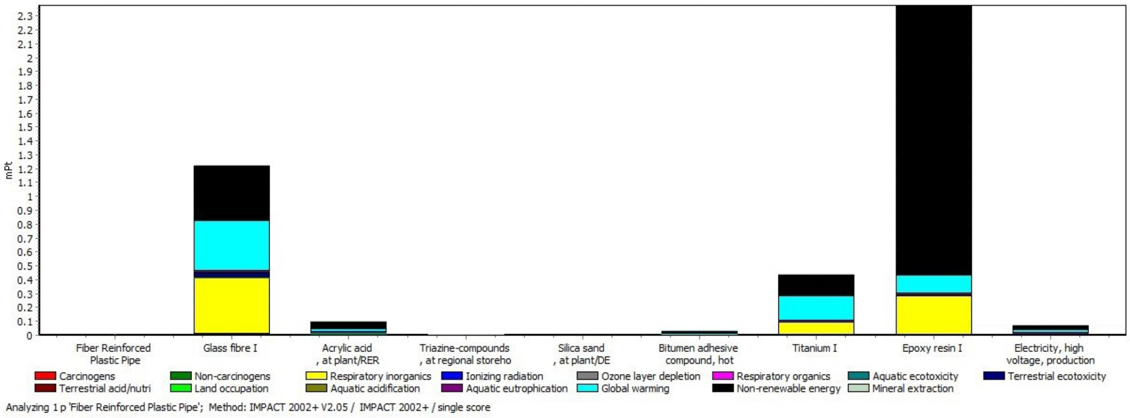

Fig. 4.4. FRP Single Score Environmental Impacts

4.3. Comparison of PVC and FRP pipes by IMPACT 2002+ method

Two conclusions about the LCA assessments of the two kinds of pipes were reached by comparing Figs. 6 and 8:

a) According to a study (Guo et al. 2015), the production phase had the greatest environmental impact, especially in terms of energy consumption and greenhouse gas emissions, and the manufacturing process had a significant influence on this impact.

b) As seen in Figs. 6 and 8, the PVC pipe had a significantly greater environmental effect than the FRP pipe (3.56E4g CO2 eq. vs. 7.53E3g CO2 eq.).(Al-Hussein et al. 2014) indicated that PVC pipes were found to have a higher impact during the production phase due to chlorine-based processes.

Since the possible environmental consequences of choosing a pipe material for a water distribution system have already been researched, the overall environmental impact throughout the manufacturing process of PVC and FRP pipes was examined separately, as indicated in Table 6. (Dinnison et al. 1999).In the "Unit" columns of Table 6, all LCA characterization factors are represented in units of an analogous reference substance. Using the formula Reduce (time) = Value (PVC) / Value (FRP) (Shi, S. Q., 2019), the comparative results are shown in the columns of "Reduc." in Table 6, showing that the use of FRP pipe greatly decreased the environmental impacts in all indices. Table 6 displays that the total

Aquatic ecotoxicity, Aquatic acidification, Aquatic Eutrophication, Respiratory inorganics, Global Warming Potential, Ozone layer depletion, Respiratory organics, Non-carcinogens, Carcinogens and Ionizing radiation of the PVC pipe were 1.1, 1.9, 1.5, 2.7, 4.6, 2.0, 36.6, 743.7, 124.4 and 38.6 times higher than those of FRP pipe, respectively. A study (Shi, S. Q., 2019) that shows that PVC pipe has 1.1_488.8 times more environmental consequences than bamboo pipe supports our findings as well. A comparison of the overall environmental impact caused by FRP and PVC pipes are shown in Fig. 8.

The environmental impact of PVC pipe is shown as 100%, while the effect of FRP is expressed as a percentage of the pipe's value. The FRP pipe's two indices, which measure its carcinogens and non-carcinogens, were too small to be shown in the image compared to PVC pipes (which have indices of 0.20% and 0.32%, respectively).Applying FRP pipe resulted in significant reductions in all indices, including aquatic ecotoxicity (88.5%), aquatic acidification (52%), aquatic eutrophication (6.5%), respiratory inorganics (2.5%), global warming potential (22.5%), ozone layer depletion (5%), respiratory organics (36.5%), and ionizing radiation (2.5%) (Fig. 8).The best materials for pipelines were PVC or polyethylene (PE) because of its low cost, great ductility, and ability to accommodate very small pipe diameters despite the fact that, compared to concrete pipes, the building of plastic pipelines resulted in significantly higher greenhouse gas emissions (Venkatesh et al., 2009). Similar findings are seen in another study (Vahidi, E., Jin, E., Das, M., Singh, M., & Zhao, F., 2016) that examines six different pipe material types, including FRP and PVC.

Table 6: Comparison of the effects on the environment assessment between PVC and FRP pipe

Impact category	**Unit**	**PVC**	**FRP**	**Reduce (Time)**
Aquatic ecotoxicity	kg TEG water	1256.501377	1113.925963	1.12
Aquatic acidification	kg SO2 eq	0.115281244	0.059939478	1.92
Aquatic eutrophication	kg PO4 P-lim	0.000777447	5.09858E-05	1.52
Respiratory inorganics	kg PM2.5 eq	0.022898903	0.008243918	2.77

Global warming	kg CO2 eq	34.37978373	7.452242924	4.61
Ozone layer depletion	kg CFC-11 eq	2.50377E-06	1.25128E-07	20.02
Respiratory organics	kg C2H4 eq	0.024620073	0.000671451	36.6
Non-carcinogens	kg C2H3Cl eq	12.76574367	0.017163272	743.7
Carcinogens	kg C2H3Cl eq	2.748525694	0.022087252	124.4
Ionizing radiation	Bq C-14 eq	197.1999226	5.098813609	38.6

Reduce. (time) = Value (PVC) / Value (FRP)

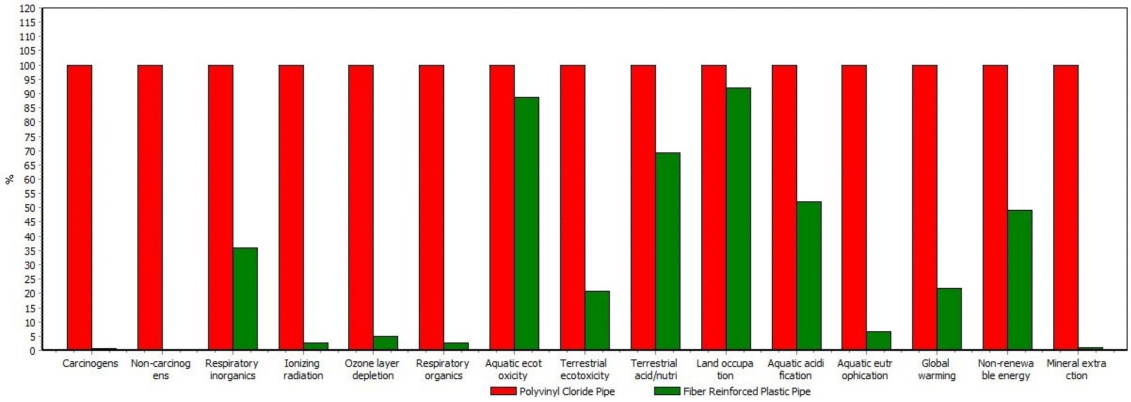

Fig. 4.5. An analysis comparing the environmental effects of FRP and PVC pipes

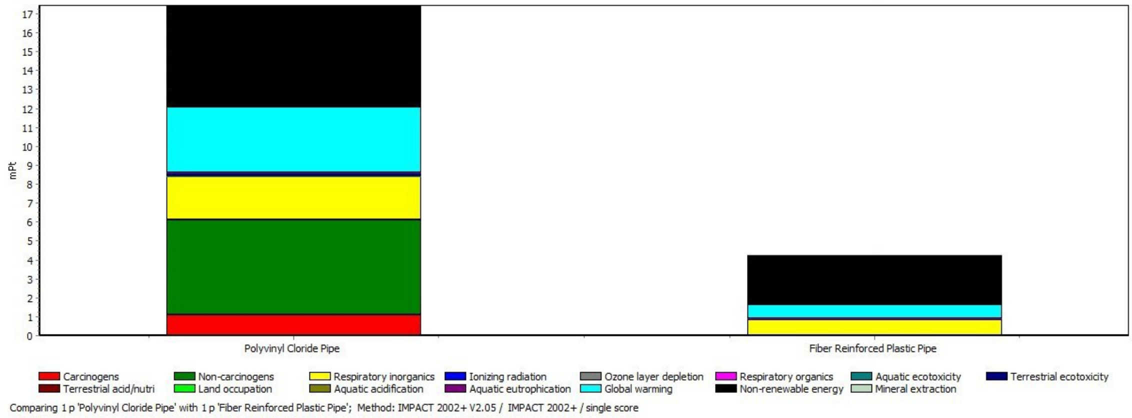

Fig. 4.6. PVC & FRP Single Score Environmental Impacts

CONCLUSIONS

The life-cycle assessments (LCA) of PVC and FRP pipes were completed using the SimaPro software. The results were compared using the IMPACT 2000+, Ecoinvent, and TRACA LCA techniques. The findings and recommendations were summed up as follows:

- This research used a gate-to-gate life cycle approach for sewer pipes in the life cycle assessment of sustainability.
- Fossil fuel is the region most affected by all piping systems; the production phase has the greatest impact among all pipe manufacturing stages and among all environmental consequences. While both FRP and PVC contribute the most to global warming, non-renewable energy is the region most impacted.
- Table 6 compares the assessment findings of the IMPACT 2000+ index for PVC and FRP. It shows that the application of FRP pipe greatly decreased the environmental consequences in all indices. In comparison to FRP pipe, Table 6 demonstrates that the total aquatic eco-toxicity, aquatic acidification, aquatic eutrophication, respiratory inorganics, global warming potential, ozone layer depletion, respiratory organics, non-carcinogens, carcinogens, and ionizing radiation of PVC pipe were, respectively, 1.1, 1.9, 1.5, 2.7, 4.6, 2.0, 36.6, 743.7, 124.4, and 38.6 times higher.
- Therefore, it is possible to further reduce the environmental impact of PVC pipe without compromising the pipes' durability by lowering the pipe's PVC and calcium content, as well as by optimizing the raw material components of PVC and using more plastic.

Furthermore, under the context of urban expansion, both rural and urban regions may become increasingly artificial, changing the needs for drainage and land use accordingly. Given their lower cost, plastic pipes may be the better choice, but decision-makers should take into account the possibility that embedding pipes in concrete may be a superior option because it eliminates the need for repositioning. The system might last longer, and even if minor changes are needed (like in the road), the sewer might be protected from outside harm. PVC pipes may be made to perform much better environmentally by concentrating on these aspects, which will make them a more sustainable option for plumbing and building applications.

RECOMMENDATIONS

To improve the understanding of the harmful effects of pipeline materials, future research in the field of life cycle assessment (LCA) for pipeline materials could be beneficial. The following potential areas for research are outlined:

- Conducting a comparative analysis of pipeline materials can be utilized to assess the environmental advantages and disadvantages of each option. Various impact categories, including greenhouse gas emissions, energy consumption, water usage, and waste generation, should be considered in these studies.

- In order to better capture the unique characteristics and impacts of pipeline materials, such as pipeline ruptures, maintenance requirements, and environmental consequences, future research should focus on enhancing existing life cycle impact assessment (LCIA) methods and establishing new impact evaluation models.

- The primary emphasis was on the long-term effects of a sewer on the environment and the economy. Further socio-economic indicators must be taken into account in order to enhance the interpretation of the findings.

- Geographical position and the hydraulics of sewer pipes were not taken into account in this study, which could have a significant impact on the findings.

- One of the limitations is the assumptions made about the transit distance (from material extraction to production, production to installation site, and installation site to disposal site). More information must be gathered in order to make better decisions.

- Pipe assessment models used in this study were sourced from published works. To obtain more realistic performance from each pipe, a thorough assessment model that takes into account all the relevant variables must be created.

- Given that the scope of this study is restricted to sanitary sewer pipes, it is advised that the investigation be expanded to include storm water pipes, which are becoming more and more common in buried infrastructure installations.

- For a more convincing argument of the relative significance of several sustainability criteria, energy results might be combined. When analyzing performance in a case study when long-term data is available, the energy-based life cycle method should be used.

- The impacts of the PVC pipes could be reduced by changing the production materials, opt for PVC pipes made from recycled PVC or other sustainable materials (plastic waste). This reduces the use of harmful additives and chemicals in the PVC formulation, such as phthalates and lead stabilizers, which can be detrimental to health and the environment.

- Future study must focus on the effects that pipeline networks' operating phase has on the environment. Inspection, rehabilitation, and maintenance should be taken into account in the LCA analysis of pipelines. Furthermore, the environmental impact study of pipelines should include the effects of metal emissions resulting from corrosion on ecotoxicity.

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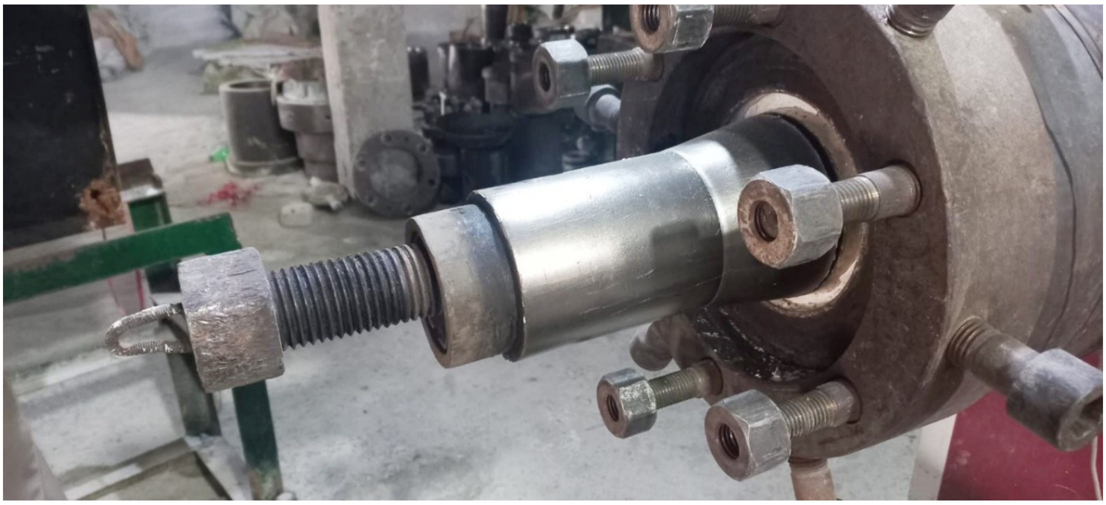
ANNEXURES

PVC Extruder Machines

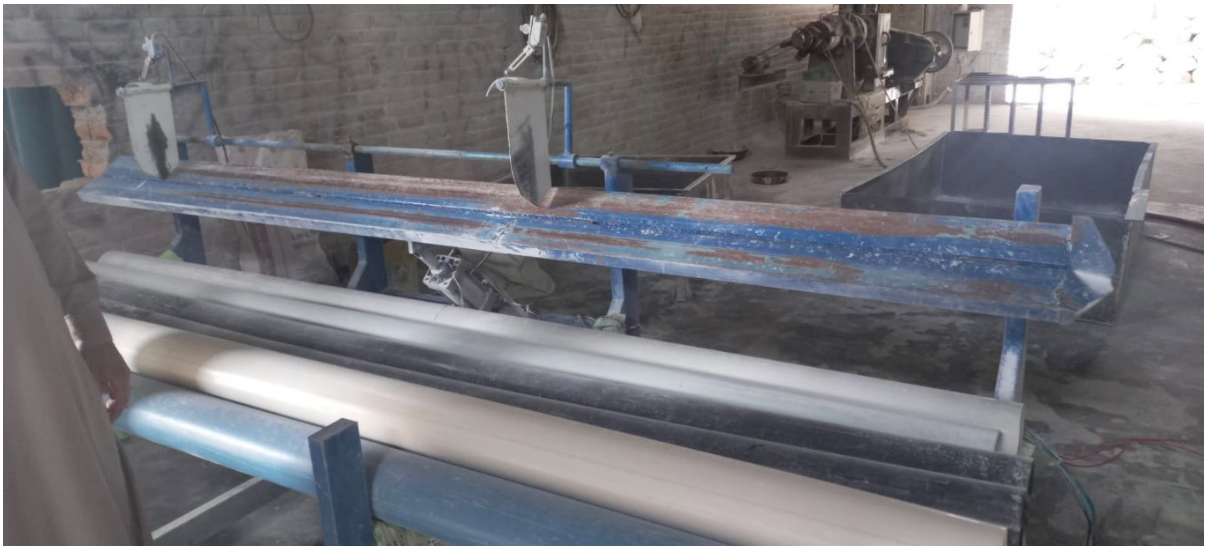
Mixer Container

Extruder Feed hopper



Sizer cup

Extruder Conveyer Belt



Electric saw to cut PVC pipe in standard lengths

Physical inspection at site

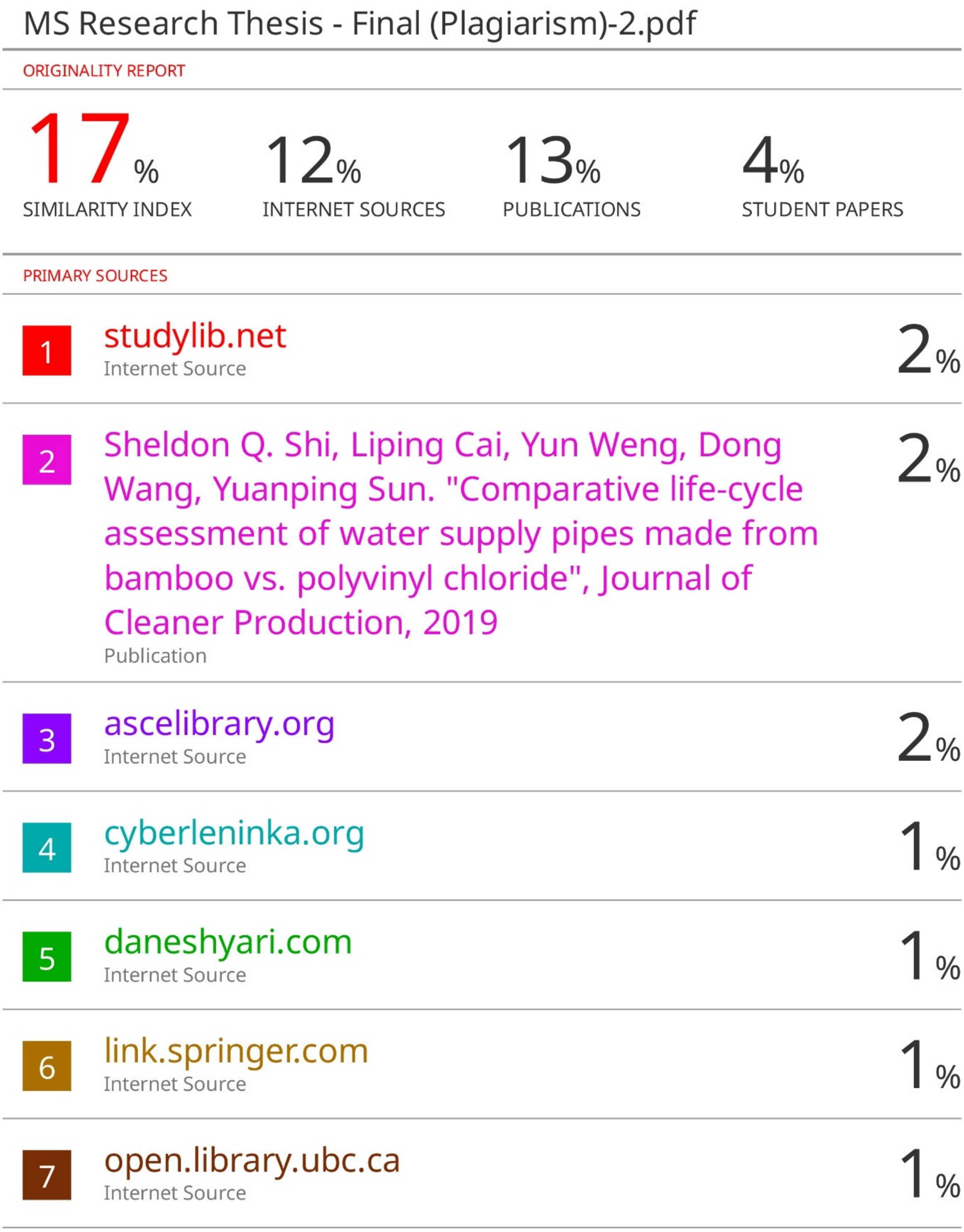
PVC Resin

PVC Pipe

FRP Filament Winding Machine

FRP pipe fittings

FRP Pipe



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