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Comparative Life Cycle Assessment of Different Rainwater Collection Systems in Philippine Public Schools

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Abstract

Rainwater Collection System (RWCS) is a sustainable water management technology suitable for the collection and storage of rainwater from roofs and surfaces for reuse to promote sustainable water resource management. This study investigated four RWCSs to be used in public schools across the Philippines. These RWCSs are: (1) Aboveground Steel Tank (A-S), (2) Aboveground Polyethylene Tank (A-P), (3) Underground Reinforced Concrete Tank (U-C), and (4) Underground Polyethylene Tank (U-P). Life Cycle Assessment was utilized to consider the environmental performance of four RWCSs with the use of SimaPro (10.5.0.1). A cradle-to-site system boundary was adopted encompassing two life cycle stages: manufacturing and installation. The results showed that the Underground Concrete Tank system (U-C) consistently exhibited the lowest environmental impact across all impact categories, and the Aboveground Steel Tank system (A-S) demonstrated the highest impacts, primarily due to the significant use of reinforcing and structural steel for its base and foundation. In particular, the global warming potential (GWP) and human carcinogenic toxicity (HCT) of U-C are lower than those of the other RWCSs from 47.3% to 59.4% and 44.1% to 93.3%, respectively. In addition, the construction cost of U-C is 20.4% to 35.1% lower than that of the other RWCSs. Future research is recommended to expand the system boundary to include use and end-of-life stages, which may influence the comparative outcomes.

Keywords: Rainwater Collection Systems; comparative Life Cycle Assessment; sustainable infrastructure; environmental impact

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1. Introduction

Water scarcity is an increasing concern in various parts of the world due to rapid urbanization and climate change impacts [1]. In the Philippines, these issues are particularly pronounced in urban areas where water demand is in sharp rise, leading to water-stressed communities. Despite the Philippines' abundant water resources and high annual rainfall, water scarcity remains prevalent in many parts of the country due to lack of infrastructure to develop reservoir and piping networks. This highlights the country's limited capacity to effectively capture, manage, and utilize rainfall, leaving a significant portion of this valuable resource underutilized [2]. It could be used for various potable and non-potable purposes, but it is being wasted as runoff and contaminated with pollutants after traversing various land uses.

As the global climate undergoes exceptional transformations in recent years, the threat of intense weather events and altered rainfall patterns continues to grow, amplifying the impacts of natural disasters such as floods and droughts, which gauge the vulnerability and resilience of communities [3]. Due to this, a proactive approach to treating the problem at the source, using technologies such as Rainwater Collection Systems, is an important consideration.

Rainwater Collection System (RWCS) is a sustainable water management technology suitable for the collection and storage of rainwater from roofs and surfaces for reuse for various purposes [4–7]. This practice has many benefits, serving as an alternative water supply [8]. It reduces dependence on local water supply systems and resources and minimizes flood risks due to extreme rainfall events and climate variations [9,10]. By intercepting runoff at its source, RWCS can reduce the transport of pollutants, sediments, and other contaminants that accumulate on roofs and other surfaces [11]. This can help minimize the pollutant load entering drainage networks, rivers, and other receiving water bodies, thereby reducing sedimentation and potential water quality degradation [12]. It also provides cost-effective strategies through the reduction in water costs from the reliance on conventional supply systems and mitigation of the need for expensive infrastructure to address water shortages [13].

In this study, public schools were considered as they are distributed across many parts of the Philippines, where the water supply remains challenging. The Department of Public Works and Highways (DPWH) implemented RWCS in public facilities, specifically for schools, offices, markets, and health centers nationwide. This initiative aligns with their INFRAgenda 2028 and/or the Performance Governance System (PGD) Strategic Plan for 2023–2028. The implemented RWCS is composed of one unit of reinforced storage tank with a storage capacity of 4000 L of water [14].

To promote sustainable water resource management, it is also crucial to determine the environmental impacts of RWCS, specifically across its design, construction, operation, and end-of-life phases. Life Cycle Assessment (LCA) is used in the investigation and quantification of the environmental impacts of a product or service within its life cycle [15]. The application of LCA to the system quantifies the trade-offs between systems, materials, and operational configurations, which are important for decision-making strategies for urban planning, policy development, and infrastructure investment. This is important, as there are research gaps in component-level performance analysis, depicting the interrelationships among components in terms of the vulnerability and resilience of these systems and infrastructures, and incorporating environmental sustainability and operational robustness that must be considered [16]. However, the limitation of this study is that it covers only the cradle-to-site stage.

As such, the study aims to conduct an LCA evaluating the environmental performance of different RWCSs by comparing different tank materials and installation methods, and identifying which materials and processes account for the highest environmental impact in different categories. The site condition and structural design are assumed to be in good condition and compliant with the codes, respectively. The assessment focuses on storage tanks, associated installation methods and materials, and accessories including pumps. It excludes gutters, catchment surfaces, first-flush diverters, filtration units, rainwater quality treatment systems, water-treatment components, and operational pumping. Additionally, this study aims to perform comparative cost analysis between the different system designs.

2. Materials and Methods

2.1. Goal and Scope Definition

This study applied a comparative Life Cycle Assessment (LCA) to evaluate the environmental impacts of selected RWCS designs, focusing on both material types and installation methods, using SimaPro (v10.5.0.1). The assessment adheres to the ISO 14040/44 framework [17,18] and aims to inform sustainable infrastructure planning for public schools in the Philippines.

2.1.1. Goal

The primary goal of this study is to evaluate and compare environmental impacts of four RWCS designs classified as aboveground or underground as integrated into DPWH standard public school buildings in the Philippines. Plans and specifications for aboveground tanks were obtained from DPWH Regional Office VI, as the region is actively implementing RWCS in public schools, while specifications for underground tanks were collected from commercially available systems. However, the underground tank systems considered are not necessarily sourced locally but represent commercially available options that could be adopted in the Philippine context.

2.1.2. Scope

Functional Unit

The functional unit was defined as one Rainwater Collection System with a nominal storage capacity of 4000 L, manufactured and installed at a public-school site, used for storage and distribution of non-potable rainwater for toilet flushing, cleaning, gardening, and other uses [19,20].

System Boundaries

A cradle-to-site system boundary was adopted in this study, encompassing two life cycle stages: manufacturing and installation. The operational (use) and end-of-life (disposal) stages were excluded. Other initial life cycle stages, such as raw material extraction, processing, and transportation, serve as the inputs determined through the life cycle inventory. The manufacturing stage includes raw material extraction and the production of the assembly components of each RWCS, while the installation stage covers on-site construction activities, including earthworks, steel works, and concrete works.

The assessment focused exclusively on the tank and installation components of the RWCS. Consequently, gutters, catchment surfaces, first-flush diverters, filtration units, rainwater quality treatment systems, water-treatment components, and operational pumping were excluded from the system boundary. These components were excluded to maintain a consistent cradle-to-site assessment of the core infrastructure; therefore, the reported environmental impacts represent only the RWCS design and implementation and do not reflect the complete life cycle impacts of fully operational rainwater harvesting systems.

Data and Data Quality Requirements, Assumptions and Limitations

The functional unit represented the nominal storage capacity of the RWCS and did not represent the quantity of rainwater delivered or consumed over a specified service life. This basis was selected because the assessment was limited to the manufacturing and installation stages; operational water yield, pumping, maintenance, replacement, and end-of-life processes were not modeled. Accordingly, the comparison did not establish equivalence in terms of long-term service delivery, durability, or service life among the tank materials. Rather, it evaluated the environmental impacts and preliminary construction

costs associated with alternative RWCS configurations providing the same nominal 4000 L storage capacity.

Local availability guided the material selection. Where Philippine-specific life cycle inventory (LCI) data were unavailable, applicable international datasets from the SimaPro databases were used. Consequently, the results are influenced by the quality, completeness, and geographical representativeness of the available datasets. Differences in manufacturing technologies, energy mixes, and supply chains between the referenced datasets and actual local production conditions may introduce uncertainty into the estimated environmental impacts.

To ensure consistency and comparability among the RWCS alternatives, representative material specifications, construction processes, and installation activities were assumed. Site-specific variations in construction practices, equipment utilization, transportation logistics, and material wastage were not explicitly modeled. These assumptions simplify the assessment while maintaining a consistent basis for comparison across the evaluated systems.

The location of the source of each reference design was not considered representative of the physical supply chain of the system. For the LCA, all systems were assumed to be locally fabricated or procured and installed within the Philippine context. Accordingly, a common domestic transportation scenario was applied across the alternatives rather than modeling the actual transportation routes associated with the source locations of the reference designs.

Although efforts were made to maintain a consistent functional basis and system capacity for comparison, the alternatives have differences in terms of system configurations and were not considered as fully equivalent designs. The relative LCA results of the four RWCSs mainly show the environmental impacts of the modeled reference systems under the given assumptions and are not universally optimized or directly interchangeable designs. These differences are an important limitation when interpreting the relative environmental performance of the alternatives.

Cost Comparison

A preliminary construction cost estimate was prepared for each RWCS based on a quantity takeoff from the available design plans and technical specifications. The bill of quantities included the major construction components required for each alternative, namely earthworks, concrete works, steel works, storage tanks, and associated accessories where applicable. Quantities were measured directly from the design drawings, while unit costs were derived from previous local projects and prevailing market rates. The adopted unit rates comprise the direct costs of materials, labor, and equipment, reflecting typical construction practices under Philippine conditions.

A consistent cost estimation methodology was applied across all RWCS alternatives to ensure a fair and comparable economic evaluation. The estimates represent direct construction costs inclusive of taxes and exclude land acquisition, design and professional fees, permits, contingencies, operation and maintenance, replacement, and end-of-life costs.

Given the preliminary nature of the estimates and the greater uncertainty associated with the underground tank and accessories, a deterministic sensitivity analysis was conducted. This uncertainty arises from the use of commercially available underground system designs and the adoption of representative local prices of comparable tank products available in the Philippine market as proxies. The costs of the underground tank and accessories were varied as follows: −20%, −10%, +10%, and +20% from the base estimate, while all other cost components were held constant. The selected sensitivity ranges were based on commonly used cost-uncertainty scenarios in project economic evaluation, including

Philippine project evaluation guidance recommending 10% and 20% variations in projected costs [21]. The resulting scenarios were compared with the base-case estimates to assess the robustness of the relative cost ranking of the four RWCS configurations.

2.2. Description of the Rainwater Harvesting System

Four RWCS configurations were evaluated in this study to represent commonly adopted storage alternatives for building-scale applications. The systems differ primarily in storage tank material and installation type, comprising: (1) Aboveground Steel Tank (A-S), (2) Aboveground Polyethylene Tank (A-P), (3) Underground Reinforced Concrete Tank (U-C), and (4) Underground Polyethylene Tank (U-P). These alternatives were selected to enable a comparative assessment of the environmental and economic implications associated with different construction materials and installation methods. Table 1 summarizes the key features of the evaluated RWCSs.

Table 1. Features of RWC system designs.

	Aboveground Tank		**Underground Tank**	
Material	**Steel (A-S)**	**Polyethylene (A-P)**	**Concrete (U-C)**	**Polyethylene (U-P)**
Capacity	4000 L			
Other Features	Single horizontal steel tank	Double vertical PE tanks	Cylindrical concrete tank	Horizontal PE tank
	No pump (gravity-fed)		With pump	

2.2.1. Aboveground Steel RWCS (A-S)

The A-S consists of a single horizontal steel storage tank installed above ground. The configuration is supported by the associated structural and foundation components required for aboveground installation. The system has a nominal storage capacity of 4000 L and is designed as a gravity-fed configuration. The steel tank and its supporting works constitute the principal components considered in the manufacturing and installation assessment. The right-side elevation of A-S tank is shown in Figure 1.

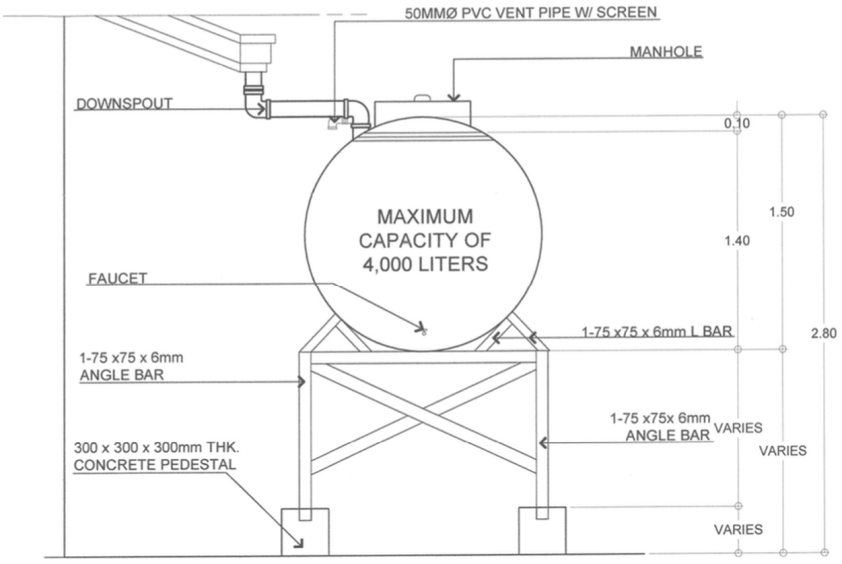


Figure 1. Right side elevation of Aboveground Steel Tank (A-S) RWCS (Reprinted with permission from Ref. [22]. Copyright 2025 Department of Public Works and Highways).

2.2.2. Aboveground Polyethylene RWCS (A-P)

The A-P uses two vertical polyethylene (PE) tanks arranged above ground to provide a combined nominal storage capacity of 4000 L. Similar to the A-S configuration, the system operates without a pump and relies on gravity for water delivery. Compared with the single-tank steel configuration, the use of two vertical PE tanks results in a different arrangement of tank and supporting components, which is reflected in the corresponding material quantities and installation requirements. Figure 2 shows the front elevation of A-P configuration.

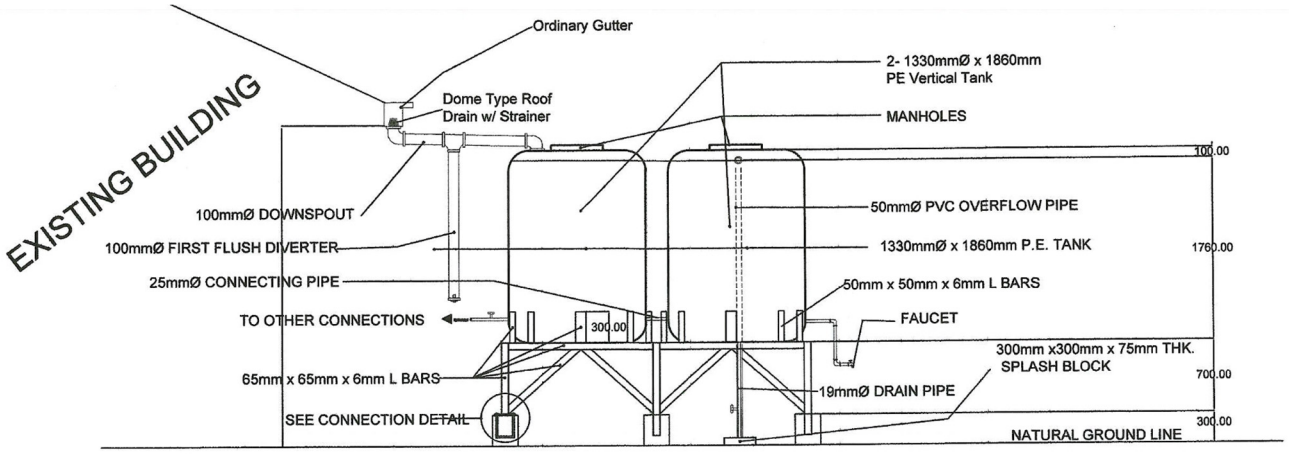


Figure 2. Front elevation of Aboveground PE Tank (A-P) RWCS (Reprinted with permission from Ref. [23]. Copyright 2019 Department of Public Works and Highways).

2.2.3. Underground Concrete RWCS (U-C)

The U-C consists of a cylindrical reinforced concrete storage tank installed below ground with a nominal storage capacity of 4000 L. The system requires excavation and associated earthworks for tank installation. The tank incorporates an integrated anchor-foot system, which requires approximately 1.5 m^3 of anchoring concrete to provide stability for the underground tank. The configuration also includes a manhole for access and a pump for water delivery from the underground storage tank. The concrete tank, anchoring system, excavation, and associated installation works were considered in establishing the material quantities and installation requirements for the LCA and preliminary cost assessment.

2.2.4. Underground Polyethylene RWCS (U-P)

The U-P consists of a horizontal polyethylene (PE) storage tank installed below ground, with a nominal storage capacity of 4000 L. The tank is installed within an excavated area with a compacted base and crushed stones or gravel backfill surrounding the tank. Provision for anchorage is included to secure the tank against movement during underground installation. The excavation is subsequently covered with suitable backfill material and topsoil. Similar to U-C, the U-P system incorporates a pump for water delivery. These excavation, backfilling, and anchorage components were considered in establishing the material quantities and installation requirements for the LCA and preliminary cost assessment. Figure 3 displays the concept of U-P configuration design.

2.3. Life Cycle Inventory (LCI)

This phase involved data collection on all relevant energy and material inputs and environmental releases associated with each life cycle stage of the materials under study.

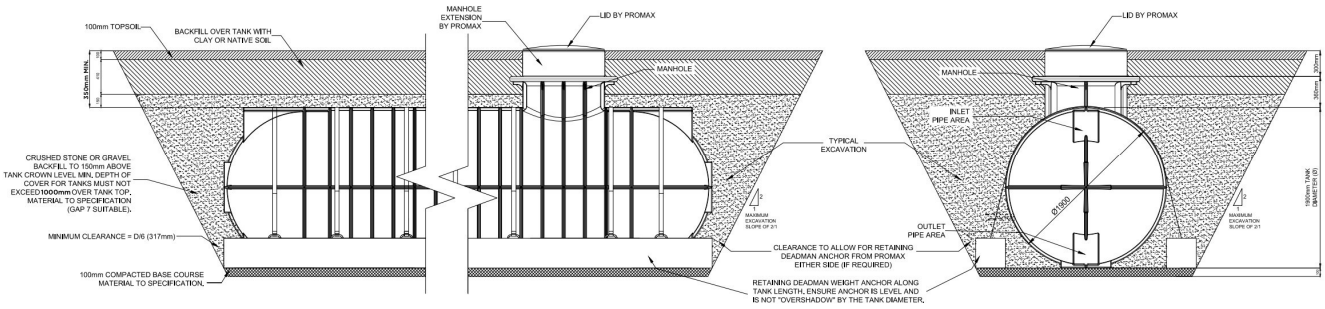


Figure 3. Concept of Underground PE Tank (U-2) RWCS (Reprinted with permission from Ref. [24]. Copyright 2020 Promax Engineered Plastics Ltd., Kerikeri, New Zealand).

2.3.1. Data Collection

Life cycle inventory (LCI) data were compiled from engineering design documents, manufacturer information, and commercially available product specifications. Detailed engineering plans for the Aboveground Polyethylene and Steel Tank systems were obtained through coordination with the DPWH Regional Office VI. For the Underground Reinforced Concrete and Polyethylene Tank systems, engineering concepts and technical specifications were developed based on commercially available products and publicly accessible manufacturer information.

The engineering plans and technical specifications served as the basis for the quantity takeoff of construction materials and the identification of installation activities included in the life cycle inventory. Material quantities, construction processes, and system components were subsequently used to develop the inventory for the manufacturing and installation stages of each RWCS alternative.

2.3.2. LCI Framework

The life phases—manufacturing and installation—of the RWCS, based on the bill of materials of each system, were broken down into relevant energy and material inputs. Data sources included the literature and reports on construction practices in the Philippines, and international databases available in SimaPro. Inventory data were compiled for each process step including production, transportation distances, and installation energy. Figure 4 shows a schematic representation of the input/output flows for each life cycle stage of RWCS which underwent assessment.

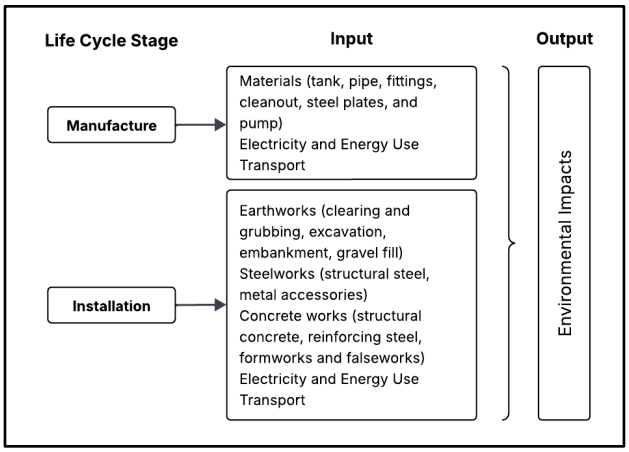


Figure 4. LCI framework diagram for RWCS.

Table 2 presents the components and material inputs by weight for each system. Certain items are not applicable to some systems, as determined by their respective designs.

Table 2. Material inputs per RWCS.

No.	Process	Unit	[A-S]	[A-P]	[U-C]	[U-P]
1	Lid HDPE	kg	-	-	-	4.54
2	Pump	kg	-	-	26	26
3	Cleanout	kg	7.22	7.22	9.63	9.63
4	Concrete Tank	ton	-	-	3	-
5	Elbow	kg	6.42	6.42	8.56	8.56
6	Metal Structure Accessories	kg	-	22.6	-	-
7	PE Tank	kg	-	92	-	175
8	Pipe	kg	5.07	5.07	5.63	5.63
9	Plywood	kg	12.4	20	-	-
10	Reinforcing Steel	kg	701	310	-	-
11	Steel Tank	kg	110	-	-	-
12	Structural Concrete	ton	5.84	6.9	3.6	-
13	Structural Concrete for Anchor	ton	-	-	3.6	-
14	Structural Steel	kg	154	204	-	-
15	Tee	kg	1.02	1.02	1.02	1.02

2.4. Life Cycle Impact Assessment (LCIA)

The life cycle inventory data were obtained from the ecoinvent database ver. 3.11—allocation and cut-off classification system models were utilized consistently throughout the assessment. The database inputs with the most relevant geographical coverage of the study area were selected. Philippine-specific datasets were prioritized in the selection and were mainly incorporated in the electricity mix processes. Other geographically appropriate datasets, such as Rest-of-World (RoW) and Global (GLO) datasets, were selected as substitutes when no Philippine-specific datasets were available. Transportation processes in this study were assumed to be the same throughout the four RWCS design plans, simulating its implementation and installation on the same target site.

The life cycle inventory (LCI) data was analyzed using the ReCiPe2016 Midpoint (H) impact assessment method in SimaPro. ReCiPe2016 provides an approach that processes life cycle inventories to a limited number of Life Cycle Impact scores on midpoint and endpoint levels [25]. This method was selected to provide a comprehensive set of environmental impact indicators that can be used to characterize emissions and resource use into scientifically defined environmental impact categories [26]. For this study, the midpoint level was adopted to evaluate the environmental performance of RWCS within the cradle-to-site boundary. The Hierarchical (H) perspective was adopted as the consensus-based approach of the method, representing time horizon and balanced long and short-term environmental mechanism assumptions. This is fitting as the study aims to compare materials and installation processes rather than modeling long-term environmental impacts.

For the LCIA of the study, key environmental impact categories included global warming potential (GWP), ozone depletion, acidification and eutrophication, human carcinogenic toxicity (HCT), ecotoxicity, fossil fuel depletion, and water consumption. This study primarily focused on GWP and HCT. Each system was compared across these categories to determine the most environmentally sustainable alternative.

2.5. Interpretation

The Life Cycle Impact Assessment (LCIA) generated insights into the environmental performance of various aboveground RWCS configurations commonly implemented in the Philippines and commercially available underground systems. Specifically, it evaluated the embodied impacts of different tank materials and installation methods. The results are intended to support evidence-based decision-making by the Department of Public Works

and Highways (DPWH) and Local Government Units (LGUs), guiding the selection of more sustainable RWCS for public schools. It should be noted, however, that the study focuses solely on the storage tanks, other major components, and their associated installation processes. Other components—such as guttering and filtration systems—were excluded from the system boundary.

3. Results and Discussion

3.1. Comparative Environmental Impacts of the RWCS

The comparative characterization results across the 18 impact categories are presented in Figure 5. It should be noted that these results represent the combined manufacturing and installation stages only, as the use and end-of-life stages were excluded from the system boundary. Across the 18 environmental impact categories evaluated, U-C consistently exhibited the lowest characterization results among the four RWCS designs. In contrast, the system with the highest impact varied by category: A-S recorded the highest impact in nine categories, U-P in eight categories, and A-P in one category. These categories include global warming potential, stratospheric ozone depletion, ionizing radiation, ozone formation (human health and terrestrial ecosystems), fine particulate matter formation, terrestrial acidification, eutrophication (freshwater and marine), ecotoxicity (terrestrial, freshwater, and marine), human toxicity (carcinogenic and non-carcinogenic), land use, resource scarcity (mineral and fossil), and water consumption.

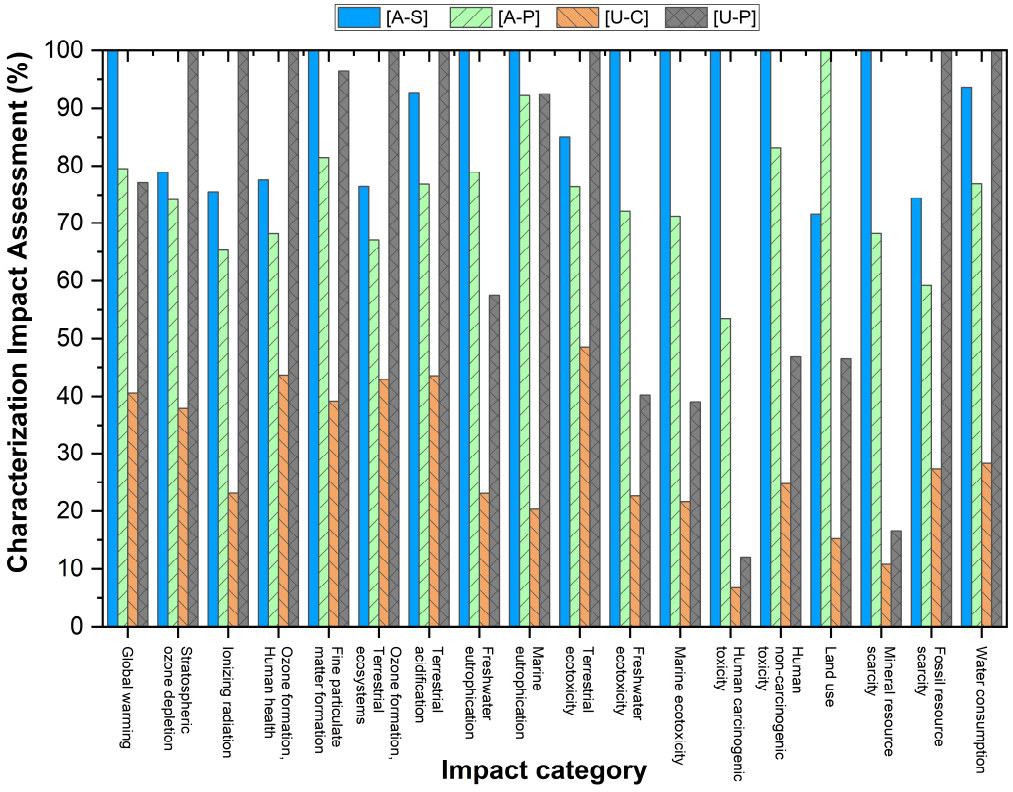


Figure 5. Characterized impact assessment of RWCS designs per impact category.

It should also be noted that the four RWCS configurations were derived from different design bases. The aboveground systems were based on locally derived DPWH designs, whereas the underground systems were based on commercial reference designs. Consequently, differences in design configuration, material quantities, and installation requirements may have contributed to the observed differences in environmental impacts. The results therefore reflect the specific configurations and assumptions evaluated in this

study and should not be interpreted as an inherent comparison of tank materials or system types independent of their design basis.

The observed differences indicate that the environmental performance of the RWCS is strongly influenced by the materials and quantities required for their respective manufacturing and installation.

Following the characterization results, normalization was performed to facilitate the interpretation and comparison of the environmental impacts across the different impact categories. This converts results expressed in different units into dimensionless normalized values, allowing the relative magnitude of the assessed impacts to be examined within each impact category. In this study, the normalized results were used to identify the impact categories that contribute most prominently to the overall environmental profile of the evaluated RWCS rather than to directly compare the absolute environmental significance of different impact categories.

The normalized results, presented in Figure 6, show that human carcinogenic toxicity exhibits the largest normalized values among the impact categories considered, particularly for the A-S, followed by A-P, U-P, and U-C. Freshwater ecotoxicity and marine ecotoxicity also exhibit relatively high normalized values compared with most of the other categories. The large, normalized values observed for human carcinogenic toxicity indicate that, relative to the selected normalization reference, this category represents a prominent component of the environmental profile of the evaluated systems.

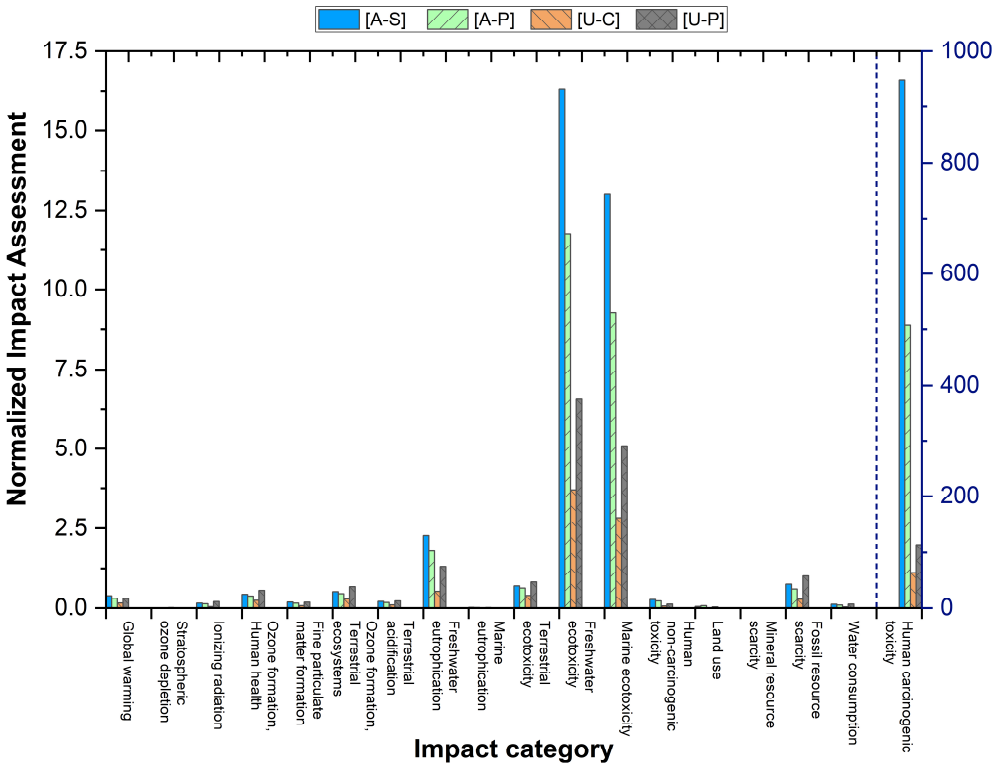


Figure 6. Normalized impact assessment of RWCS types per impact category. The vertical dashed line divides the plot into two sections corresponding to the left and right y-axes due to differing data scales.

The normalized results provide a basis for identifying impact categories warranting further contribution analysis, specifically HCT. To further investigate the sources of environmental impacts, GWP and HCT were selected for detailed contribution analysis. The selection was based on both the relevance of these impact categories to construction materials and the patterns observed in the normalized results.

Global warming potential (GWP) was selected as a key impact category because it represents the potential contribution of greenhouse-gas emissions associated with the production and use of materials and processes. In the construction sector, Life Cycle Assessment is widely applied to quantify the embodied environmental impacts of construction materials, with GWP serving as an important indicator of their associated carbon emissions. Studies assessing construction materials and systems have identified GWP as one of the major impact categories for evaluating environmental performance [27–29]. The relevance of GWP is also particularly appropriate for the present study because the evaluated RWCSs differ considerably in their material composition and construction requirements, allowing the contribution of individual materials and processes to greenhouse-gas emissions to be examined.

Figure 7 highlights the contribution of each RWCS design, life cycle stage, and major construction process to the overall GWP. Among the four configurations, the Aboveground Steel Tank system (A-S) exhibited the highest GWP at 3114.08 kg CO_2-eq, whereas the Underground Concrete Tank system (U-C) had the lowest at 1263.61 kg CO_2-eq. Compared with the other configurations, U-C resulted in a GWP that was approximately 47.3% to 59.4% lower.

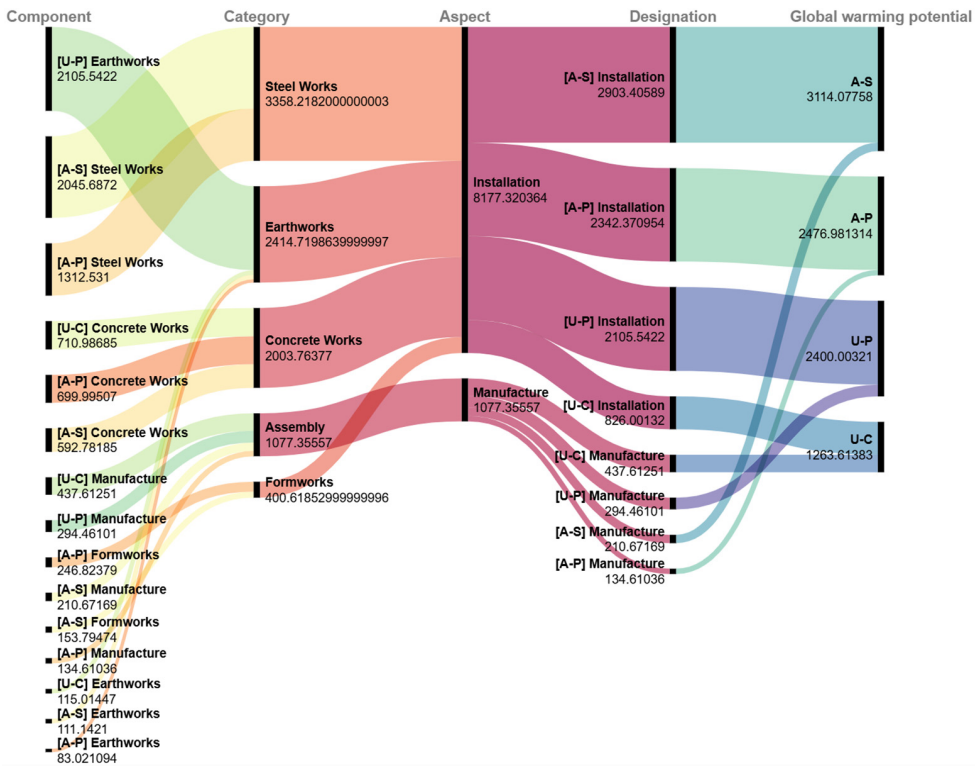


Figure 7. Sankey diagram of life cycle stages of RWCS options in terms of GWP.

For A-S, installation accounted for approximately 93.2% of the total GWP (2903.41 kg CO_2-eq), while manufacturing contributed only 6.8% (210.67 kg CO_2-eq). A similar predominance of installation-stage impacts was observed for the other RWC configurations, indicating that on-site construction activities constitute an important source of GWP within the defined cradle-to-site boundary. Within the installation stage across all four systems, steel works and earthworks account for the highest impacts, with 3358.22 kg of CO_2-eq and 2414.72 kg of CO_2-eq, respectively.

Human carcinogenic toxicity (HCT) was selected as a complementary impact category because it represents a human-health dimension that is distinct from climate-related impacts. This category was also identified as the most prominent normalized impact

category in the present assessment. Its inclusion therefore provides an opportunity to examine whether the materials and processes that drive GWP also contribute to human-health-related impacts. The relevance of considering toxicity alongside GWP has been emphasized in LCA studies of construction materials, as toxicity impacts may otherwise receive less attention when environmental performance is assessed primarily through carbon emissions [30–32].

Figure 8 illustrates the contributions to human carcinogenic toxicity. Among the four configurations, A-S exhibited the highest impact at approximately 9757 kg of 1,4-DCB, followed by A-P at approximately 5218 kg of 1,4-DCB, and U-P at 1173 kg of 1,4-DCB-eq. U-C had the lowest HCT impact at 656.44 kg of 1,4-DCB-eq. Compared with the other configurations, the HCT impact of U-C was approximately 44.1% to 93.3% lower. The results indicate that the aboveground configurations, particularly A-S, contribute more strongly to human carcinogenic toxicity within the defined cradle-to-site system boundary.

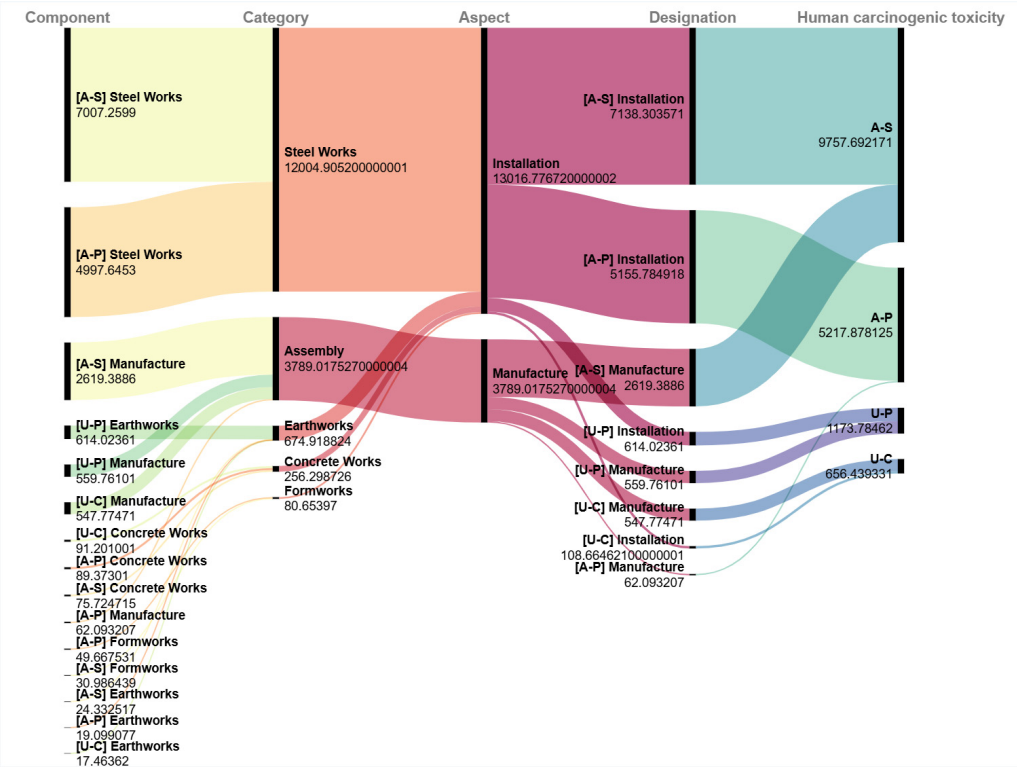


Figure 8. Sankey diagram of life cycle stages of RWCS options in terms of human carcinogenic toxicity.

For A-S, the installation stage accounted for the majority of the total human carcinogenic toxicity, contributing approximately 7138 kg of 1,4-DCB, compared with approximately 2619 kg of 1,4-DCB from manufacturing. This indicates that, similar to the GWP results, installation is an important contributor to the human-health-related impacts of the evaluated systems. However, the contribution of manufacturing is considerably more pronounced for human carcinogenic toxicity than it was for GWP, particularly for the systems requiring substantial steel components.

At the process level, steel works represent the dominant contributor to human carcinogenic toxicity across the evaluated systems. In the study by Harasymchuk et al. (2024) [33], they conducted LCA of two most common routes of steel production, and found out that pig iron production in blast furnaces which emits carbon monoxide (CO) is the most hazardous process for the human body. Heavy metals such as lead, cadmium, chromium, and nickel can enter and exit at different stages of pig iron production [33].

3.2. GWP and Human Carcinogenic Toxicity Contributions by RWCS Design

The environmental performance of the cradle-to-site processes of the RWCS designs was detailed and further examined using network diagrams in the global warming and human carcinogenic toxicity categories. The network diagrams allow the contributions of individual life cycle stages, processes, and material inputs to be identified. The red arrows indicate the contributions of the components to the impact category, the width proportional to the magnitude of the impact.

3.2.1. Aboveground Steel (A-S)

A. A-S Global Warming

Figure 9 presents the network diagram illustrating the relative contribution of the different life-cycle processes and material inputs to the overall global warming potential (GWP) of the A-S. Based on the network, 93.2% of the entire global warming impact contribution originates from the installation life cycle stage, while manufacturing accounts for approximately 6.8%. This distribution demonstrates that construction- and installation-related activities are the principal drivers of GWP in the assessed system. This is attributed to reinforcing steel, representing the highest individual contribution accounting for 53.1% of the total GWP, followed by structural concrete at 19.1% and structural steel at 12.9%. These three components contribute over 85% of the global warming impact, depicting steel- and concrete-related activities to be a core part in the increase in environmental impacts throughout the A-S RWCS cradle-to-site life cycle. The substantial contribution from reinforcing steel is associated primarily with the production of approximately 701 kg of reinforcing steel, while the structural concrete and structural steel contributions are approximately 5.84 tons and 154 kg, respectively. These results are aligned with the energy-intensive nature of steel production, relying heavily on the use of fossil fuels for energy, which led to the steel industry having the largest energy consumption across various sectors [34].

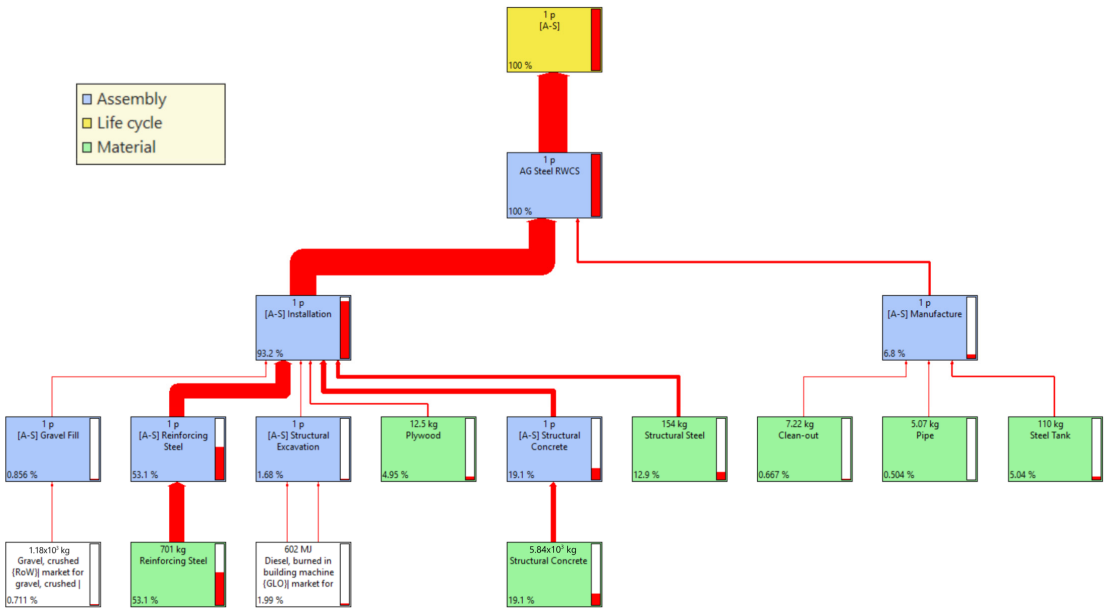


Figure 9. A-S GWP network diagram.

The major contributor succeeding in the installation stage is plywood with 4.95%. Despite being evidently lower, plywood being procured and utilized during construction and installation activities should also be identified as a contributor to global warming. This is also due to the usage of fossil fuel resources at various processes in the production of ply-

wood, leading to greenhouse-gas (GHG) emissions [35]. Other processes under installation such as gravel filling and structural excavation have lower values, depicting associated diesel consumption for construction machineries (420 MJ) and equating construction equipment and site activities to have lower contributions in global warming potential.

For the manufacturing stage, steel tank accounts for the most with 5.04% of the total global warming impact, followed by other materials such as cleanouts and pipes. This indicates that the components and materials provide lower environmental burden relevant to global warming.

B. A-S Human Carcinogenic Toxicity

Figure 10 presents the network diagram illustrating the relative contribution of the different life-cycle processes and material inputs to the overall human carcinogenic toxicity (HCT) of the aboveground steel RWCS (A-S). Based on the network, 73.1% of HCT in the system originates from the installation stage, while manufacturing accounts for 26.9%. This distribution demonstrates that installation-related activities are the core contributors of HCT in A-S. This is attributed to reinforcing steel, representing the highest individual contribution accounting for 51.6% of the total HCT, produced by the usage of approximately 701 kg of reinforced steel and structural steel weighing 154 kg which accounts for 20.2% of HCT, identifying steel as a major hotspot in impact contribution. In comparison, other installation materials and processes such as structural concrete, plywood, structural excavation, and gravel fill account for 0.773, 0.316, 0.079 and 0.0848%, respectively, having minor impact contributions. Meanwhile, in the manufacturing stage, steel tanks with about 110 kg of steel material account for the highest with 26.5% of the total human carcinogenic toxicity. Considering the individual contributions of materials in the whole network, the steel materials are the main contributors of human carcinogenic toxicity in the entire A-S RWCS, accounting for 98.3%.

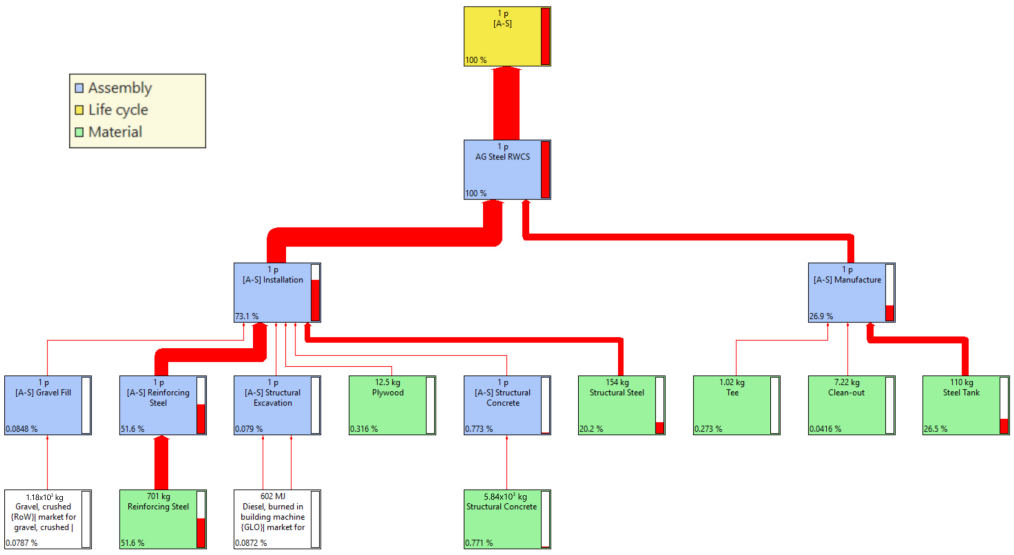


Figure 10. A-S HCT network diagram.

3.2.2. Aboveground Polyethylene (A-P) RWCS

A. A-P Global Warming

Figure 11 presents the network diagram illustrating the contribution of the different life-cycle processes and material inputs to the overall global warming potential (GWP) of the aboveground polyethylene (PE) RWCS. Based on the diagram, 94.6% of the global warming impact in A-P is found in the installation stage, while manufacturing accounts for 5.43%. This distribution shows that installation-related activities cause the most GWP emissions in

the system. This is attributed to reinforcing steel, which represents the component with the largest contribution, accounting for 29.4% of the total GWP, followed by structural concrete at 28.2% and structural steel at 21.4%. These three components alone account for about 79% of the global warming impact, indicating that steel- and concrete-related activities are core contributors to the increase in environmental impacts throughout the A-P RWCS cradle-to-site life cycle. The substantial contribution from reinforcing steel is associated primarily with the production of approximately 310 kg of reinforcing steel, while the structural concrete contribution is linked to approximately 6.93 tons of structural concrete. The next highest in the installation stage is plywood at 9.95%. Although plywood is evidently lower, it should also be recognized as contributing to global warming during construction and installation.

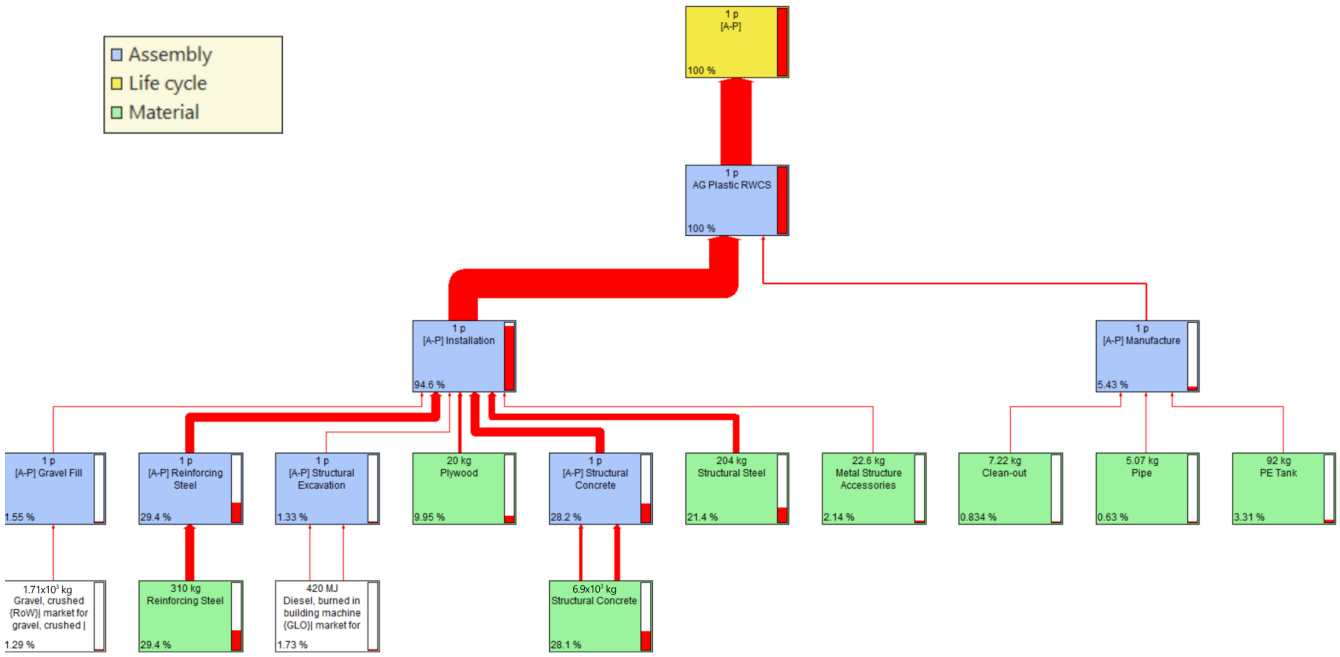


Figure 11. A-P GWP network diagram.

In the manufacturing stage, steel tanks account for the most, with 3.31% of the total global warming impact, followed by other materials such as cleanouts and pipes. This indicates that the components and materials have a lower environmental burden associated with global warming.

B. A-P Human Carcinogenic Toxicity

Figure 12 presents the network diagram illustrating the relative contribution of the different life-cycle processes and material inputs to the overall human carcinogenic toxicity (HCT) of the aboveground polyethylene (PE) RWCS (A-P). Based on the diagram, 98.8% of the global warming impact comes from the installation stage, while manufacturing accounts for 1.19%. This distribution entails that installation-related activities are the main contributors of HCT in the A-P system. This is attributed to reinforcing steel, representing the highest individual contribution accounting for 42.7% of the total HCT, produced by the usage of approximately 310 kg of reinforced steel and structural steel weighing 204 kg which accounts for 50.2% of HCT, identifying steel as a major hotspot in impact contribution. In comparison, other installation materials and processes such as structural concrete, plywood, structural excavation, and gravel fill account for 1.71, 0.948, 0.0931, and 0.23%, respectively, having minor impact contributions. Meanwhile, in the manufacturing stage, PE tank with about 92 kg of plastic material and other components such as tee and cleanouts account

to 0.497, 0.511, and 0.0777% of the total human carcinogenic toxicity. Considering the individual contributions of materials across the entire network, steel materials are the primary contributors to human carcinogenic toxicity in the A-P, accounting for 92.9%.

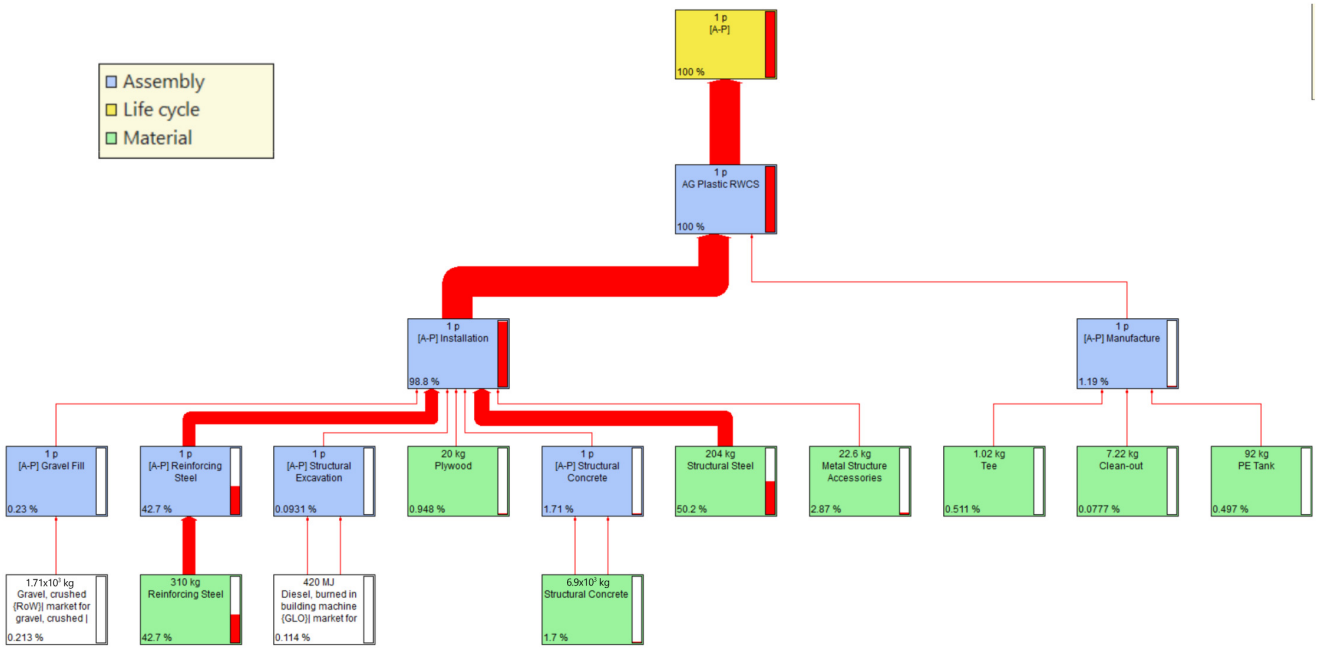


Figure 12. A-P HCT network diagram.

3.2.3. Underground Concrete (U-C) RWCS

A. U-C GWP

The SimaPro network diagram presented in Figure 13 illustrates the contribution of the different processes and material inputs associated with the life cycle of the underground concrete (U-C) RWCS. The network indicates that the overall global warming potential is identified in the installation stage, which contributes approximately 65.3% of the impact, while the manufacturing stage contributes 34.6%. This distribution depicts that construction-related activities are more environmentally impactful than the production of the prefabricated system components.

Within the installation stage, the components with largest contributions are structural concrete (28.8%) and structural concrete for anchor (27.3%), both with 3.63 $\times$ 10^3 kg of input. These two processes account for approximately 56.1% of the total GWP impact. Structural excavation contributes a further 7.95% with an input of 20.6 m^3 for excavation and 1.18 $\times$ 10^3 MJ of diesel, while cleaning and grubbing represent only 0.993%. The network demonstrates that the GWP profile of the installation phase is dominated by concrete-related activities than site preparation.

For the manufacturing stage, the concrete tank is the dominant contributor at 24%, followed by the pump at 5.55%. The cleanout and pipe contribute 2.18% and 1.37%, respectively, while the elbow contributes approximately 1.0%. Consequently, the concrete tank alone represents a substantial portion of the modeled GWP and is considerably more influential than the smaller piping components.

The results indicate that concrete is the core environmental hotspot of the U-C RWCS. The structural concrete, concrete anchoring elements, and concrete tank collectively account for approximately 80.1% of the contributions displayed in the network. This finding is important because it demonstrates that the system's environmental performance is strongly influenced by the quantity and production pathway of the concrete used in both construction and in the tank itself.

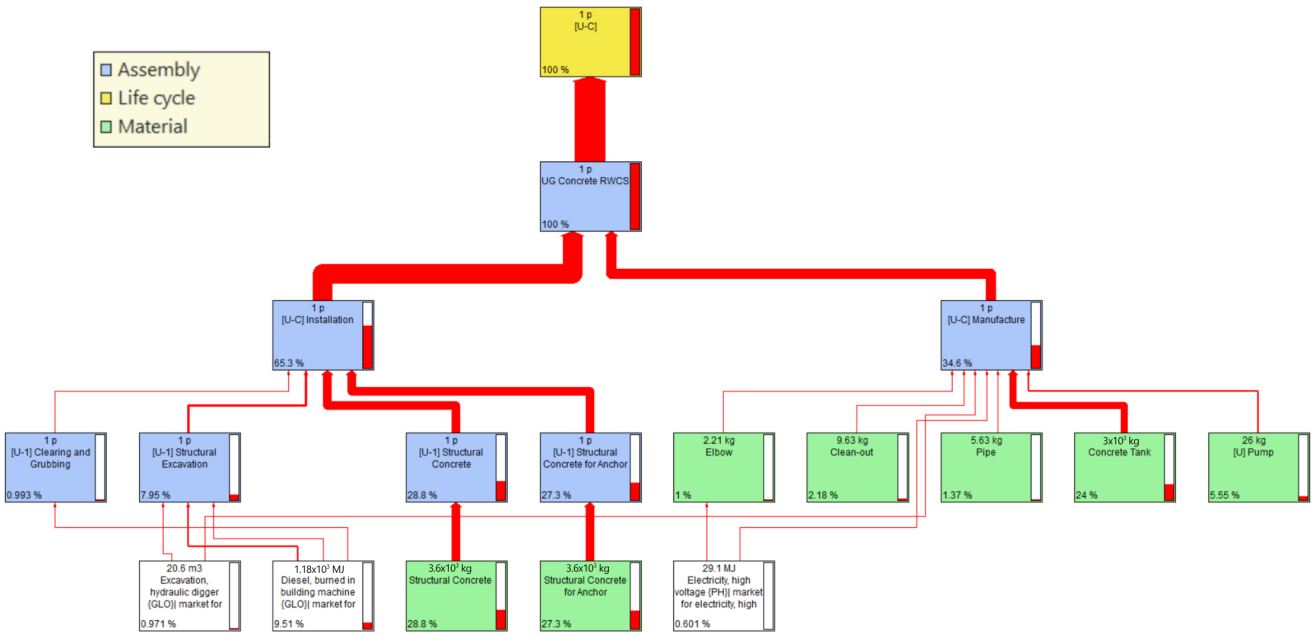


Figure 13. U-C GWP network diagram.

B. U-C HCT

The network diagram presented in Figure 14 illustrates the life-cycle contribution flow for the underground concrete rainwater collection (U-C RWC) system. Based on the network, human carcinogenic toxicity is predominantly associated with the manufacturing stage, which accounts for 83.4% of the total contribution. The 26 kg pump, which independently accounts for 71.7% of the total contribution, is the dominant environmental hotspot of the U-C RWCS. The concrete tank, on the other hand, accounts for only 5.88%, making it the second largest manufacturing contributor. Although the tank is a core structural component of the system, its contribution is substantially lower than that of the pump. This suggests that the HCT emissions from the concrete tank are moderated by the characteristics of the modeled concrete production process, relative to the manufacturing processes associated with the pump.

In comparison, the installation stage accounts for only 16.5%. This indicates that, unlike the previously assessed gravity-fed, aboveground RWCS, the environmental performance of the underground concrete system is primarily influenced by the production of its major equipment and components rather than by site installation activities. Structural concrete is the largest contributor at approximately 7.05%, followed closely by structural concrete for the anchor at approximately 6.70%. Together, these concrete-related components account for a substantial portion of the installation stage's HCT contribution.

3.2.4. Underground Polyethylene (U-P) RWCS

A. U-P GWP

The network diagram presented in Figure 15 illustrates the life-cycle flow of the underground plastic Rainwater Collection System (U-P RWCS) and illustrates the relative contribution of the manufacturing and installation stages to the overall GWP. The results indicate that the system predominantly emits GWP from installation activities, which account for 87.8% of the total contribution. Gravel fill is the most significant contributor, representing approximately 76.6%. This substantial contribution is associated with the large quantity of gravel required for the underground installation, with an input of 8.18×10^4 kg of gravel in the network.

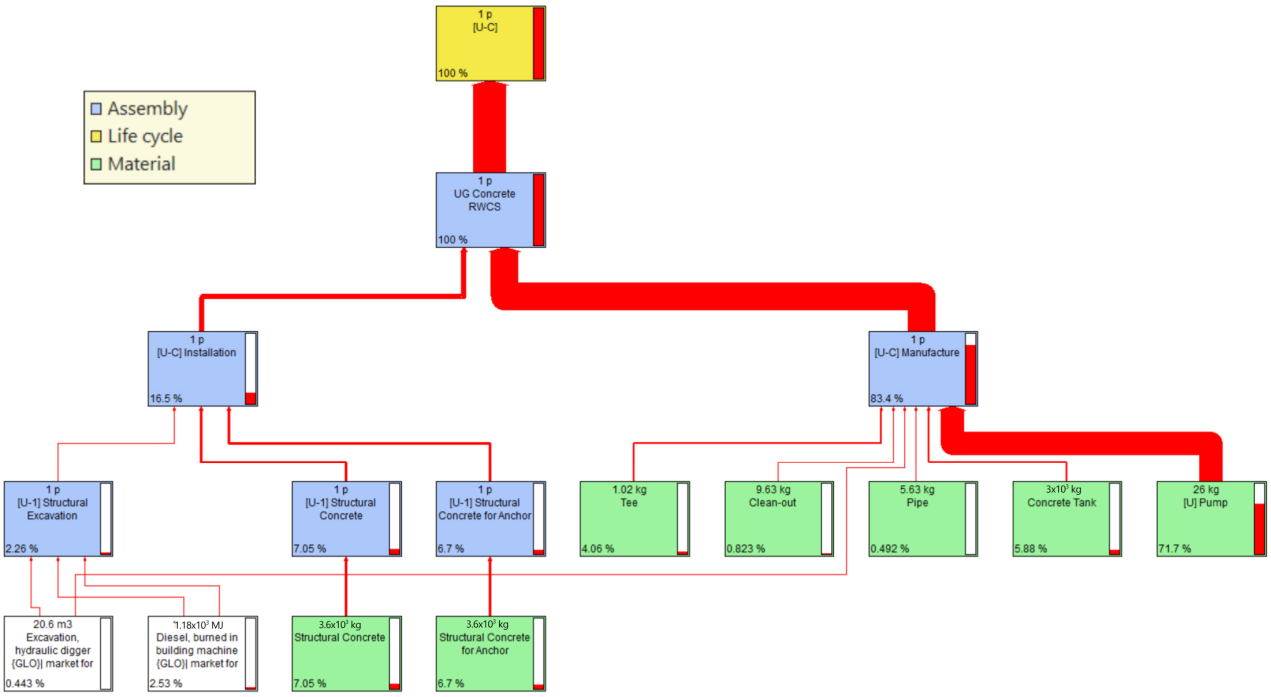


Figure 14. U-C HCT network diagram.

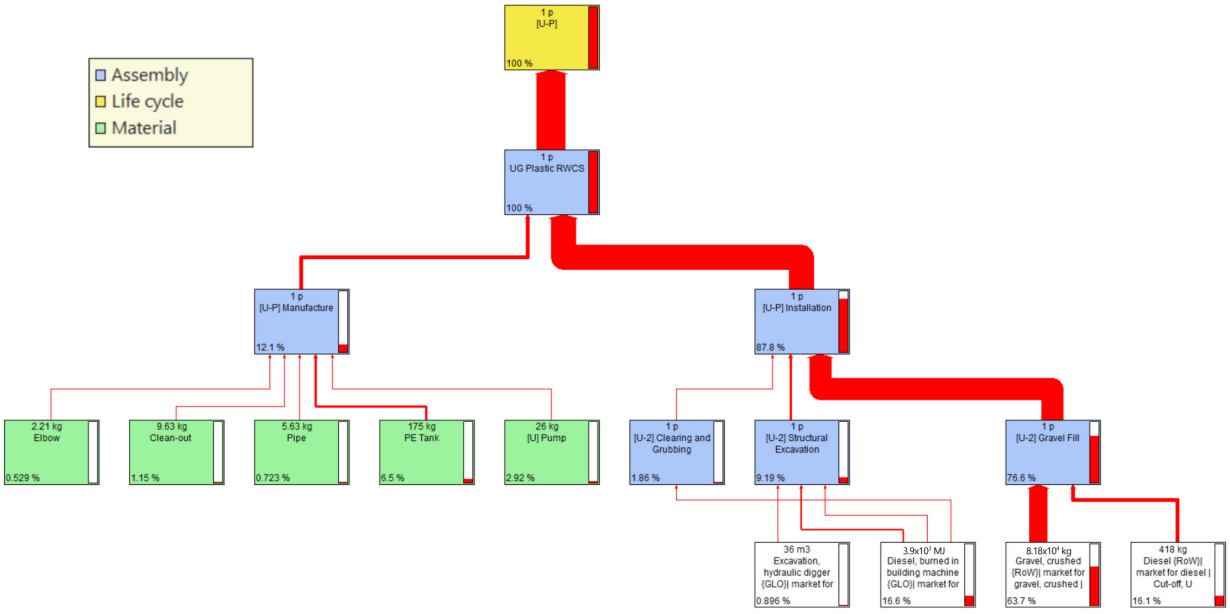


Figure 15. U-P GWP network diagram.

In comparison, the manufacturing stage accounts for only 12.1% of all GWP contributions. This distribution demonstrates that, for the underground plastic RWCS, the GWP is driven mainly by the materials and processes required for preparation and underground installation rather than by the production of the plastic tank, which accounts for only 6.5%.

B. UP-HCT

The network diagram presented in Figure 16 illustrates the life-cycle flow of the underground plastic Rainwater Collection System (U-P RWCS) and illustrates the relative contribution of the manufacturing and installation stages to the overall HCT. The results indicate that the system predominantly emits HCT from installation activities, which account for 52.4% of the total contribution. Gravel fill is the most significant contributor,

representing approximately 48.9%. This substantial contribution is associated with the large quantity of gravel required for the underground installation, with an input of 8.18×10^4 kg of gravel into the network and 418 kg of diesel for machinery used to incorporate the gravel at the site.

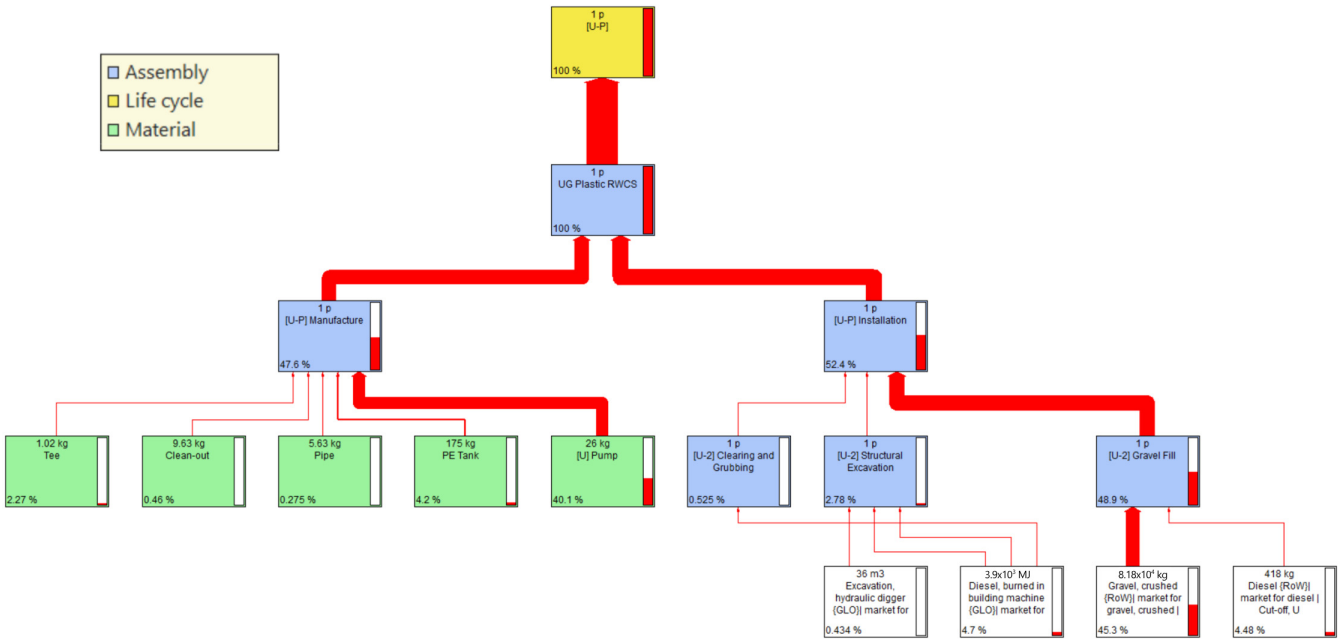


Figure 16. A-UP HCT network diagram.

In comparison, the manufacturing stage accounts for 47.6% of all HCT contributions. The pump represents the largest contribution, accounting for 40.1% of the total impact. This is considerably higher than the contributions of the PE tank (4.2%) and other components. This distribution demonstrates that, for the underground plastic RWCS, the HCT is driven mainly by the materials and processes required for preparation and underground installation rather than by the manufacturing of the U-P RWCS.

3.3. Construction Cost Comparison

The comparative cost analysis evaluated the preliminary construction costs of the four Rainwater Collection System (RWCS) designs, categorized into four major work components: earthworks, concrete works, steel works, and tanks and associated accessories (e.g., pump and anchorage system). The estimates represent direct construction costs, including materials, labor, and equipment, based on the quantity takeoffs and unit costs described in the Cost Comparison Section.

Table 3 summarizes the estimated construction costs of the four RWCS configurations. Among the evaluated alternatives, the Underground Concrete Tank system (U-C) showed the lowest total estimated cost at Php 149,857.21, followed by the underground plastic tank system (U-P) at Php 188,312.06 then the aboveground plastic tank system (A-P) at Php 208,780.76. The highest cost was observed in the Aboveground Steel Tank system (A-S), with a total of Php 230,980.65. Compared with the other configurations, U-C was approximately 20.4% to 35.1% less costly. These results indicate that, under the assumptions adopted in this study, the underground configurations were generally less costly than the aboveground alternatives, with U-C providing the lowest estimated construction cost among the four systems.

Table 3. Estimated cost breakdown of RWCS designs by major work category (costing year: 2025).

Description	Estimated Cost (Php)			
	A-S (Steel)	**A-P (Plastic)**	**U-C (Concrete)**	**U-P (Plastic)**
Earthworks	6039.61	4325.00	11,732.21	45,311.06
Concrete Works (base and foundation)	96,088.43	95,160.00	-	-
Steel Works (base and foundation)	28,252.61	41,695.76	-	-
Tank and accessories	100,600.00	67,600.00	138,125.00	143,001.00
Total	230,980.65	208,780.76	149,857.21	188,312.06

The results indicate that concrete and steel works contributed a significant portion of the total cost, primarily due to the base and foundation requirements for aboveground systems—elements not present in the underground configurations. In contrast, the underground systems do not require the same aboveground supporting structures but involve substantially greater earthwork quantities due to excavation requirements. This is particularly evident for U-P, where the installation procedure for the commercial polyethylene tank requires extensive excavation and associated site works. Thus, the lower cost of the underground systems does not necessarily result from reduced construction requirements overall, but rather from a different distribution of costs among the major work components.

The tank and accessories component also contributes to the differences among the alternatives. For the underground configurations, additional components such as pumps and tank anchorage systems increase the associated costs compared with the aboveground systems.

The cost results should, however, be interpreted as preliminary comparative estimates rather than definitive project costs. The analysis uses the costing basis and unit rates applicable to the reference month and year (July 2025), and the Philippine construction context, with the unit rates incorporating materials, labor, and equipment. Items outside the defined direct construction cost were not considered, including operation and maintenance, replacement, end-of-life costs, land acquisition, professional and design fees, permits, and contingencies. Additionally, transportation costs were excluded, and applicable taxes were included from the adopted unit rates.

Greater uncertainty is associated with the underground configurations, particularly because their designs were based partly on commercially available systems and their tank costs were estimated using locally available tank prices rather than direct quotations for identical locally manufactured products. This approach provides a consistent basis for comparison but may not fully capture differences in manufacturing, transportation, installation requirements, and market availability between the reference tanks and the evaluated underground systems. Since the underground designs analyzed are not locally sourced from the Philippines, representative prices of comparable tank products available in the Philippine market were adopted for the cost estimate. These representative prices were used as proxies to establish a consistent local cost basis rather than directly applying foreign product prices. This introduces uncertainty because the locally available products may differ from the referenced systems in terms of manufacturer, specifications, and market pricing.

To examine the robustness of the cost comparison to this uncertainty, the estimated costs of the underground tank and accessories were varied by ±10% and ±20%, while the costs of the remaining construction components were held constant. The resulting sensitivity scenarios are presented in Table 4.

The sensitivity analysis shows that U-C remained the lowest-cost alternative across all tested scenarios. Its estimated cost ranged from Php 122,232.21 under the −20% sce-

nario to Php 177,482.21 under the +20% scenario, compared with its base-case estimate of Php 149,857.21. Similarly, the estimated cost of U-P ranged from Php 159,711.86 to Php 216,912.26, compared with its base-case value of Php 188,312.06.

Table 4. Sensitivity analysis for the preliminary cost estimates of RWCS configurations (darkest green highlights lowest cost).

Scenario	U-C	U-P	A-P	A-S	Lowest
Tank and accessories (A)	138,125.00	143,001.00	-	-	-
Earthworks (B)	11,732.21	45,311.06	-	-	-
Base (A + B)	149,857.21	188,312.06	208,780.76	230,980.65	U-C
Underground tank and accessories − 20% (A × 0.8 + B)	122,232.21	159,711.86	208,780.76	230,980.65	U-C
Underground tank and accessories − 10% (A × 0.9 + B)	136,044.71	174,011.96	208,780.76	230,980.65	U-C
Underground tank and accessories + 10% (A × 1.1 + B)	163,669.71	202,612.16	208,780.76	230,980.65	U-C
Underground tank and accessories + 20% (A × 1.2 + B)	177,482.21	216,912.26	208,780.76	230,980.65	U-C

The relative ranking of U-C as the least-cost alternative was therefore robust to a ±20% variation in the estimated underground tank and accessories costs. This indicates that the uncertainty associated with this component does not affect the identification of U-C as the most economical configuration among the alternatives evaluated considering the scope and limitations of this study.

However, the sensitivity analysis also demonstrates that the ranking of the intermediate alternatives is more sensitive to underground tank pricing. Under the +20% scenario, the estimated cost of U-P increases to Php 216,912.26, exceeding the estimated cost of A-P at Php 208,780.76. Thus, while the overall identification of U-C as the lowest-cost alternative remains unchanged, the relative economic position of U-P and A-P may change depending on the actual costs of the underground tank and accessories.

Overall, the sensitivity results support the robustness of the finding that U-C has the lowest preliminary construction cost, while also highlighting the importance of obtaining actual local supplier quotations for underground tank systems in future assessments.

4. Conclusions and Recommendations

This study conducted a comparative life cycle and cost assessment of four Rainwater Collection System (RWCS) designs with a 4000 L capacity, considering a cradle-to-site system boundary that included the manufacturing and installation stages. The results revealed that the Underground Concrete Tank system (U-C) consistently exhibited the lowest environmental impact across all 18 impact categories. Among the four alternatives, the underground concrete system (U-C) exhibited the lowest characterized environmental impacts across all 18 impact categories. In comparison, the aboveground steel system (A-S) recorded the highest impact in nine categories, while the aboveground polyethylene (A-P) and underground polyethylene (U-P) systems recorded the highest impacts in one and eight categories, respectively. The higher impacts associated with A-S were primarily attributed to its substantial steel requirements, particularly for structural and foundation components. The contribution analysis further showed that steel works were a major source of environmental burdens, including human carcinogenic toxicity, while gravel fill and concrete components also contributed appreciably to selected impact categories.

The preliminary cost assessment showed that U-C has the lowest estimated construction cost at PHP 149,857.21, followed by U-P, A-P, and A-S. Although the underground configurations required greater earthwork quantities, the aboveground systems incurred higher costs associated with structural and foundation requirements. Sensitivity analysis

of the uncertain underground tank and accessories costs showed that U-C remained the lowest-cost alternative across the assessed ±10% and ±20% scenarios.

The findings should be interpreted within the defined cradle-to-site scope and should not be taken as an assessment of the overall long-term sustainability or service performance of the systems. Operational water yield, pumping during use, maintenance, replacement, durability, and end-of-life processes were not evaluated. Future studies should therefore expand the system boundary to incorporate these stages and assess the influence of differences on service life and water delivery among tank materials. Further research may also investigate alternative design strategies, including prefabricated or modular components, low-carbon concrete, and recycled aggregates. Incorporating site-specific information on transportation distances, soil conditions, construction practices, material sourcing, and local cost factors would further improve the accuracy and applicability of future assessments.

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