Abstract: This research examines the potential impact on the procurement sustainability of replacing steel rebars with Glass Fiber-Reinforced Polymer (GFRP) rebars in the construction industry, focusing on screed pre-cast hollow core topping in a project in the Kingdom of Saudi Arabia. A comparative life cycle assessment (LCA) is conducted using One Click LCA (Version 0.26.0) software for cradle-to-grave analysis. The assessment covers various stages, including raw material extraction, manufacturing, transportation, usage, and recycling. The comprehensive LCA highlights GFRP rebars as a more sustainable alternative to steel, emitting 17% less CO₂ equivalent (2e) per kilogram throughout its life cycle. Additionally, GFRP requires substantially less mass compared to steel, resulting in a dramatic reduction in CO₂ emissions ranging from 77.89% to 85.26% across different spacing configurations in real-world construction scenarios, as presented in this research case study. These findings suggest that GFRP rebars offer a promising solution for reducing the environmental impact of construction activities while potentially yielding significant cost savings over the project’s life cycle. Integrating environmental considerations into material selection processes can prioritize sustainability without compromising performance or safety, contributing to a more sustainable future for the construction industry globally.

Keywords: life-cycle assessment; steel rebars; GFRP rebars; sustainability; procurement sustainability; Kingdom of Saudi Arabia

1. Introduction
1.1. Construction Industry

The construction industry has been on a trajectory of significant global growth in recent decades, attributed to several driving forces such as urbanization, population growth, infrastructure development, and economic expansion [1]. As indicated by various reports and studies, the construction sector stands as one of the largest industries globally, making substantial contributions to the overall global GDP. Not necessarily

Urbanization has emerged as a pivotal factor propelling the growth of the construction industry worldwide. Particularly notable is the rapid urbanization witnessed in developing countries, which has spurred an unprecedented demand for residential, commercial, and infrastructure construction. With the migration of populations from rural to urban areas in pursuit of better opportunities, the necessity for housing, transportation networks, educational institutions, healthcare facilities, and other essential amenities has surged [2].

Governments across the globe have recognized the pivotal role of infrastructure development in fostering economic growth and bolstering connectivity. Consequently, substantial investments have been allocated to infrastructure projects encompassing roads, bridges, airports, railways, ports, and energy facilities. These investments not only create lucrative opportunities for construction firms but also catalyze growth across the entire industry.

The construction landscape has been significantly reshaped by technological advancements. The adoption of cutting-edge technologies such as Building Information Modeling
(BIM), 3D printing, drones, and the Internet of Things (IoT) has revolutionized construction processes, rendering them more efficient, cost-effective, and conducive to superior project outcomes [3].

Globalization has played a pivotal role in propelling the construction industry onto a broader stage. The globalization phenomenon has facilitated the expansion of construction firms into new markets, fostering international collaboration and enabling access to diverse expertise and resources from different regions.

In tandem with technological progress, there has been a marked shift toward sustainability initiatives within the construction sector. A heightened awareness of environmental concerns has prompted a growing emphasis on sustainable construction practices aimed at minimizing ecological footprints and promoting energy efficiency. Consequently, green building certifications, renewable energy installations, and the utilization of eco-friendly materials have become increasingly prevalent in construction projects worldwide [4].

Turning our attention to Saudi Arabia, the kingdom has been undergoing remarkable growth in its construction industry, driven by a confluence of factors unique to the region. The ambitious Vision 2030 initiative, launched in 2016, has been instrumental in diversifying the economy away from oil dependency and fostering growth in sectors such as construction, tourism, and entertainment. This visionary blueprint has spurred substantial investments in infrastructure development, real estate, and transformative mega-projects like NEOM, Diriyah, ROSHN, Qiddiya, and the Red Sea Project [3].

Moreover, Saudi Arabia’s burgeoning population growth and urbanization trends have catalyzed an increased demand for various forms of infrastructure. The kingdom’s robust investment in infrastructure projects, spanning the expansion of airports, and construction of new cities, metro systems, roads, and railways, underscores its commitment to fostering sustainable growth and development.

Simultaneously, the Saudi government’s proactive promotion of the real estate sector has fueled significant momentum in real estate development endeavors. This encompasses the construction of residential complexes, commercial properties, and mixed-use developments across the kingdom, catering to the evolving housing needs of its citizens [5].

1.2. Steel and GFRP Rebars

Both steel and Glass Fiber-Reinforced Polymer (GFRP) rebars are widely used to reinforce concrete structures. Steel rebars, also known as reinforcing bars, are a crucial component of concrete structures. They provide the tensile strength that concrete lacks, making it possible to build strong and durable structures; while GFRP is a strong and durable material, it can be used to reinforce concrete structures instead of steel. It is made up of glass fibers that are embedded in a polymeric resin. GFRP has a number of advantages over steel, including being lightweight, corrosion-resistant, and easy to work with. GFRP has a high strength-to-weight ratio, is chemically resistant, and has excellent electrical insulating properties. It can withstand a very high voltage before it breaks down, making it a valuable material for a variety of applications. According to research published in the journal “Resources, Conservation and Recycling”, the production of steel is responsible for substantial carbon dioxide emissions, primarily due to the use of coal in the production process [6]. Additionally, steel manufacturing involves the mining of raw materials, such as iron ore and coal, which can lead to habitat destruction, soil erosion, and water pollution [7]. A study published in the “Journal of Composite Materials” emphasizes the importance of considering the environmental impact of composite materials throughout their lifecycle, from raw material extraction to disposal [8].

The use of Glass Fiber-Reinforced Polymers (GFRP) has become widespread in various industries such as shipbuilding, vehicle manufacturing, wind power systems, and pipe production [9].

The mechanical characterizations of reinforced concrete with GFRP rebars were compared with those of steel rebars in previous studies and research and the results indicated that GFRP reinforcing bars have higher tensile strength and higher corrosion resistance than
Steel rebar; in addition to moderate flexural strength, these properties make GFRP is a good alternative to steel in foundations application [10]. Steel rebars typically exhibit a tensile modulus of 200 GPa, providing high stiffness and load-bearing capacity. In contrast, GFRP rebars offer a lower tensile modulus, ranging from 41 GPa to 55 GPa, with advantages such as corrosion resistance and lower density [11]. This difference in modulus reflects the varying stiffness between the two materials, with steel being stiffer than GFRP. Despite the lower modulus, GFRP rebars remain suitable for applications prioritizing weight reduction and durability. Understanding these mechanical properties is crucial for selecting the appropriate material for structural applications. Fiber-reinforced polymer (FRP) composites exhibit exceptional attributes, characterized by elevated strength levels and exceptional resistance against corrosion [12].

Steel bars offer comparable bond strength to GFRP bars but are susceptible to corrosion. GFRP bars are corrosion-resistant and lightweight but their higher strength necessitates a larger anchorage length, potentially impacting design. Additionally, the bond-slip curve of GFRP bars lacks a sufficient plateau, affecting concrete structure resilience and damage controllability [13]. The bond strength between reinforcement materials like steel rebars and GFRP bars and concrete is essential for the structural integrity and performance of reinforced concrete structures, facilitating load transfer, crack control, stability, and durability. Optimizing bond strength is crucial for infrastructure longevity. Additionally, in a study by X. Fu and D.D.L. Chung (1997), an increase in bond strength between steel re-bar and concrete was observed with an increasing water-cement ratio, reaching a range of 6 to 8.7 MPa [14]. Moreover, due to the lack of standardization in FRP rebars, evaluating mechanical properties and bond characteristics is vital, as highlighted in the introduction of newly developed GFRP rebars and headed GFRP rebars, which exhibited a bond strength range of 10–12.1 MPa [15]. The combination of Fiber-Reinforced Polymer (FRP) and Air-Entrained Concrete (AEC) offers an alternative to traditional steel-reinforced concrete, which is less prone to corrosion and freeze-thaw cycles. A study by Sandor Solyom et al. [16] with 236 pull-out specimens investigated the bond behavior of FRP bars in concrete with varying compressive strengths, particularly focusing on the effect of air-entraining admixtures (AEA). The results revealed that while the bond strength of FRP bars in AEC was lower compared to normal concrete, the reduction was small enough to be addressed by increasing the reinforcement development length during the design stage. Table 1 shows a comparison between steel and GFRP rebars various characteristics.

<table>
<thead>
<tr>
<th>Comparison Characteristic</th>
<th>Steel Rebars</th>
<th>GFRP Rebars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength ¹</td>
<td>483–690 MPa</td>
<td>517–1207 MPa</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>200 GPa</td>
<td>41–55 GPa</td>
</tr>
<tr>
<td>Bond strength to concrete</td>
<td>6–8.7 MPa</td>
<td>10–12.1 MPa</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Electrical insulation</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Corrosion resistance ²</td>
<td>Yes</td>
<td>Longer</td>
</tr>
<tr>
<td>Life cycle cost advantage</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Transport savings</td>
<td>NO</td>
<td>YES</td>
</tr>
</tbody>
</table>

¹ Data from [17] Barker, C. (2016). The feasibility of fiber-reinforced polymers as an alternative to steel in reinforced concrete. McGill University. ² In the application of screed pre-cast hollow core topping, which is a non-critical structural concrete layer, it is primarily subjected to minimal temperature fluctuations and shrinkage loads.

GFRP has a lower thermal conductivity than steel. Thermal conductivity is a measure of how easily heat can flow through a material. The lower the thermal conductivity, the more difficult it is for heat to flow through the material. This property makes GFRP a good choice for applications where heat insulation is important, such as in buildings, appliances,
and industrial equipment. For example, GFRP can be used to make insulation panels for walls and roofs, to insulate pipes and ducts, and to create thermal barriers in appliances such as refrigerators and ovens [18].

A fiberglass mesh is a popular material for civil engineering and construction such as reinforcing concrete structures in various construction projects. GFRP is a versatile and cost-effective material that is well-suited for a variety of applications, including scientific and medical buildings. It is important to note that GFRP is not a replacement for steel in all cases but it can be a good option for many applications, especially where cost and weight are important factors. Steel has reigned supreme as the go-to reinforcement material for concrete structures. However, inherent disadvantages like susceptibility to corrosion and significant weight have spurred the exploration of alternative materials. Among these, Glass Fiber-Reinforced Polymer (GFRP) rebars have emerged as a compelling candidate due to their unique properties [19].

For example, a study by Al-Salloum et al. [20] in 2007 investigated the performance of GFRP-reinforced concrete beams under sustained loads and aggressive environments. The study found that GFRP-reinforced concrete beams performed well under sustained loads and that their performance was not significantly affected by exposure to aggressive environments.

Another study by Benmokrane et al. [21] investigated the performance of GFRP-reinforced concrete bridge decks. The study found that GFRP-reinforced concrete bridge decks exhibited good durability and load-carrying capacity. The significant density of steel rebars burdens concrete structures with considerable weight, inflating material and transportation costs. Fortunately, GFRP rebars offer a lighter solution due to their low density.

A 2007 study by Kretzer investigated the weight-reduction potential of GFRP rebars in reinforced concrete beams. Their findings were remarkable: replacing steel rebars with GFRP rebars achieved substantial weight reduction while maintaining structural integrity. This not only impacts construction costs but also enables faster construction and reduces the overall dead load on the structure, allowing it to soar higher and lighter [22].

Jabbar and Farid in their study “Replacement of steel rebars by GFRP rebars in the concrete structures” conclude that Glass Fiber-Reinforced Polymer (GFRP) reinforcing bars offer superior tensile strength and corrosion resistance compared to steel rebars, making them a viable alternative for foundation applications. Specifically, GFRP bars exhibit a 13% higher tensile strength and a 58% higher yield strain than steel rebar. Additionally, their bend strength reaches 72% of steel’s strength with a 20% higher yield strain [18].

In 2022, Valizadeh A. and Aslani F. published a study that compared the environmental impacts of Fiber-Reinforced Polymers (FRP) to traditional brick and timber construction materials through a comprehensive life cycle assessment (LCA) using eTool software (CML-IA baseline V4.5). One of the major findings in their study is that FRPs demonstrated the lowest overall global warming potential and embodied energy across their life cycles, making them the most environmentally sustainable option among the three materials evaluated. Also, while FRPs exhibited the highest emissions during construction, they compensated for this with significantly lower emissions in other phases, particularly the recurring phase as timber released the highest emissions during the recurring phase, followed by double-brick walls [23].

A study titled ‘A comparative life cycle assessment of Fiber-Reinforced Polymers as a sustainable reinforcement option in concrete beams’ by Sbahieh et al. investigated the environmental impact of Fiber-Reinforced Polymer (FRP) bars compared to steel bars. The study utilized life cycle assessments (LCA) to evaluate the environmental performance of GFRP, CFRP, SGFRP, and steel bars, both individually and when used in reinforced concrete beams.

The key finding of this study can be summarized in the following points:
1. GFRP bars emerged as the most environmentally friendly option, outperforming steel in 10 out of 14 evaluated categories;
2. CFRP bars displayed the highest environmental impact, exceeding steel in 10 categories;
3. SGFRP bars exhibited performance between GFRP and steel, surpassing steel in 10 categories;
4. GFRP and CFRP-reinforced beams demonstrated better environmental performance than steel-reinforced beams in 9 and 8 categories, respectively;
5. Cement and steel were identified as the primary contributors to the environmental impact of steel-reinforced concrete members;
6. Replacing desalinated freshwater with seawater in concrete mixtures had a negligible overall environmental impact but significantly reduced $\text{CO}_2$ emissions related to freshwater production.

We can conclude from the research that using GFRP, SGFRP, or CFRP bars instead of steel for internal reinforcement offers a promising solution for reducing the environmental impact of construction. Also, further research and development are necessary to address challenges like recycling FRP materials and developing clear design and construction guidelines. In addition, future advancements in technology and mass production of FRP bars have the potential to further minimize their environmental footprint. Finally, selecting the optimal reinforcement material depends on specific applications, desired environmental outcomes, and design trade-offs [24].

The environmental impact of reinforcement materials such as steel and GFRP is significant, encompassing aspects such as carbon emissions, resource depletion, habitat destruction, and pollution. Sustainable alternatives and practices, including material recycling, energy efficiency improvements, and responsible sourcing, are crucial for mitigating these impacts and promoting environmentally friendly construction and engineering practices.

1.3. Procurement and Procurement Sustainability

Procurement is a critical function within organizations that involves the acquisition of goods, services, and works from external sources. It plays a pivotal role in supply chain management, ensuring the timely availability of necessary resources to meet organizational objectives. As a multifaceted process, procurement encompasses strategic sourcing, negotiations, contract management, supplier relationship management, and risk mitigation.

According to the Chartered Institute of Procurement and Supply (CIPS), “Procurement is the overarching function that describes all activities and processes to obtain goods and services” [25].

The International Federation of Purchasing and Supply Management (IFPSM) defines procurement as “the business function that ensures identification, sourcing, access, and management of the external resources that an organization needs or may need” [21].

In their book, “Operations and Supply Chain Management”, Jacobs and Chase in 2020 emphasize that procurement aims to acquire the right goods and services, at the right time, from the right sources, and at the right price [26].

According to the World Bank Group, procurement is “the process through which funds are converted into goods, works, and services” [27].

In the context of public procurement, the European Commission defines procurement as “the acquisition, whether under formal contract or not, of works, supplies, or services by any means” [28].

Procurement sustainability is the process of acquiring goods, services, and works in a way that minimizes environmental, social, and economic impacts. It is a holistic approach to procurement that takes into account the entire life cycle of a product or service from raw material extraction to disposal [29].

Procurement sustainability is important for a number of reasons. First, it can help organizations to reduce their environmental impact. By sourcing sustainable products and services, organizations can reduce their greenhouse gas emissions, water consumption, and waste production. Second, procurement sustainability can help organizations to improve their social impact. By working with suppliers that have good labor practices and that respect human rights, organizations can help to create a more just and equitable world. Third, procurement sustainability can help organizations to improve their economic
performance. By investing in sustainable products and services, organizations can reduce their long-term costs and improve their reputation [8]. There are a number of ways that organizations adapt to achieve procurement sustainability. Some of the most important steps include

1. Developing a procurement sustainability policy
   This policy should outline the organization’s commitment to procurement sustainability and its specific goals.

2. Identifying and evaluating sustainable suppliers
   Organizations should work to identify and evaluate suppliers that meet their sustainability criteria. This can be conducted through a variety of methods, such as supplier surveys, audits, and site visits.

3. Negotiating sustainable contracts
   Organizations should negotiate contracts with suppliers that include sustainability requirements. This could include requirements for suppliers to reduce their environmental impact, improve their labor practices, or meet certain social and ethical standards.

4. Monitoring and managing supplier performance
   Organizations should monitor and manage supplier performance to ensure that they are meeting their sustainability requirements. This can be conducted through regular audits and performance reviews [25].

1.4. Benefits of Implementing Sustainable Procurement
   The benefits of procurement sustainability can include the following [29,30]:

1. Reduced environmental impact: Procurement sustainability involves sourcing goods and services in a way that minimizes negative environmental effects. By using sustainable procurement practices, organizations can reduce their carbon footprint, decrease waste and pollution, and conserve natural resources;

2. Improved social impact: Sustainable procurement also takes into account the social impact of the goods and services being purchased. This includes ensuring that products are produced under fair labor practices and that workers’ rights are respected. It also includes promoting diversity and inclusion, supporting local communities, and minimizing the use of materials that are harmful to human health;

3. Improved economic performance: Implementing sustainable procurement practices can also lead to improved economic performance for organizations. By reducing waste and optimizing resource use, organizations can save money on procurement costs, increase efficiency, and create opportunities for innovation and growth;

4. Enhanced reputation: Sustainable procurement can also enhance an organization’s reputation among stakeholders, including customers, investors, and employees. By demonstrating a commitment to sustainability, organizations can build trust and goodwill, attract socially conscious customers, and improve employee engagement and loyalty;

5. Reduced long-term costs: Finally, sustainable procurement can also help organizations reduce long-term costs by identifying and mitigating risks associated with climate change, resource scarcity, and other environmental and social challenges. By taking a proactive approach to sustainability, organizations can avoid costly disruptions and ensure their long-term viability.

1.5. Aim of This Research
   This research explores the potential impact of replacing steel rebars with Glass Fiber-Reinforced Polymer (GFRP) Rebars on procurement sustainability in the construction industry. Specifically, the study examines the screed pre-cast hollow core topping in one of the projects in the Kingdom of Saudi Arabia, KSA, as an example.
Through a comprehensive analysis using a life cycle assessment [31], the research aims to compare the environmental impact of both steel rebars and GFRP rebars throughout their entire life cycles.

The life cycle assessment in construction rebars encompasses various stages, starting from raw material extraction, manufacturing of the rebars, distribution or delivery to the project site, usage, and, ultimately, recycling. By evaluating these stages for both materials, the study seeks to determine the positive and/or negative impacts of utilizing GFRP rebars on procurement sustainability in the construction industry.

By recognizing the potential benefits of substituting steel rebars with GFRP rebars, decisionmakers in the construction sector worldwide and in Saudi Arabia, in particular, can make informed decisions that contribute to sustainable procurement practices. This research focuses on screed pre-cast hollow core topping application, which functions as a structural concrete layer that is mainly not sensitive to temperature changes and shrinkage stresses. This example, which serves as a case study for this research, emphasizes the possibility of using GFRP rebars in other structural applications to adopt more sustainable replacements.

2. Methodology

2.1. LCA Framework Overview

The impact of replacing steel rebars with Glass Fiber-Reinforced Polymer (GFRP) rebar on procurement sustainability will be investigated by performing a comparative life cycle assessment (LCA) for selective steel and GFRP rebar categories to study the environmental impact.

The life cycle assessment will follow the LCA framework established by the International Organization for Standardization, ISO 14040 (ISO 14040, 2006). The ISO (International Organization for Standardization) has developed a series of standards, known as ISO 14040, for life cycle assessment (LCA). ISO is responsible for setting standards for the LCA methodology, including both technical and organizational aspects. Organizational aspects include designing critical review processes and involving stakeholders.

ISO 14040 can be considered as a compass for environmental analysis as it lays out the blueprint for conducting thorough life cycle assessments (LCA) of products and services. This comprehensive standard, encompassing four key phases—goal and scope definition, inventory analysis, impact assessment, and interpretation—promotes consistency and comparability across LCA studies, enabling a holistic evaluation of the environmental footprint and potential impacts throughout a product’s or service’s entire journey, from raw material extraction to end-of-life disposal. By ensuring transparency and methodological rigor, ISO 14040 empowers informed decision making, guiding us toward choices that minimize environmental burden and pave the way for a more sustainable future [32].

(LCA) is a comprehensive tool used to evaluate the environmental impacts of products, processes, and activities throughout their life cycle. By conducting an LCA, the following decisionmakers can be empowered, allowing them to undertake informed decision making and the development of sustainable strategies can be facilitated:

1. Businesses: By pinpointing resource inefficiencies and environmental hotspots, LCA guides product design and process optimization, ultimately leading to cost reduction and enhanced brand reputation;
2. Policymakers: LCA forms a robust evidence base for crafting effective environmental regulations and policies, incentivizing sustainable practices across industries;
3. Consumers: Understanding the environmental footprints of products enables consumers to make responsible choices, promoting green purchasing and driving market demand for sustainability [33].

Some of the key benefits of conducting an LCA include its ability to systematically quantify and assess the potential environmental impacts associated with all stages of a product’s life cycle, including raw material extraction, production, use, and end-of-life disposal. This holistic approach provides a clear understanding of environmental “hotspots” and helps in identifying opportunities for improvement and optimization in
terms of energy consumption, resource use, emissions, and waste generation. Furthermore, the results of an LCA can aid in product design, supply chain management, eco-labeling, and policy development, ultimately contributing to the transition toward more sustainable and environmentally friendly products and processes [34].

The necessary steps of conducting the LCA are illustrated in Figure 1.

![Figure 1. Steps for LCA methodology [35].](image)

The ISO 14040 series of standards is the starting point for developing LCA methodology in the building industry. The following standards are included in the 14040 series [35,36]:

- ISO 14040—General Principles and Framework: Establishes general principles and a framework for conducting life cycle assessments;
- ISO 14041—Goal and Scope Definition and Inventory Analysis: Defines goals and scopes and conducts inventory analysis for life cycle assessments;
- ISO 14042—Life Cycle Impact Assessment (LCIA): Evaluates the environmental impacts in life cycle impact assessment (LCIA);
- ISO 14043—Life Cycle Interpretation: Provides guidance for interpreting results from life cycle assessments.

In this research, the primary data will be analyzed using the following equations:

a. Rebar Mass

To calculate the rebar mass, knowing the diameter and density of the rebar, the following equation will be used

\[ m = v \times \rho \]  

(1)

where:

- \( m \) is the mass in kg
- \( v \) is the volume in \( m^3 \)
- \( \rho \) is the density in kg/m\(^3\)

However, and since we are aiming to know the mass per unit length, Equation (1) will be:

\[ m = v \times \rho \rightarrow m = (A \times L)\rho \rightarrow \frac{m}{L} = A \times \rho \]  

(2)

where
\( \mu \) is the mass per unit length (linear density) in \( \text{kg/m} \)

\( A \) is the Area in \( \text{m}^2 \)

\( \rho \) is the density in \( \text{kg/m}^3 \)

b. Reinforcement ratio

Additionally, the following equation for the reinforcement ratio (\( \delta \)) will be used to calculate and validate the reinforcement in concrete:

\[
\delta = \frac{A_r}{A_c} = \frac{\pi \times r^2}{bd}
\]

where

\( A_r \) is the Area of the rebar \( \text{m}^2 \)

\( A_c \) is the area of concrete \( \text{m}^2 \)

\( r \) is the rebar radius in \( \text{m} \)

\( b \) is the width of the slab in \( \text{m} \)

\( d \) is the depth of the slab in \( \text{m} \)

Steps for LCA methodology:

2.2. Goal and Scope Definition

In the goal and scope phase of a life cycle assessment, the following tasks are completed.

➢ Define the product(s) or service(s) to be assessed. What are we trying to evaluate?
➢ Choose a functional unit. What is the purpose or function of the product(s) or service(s)?
➢ Define the required level of detail. How much detail do we need to collect in order to answer our research question?
➢ Identify the type of analysis, impact categories, and data to be collected. What kind of analysis do we want to do? What environmental impacts do we want to evaluate? What data do we need to collect to do the analysis?

The purpose of this life cycle assessment is to do a comparative analysis between steel rebars and Glass Fiber-Reinforced Polymer (GFRP) rebars, to allow us to understand the environmental impact on the procurement sustainability. Furthermore, the results of this LCA will be applied on the application of screed pre-cast hollow core topping in one of the projects in KSA as a case study.

2.2.1. Functional Unit

In an LCA, the functional unit serves as the benchmark across different products or systems. Choosing an appropriate functional unit is crucial for ensuring objective comparisons and reliable interpretation of LCA results. It should be quantifiable with a specific reference unit (e.g., kilograms and square meters) and relevant to the intended use of the product and the goals of the LCA [36].

The functional units of this study are 1 kg of steel rebars and 1 kg of GFRP rebars that are used in floor screed reinforcement. This will help to compare the carbon footprint between these materials in the screed reinforcement application or other applications.

2.2.2. LCA System Boundaries

LCA system boundaries act as a roadmap for environmental analysis, outlining the specific stages and processes considered within a study. They are the gatekeepers of focus, relevance, and comparability, ensuring every LCA tells a clear and reliable story about a product or service’s environmental footprint. The following are the common system boundaries:

Cradle-to-Grave: The grand journey, encompassing everything from resource extraction to final resting place. This comprehensive approach paints a complete picture of environmental impact, perfect for holistic evaluations.
Cradle-to-Gate: This focuses on the production side, starting with raw materials and ending when the product leaves the factory gates. Ideal for intermediate products or situations where end-of-life data are scarce.

Gate-to-Gate: Zooming in on a specific production segment, this approach dissects individual facilities or processes. It is a powerful tool for internal improvement and comparing production alternatives.

Cradle-to-Cradle: Embracing circularity, this approach reimagines products as resources in a continuous loop. It prioritizes design for reuse, recycling, and composting, minimizing waste and maximizing resource recovery. While it considers the entire life cycle, its focus lies on closing the material loop [37].

In this life cycle assessment, the cradle-to-grave life cycle assessment will be conducted [32]. Figure 2 illustrates the previously discussed and common system boundaries:

![Figure 2. Common system boundaries for LCA][1]

2.3. Inventory Analysis

In the life cycle inventory (LCI) phase of a life cycle assessment, the following tasks are completed:

- Quantify the energy and raw materials used and the emissions to air, water, and soil for each step in the process.
- Combine this information in a process flow chart and relate it back to the functional unit.
- Prepare an inventory of all the inputs and outputs to and from the production system.

In other words, the LCI phase involves identifying and quantifying all the environmental impacts associated with a product or service over its entire life cycle. This information is then used to assess the environmental performance of the product or service in the life cycle impact assessment (LCIA) phase.

Data of this study for the life cycle assessment are collected and analyzed using the One Click LCA software and database as seen in Table 2. (Secondary Data). The data related to a specific construction project in Riyadh are collected directly from the project for the case study analysis. (Primary data).
### Table 2. Inventory data.

<table>
<thead>
<tr>
<th>Material</th>
<th>Functional Unit</th>
<th>Building Part</th>
<th>Transportation</th>
<th>Distance</th>
<th>Service life</th>
<th>EOL Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel rebar</td>
<td>kg</td>
<td>Screed Slab</td>
<td>Delivery Truck</td>
<td>70 km</td>
<td>30 Years</td>
<td>Recycling</td>
</tr>
<tr>
<td>GFRP rebar</td>
<td>kg</td>
<td>Screed Slab</td>
<td>Delivery Truck</td>
<td>370 km</td>
<td>30 Years</td>
<td>Landfilling</td>
</tr>
</tbody>
</table>

The below table shows the inventory date table for the LCA. The transportation of the rebars is assumed to be by using a delivery truck; however, the distance is different as the location of the GFRP rebar is assumed to be in the Eastern province of KSA, while the steel rebar factory is in Riyadh. Furthermore, the end of life (EOL) process is assumed to be recycling for steel rebars and landfilling for GFRP rebars based on the current circumstances in Saudi Arabia.

### 2.4. Impact Assessment

In the life cycle impact assessment (LCIA) phase of a life cycle assessment, the emissions from a given product or process are translated into impacts on various human and terrestrial ecosystems. To make the impacts easier to understand, the effects of resource use and emissions are grouped and quantified into a limited number of categories, such as climate change, human toxicity, and water depletion. These categories can then be weighted for importance, depending on the goals of the study. In other words, the LCIA phase involves taking the data from the life cycle inventory (LCI) (step 2) and assigning it to the appropriate impact categories defined in the scoping (step 1). LCIA can be conducted by employing midpoint or endpoint analysis.

Midpoint indicators refer to the environmental pressures and potential effects that arise as a direct consequence of a specific activity or process. They cover specific environmental categories, including global warming potential (GWP), acidification potential (acidification), eutrophication (eutrophication potential), and others. Midpoint indicators provide detailed and technical information about the extent of the environmental pressures a product or process is subject to, enabling a more granular view of its environmental performance. In contrast, endpoint indicators capture the wider and more comprehensive environmental impacts and results that result from midpoint indicators, which are often related to human and environmental health, ecosystem health, and resource constraints. Endpoint indicators offer a more holistic view of the environmental impact of a particular product or process. This makes it easier to convey the wider impacts of different decisions as shown in Figure 3.

In this study, the analysis will be a midpoint analysis and the total impact can be calculated by performing the following steps:

1. Estimate the quantities of steel/GFRP rebars to be used in each villa and then multiply it by the number of villas to find the total quantities. In this stage, data will be collected from a certain project in Riyadh (Primary data);
2. Estimate the environmental impact of each material and process. This will be performed and analyzed using One Click LCA software and database (Secondary data);
3. To find the total impact, multiply the result of stage 1 by the result of stage 2.

Below is an example of the calculation of this study.

\[
1000 \text{ kg of Steel} \times 2 \frac{\text{kg CO}_2e}{\text{kg steel}} = 2000 \text{ kg CO}_2e
\]

\[
200 \text{ kg of GFRP} \times 1.5 \frac{\text{kg CO}_2e}{\text{kg GFRP}} = 300 \text{ kg CO}_2e
\]

As we completed the goal and scope definition, in addition to the inventory analysis and impact assessment steps, the major points are summarized in Table 3 below.
Table 3. Goal and scope definition step summary.

<table>
<thead>
<tr>
<th>Goal</th>
<th>Function Units</th>
<th>System Boundaries</th>
<th>LCIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon footprint comparison between Steel and GFRP rebars</td>
<td>1 kg of steel rebar</td>
<td>Cradle to grave</td>
<td>Midpoint</td>
</tr>
<tr>
<td></td>
<td>1 kg of GFRP rebar</td>
<td>Cradle to grave</td>
<td>Midpoint</td>
</tr>
</tbody>
</table>

2.5. Interpretation

In this phase, LCA results are reported in a way that is easy to understand. The results are also used to identify ways to reduce the environmental impact of the product or service. The LCA process can be repeated to make sure that the changes have the desired effect [38].

2.6. Data Source and Analysis

As previously mentioned in this research, the data used for this report can be categorized in two groups.

Primary data: Data collected directly from original sources, typically through surveys, observation, experimentation, or interviews. The data are collected first-hand and are relevant to the subject matter of the research [39].

In this report, data related to the case study of one construction project in Riyadh will be collected directly, this includes the following data:

1. Total floor area per villa in square meters;
2. Number of villas in the project;
3. Distance for transportation of steel rebars from the assumed factory to the project site;
4. Distance for transportation of GFRP rebars from the assumed factory to the project site.

Table 4 shows the details of the above four points for both steel and GFRP rebars.
Table 4. Case study data summary.

<table>
<thead>
<tr>
<th>Rebar Material</th>
<th>Number of Floors</th>
<th>Transportation Distance (km)</th>
<th>Transportation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>2</td>
<td>70</td>
<td>Delivery Truck 40 t, 80%, Street Driving</td>
</tr>
<tr>
<td>GFRP</td>
<td>2</td>
<td>370</td>
<td>Delivery Truck 40 t, 80%, Highway Driving</td>
</tr>
</tbody>
</table>

Secondary data: Refers to information that has been collected and published previously, such as data from books, journals, government reports, databases, or websites [40].

2.7. Database and Data Analysis

In this report, One Click LCA Database and software will be used for the life cycle assessment. Table 5 shows the characteristics of the selected steel and GFRP rebars, in addition to the data used for the assessment.

Table 5. Characteristics of the rebar materials.

<table>
<thead>
<tr>
<th>Rebar Material</th>
<th>Diameter</th>
<th>Spacing</th>
<th>Area</th>
<th>Density</th>
<th>Mass per SQM</th>
<th>Total Length per SQM</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>8</td>
<td>200</td>
<td>50</td>
<td>7850</td>
<td>0.394</td>
<td>10</td>
<td>3.94</td>
</tr>
<tr>
<td>GFRP</td>
<td>8</td>
<td>200</td>
<td>50</td>
<td>2100</td>
<td>0.106</td>
<td>10</td>
<td>1.06</td>
</tr>
<tr>
<td>GFRP</td>
<td>8</td>
<td>300</td>
<td>50</td>
<td>2100</td>
<td>0.106</td>
<td>6.67</td>
<td>0.70</td>
</tr>
</tbody>
</table>

The mass per unit length was calculated using equation number (2); in addition, we need to verify that GFRP rebars at 300 mm spacing can be used by employing Equation (3) as follows.

Knowing the rebar radius is 4 mm with 3.33 spacing rebars per meter, the width is 1 m and 60 mm for the depth

\[
\delta = \frac{A_r}{A_c} = \frac{\pi \times r^2}{bd} = \frac{\pi \times 0.004^2 \times 3.33}{1 \times 0.06} = 0.00279 = 0.279\% 
\]

which is suitable since the acceptable range for the reinforcement ratio is \[40\]

\[0.3\% \leq \delta \leq 0.15\%
\]

Furthermore, the software analysis uses the international standards like ISO 14040 and the specific ISO 21930 for building products as a guide for life cycle assessments (LCAs) for construction [41]. This standardized approach breaks down a building’s life cycle into four main stages [42]:

Production (Cradle-to-Gate):
- A1 (Raw Materials): Extraction or harvest of resources.
- A2 (Transport): Moving materials to the manufacturing site.
- A3 (Manufacturing): Creating the building product itself.

Construction:
- A4 (Delivery): Transporting the product to the building site.
- A5 (Installation): Putting the product in place and any construction-related activities.

Use:
- B1 to B7 (Maintenance and Operation): Keeping the building functioning, including repairs, replacements, and resource consumption like water and energy.

End-of-Life (Cradle-to-Grave):
C1 (Demolition): Taking down the building.
C2 (Waste Transport): Moving demolition waste to a processing or disposal site.
C3 (Waste Processing): Treating the waste, like recycling or incineration.
C4 (Disposal): Final destination of the processed waste.

These stages (A1–C4) create a complete picture of the building’s environmental impact, known as “cradle-to-grave”.

In addition, there is an additional module, beyond the system boundary, which is Module D.

Module D is an optional section for information outside the defined life cycle but with potential environmental benefits. This could include materials reused or recycled in other products [38].

Figure 4 is an illustration of the Whole Building Life Cycle Assessment building’s module as presented in reference [42].

**Figure 4.** Building assessment module [42].

### 2.8. System Boundaries for Steel and GFRP Rebars

The system boundary defines the extent of the environmental impacts that are considered in the assessment. It delineates the life cycle stages, processes, and inputs and outputs that are included in the assessment, as well as those that are excluded. The system boundary is a fundamental aspect of LCA, as it determines what aspects of a product or process are to be considered in the analysis. It has a significant impact on the comprehensiveness and accuracy of the results. Figure 5 illustrates system boundaries for steel rebars and GFRP rebars used for screed pre-cast hollow core topping [31].

**Figure 5.** System boundary for steel rebars.

#### 2.8.1. System Boundary for Steel Rebars

The above graph shows that during the production stage (raw material extraction, transportation to the factory, and then manufacturing), the environmental impact is 3.02 kg of CO₂; after that, the transportation will be using a delivery truck (assuming 15 t capacity...
and street driving for 70 km) and the impact will remain as 0.01 CO₂ₑ. For the usage stage, with assumption of 30 years’ service life, the impact is 3.02 CO₂ₑ for every 1 kg of steel rebars. Finally, for the end of life, with assumption of recycling, the impact is estimated to be 0.04 CO₂ₑ.

Table 6, summarizes the data related to the system boundary of steel rebars.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Environmental Impact CO₂ₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product stage</td>
<td>3.02</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.01</td>
</tr>
<tr>
<td>Transportation for 70 km, using 15 t delivery truck, and street driving.</td>
<td></td>
</tr>
<tr>
<td>Use</td>
<td>3.02</td>
</tr>
<tr>
<td>Assuming 30 years service life</td>
<td></td>
</tr>
<tr>
<td>End of life (recycling)</td>
<td>0.04</td>
</tr>
</tbody>
</table>

2.8.2. System Boundary for GFRP Rebars

Figure 6 shows that during the production stage of GFRP rebars, (raw material extraction, transportation to the factory, and then manufacturing), the environmental impact is 2.5 kg of CO₂ₑ, which is less than steel rebars. Transportation is assumed to be using a delivery truck with 15 t capacity, the same as steel rebars, but with highway driving for 370 km since the factory is located in the eastern province, which results in the impact of 0.03 CO₂ₑ. Similarly, for the usage stage, with an assumption of 30 years’ service life, the impact is 2.5 CO₂ₑ for every 1 kg of steel rebars. Finally, it can be seen in Table 7 for the end of life, with the assumption of landfilling, the impact is estimated to be 0.04 CO₂ₑ.

![Figure 6. System boundary for GFRP rebars.](image)

Table 7. GFRP rebars system boundary data and assumptions.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Environmental Impact CO₂ₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product stage</td>
<td>2.5</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.03</td>
</tr>
<tr>
<td>Transportation for 370 km, using 15 t delivery truck, and highway driving</td>
<td></td>
</tr>
<tr>
<td>Use</td>
<td>2.5</td>
</tr>
<tr>
<td>Assuming 30 years service life</td>
<td></td>
</tr>
<tr>
<td>End of life (landfilling)</td>
<td>0.01</td>
</tr>
</tbody>
</table>
3. Results

This section presents the outcomes of the life cycle assessments (from cradle to grave) conducted for steel and GFRP rebars in a screed pre-cast hollow core topping application. Prior to the analysis, the quantities of steel and GFRP rebars needed for the project were calculated based on project data.

3.1. Life Cycle Assessment for 1 kg of Steel and GFRP Rebars

Figure 7 shows the comparison of 1 kilogram for different factors used in the life cycle assessment for both GFRP and steel bars. The data in the figure will be used as the benchmark for our case study.

3.2. Case Study

To further evaluate the environmental impact, life cycle assessments (LCAs) will be carried out on a construction project situated in Riyadh. These assessments will enable the measurement of the environmental impact by considering project specifics such as the type and quantities of both rebars, transportation distance and method, and other relevant factors.

3.2.1. Required Quantities of Steel and GFRP Rebars

Tables 8 and 9 below show the required quantities of steel and GFRP rebars.

Table 8. Calculation of the mass per SQM for rebars.

<table>
<thead>
<tr>
<th>Rebar Material</th>
<th>Diameter</th>
<th>Spacing</th>
<th>Area</th>
<th>Density</th>
<th>Mass per Unit Length</th>
<th>Total Length per SQM</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>mm</td>
<td>mm</td>
<td>m²</td>
<td>Kg/m³</td>
<td>Kg/m</td>
<td>m</td>
<td>kg</td>
</tr>
<tr>
<td>Steel</td>
<td>8</td>
<td>200</td>
<td>0.000050</td>
<td>7850</td>
<td>0.394</td>
<td>10</td>
<td>3.94</td>
</tr>
<tr>
<td>GFRP</td>
<td>8</td>
<td>200</td>
<td>0.000050</td>
<td>2100</td>
<td>0.106</td>
<td>10</td>
<td>1.06</td>
</tr>
<tr>
<td>GFRP</td>
<td>8</td>
<td>300</td>
<td>0.000050</td>
<td>2100</td>
<td>0.106</td>
<td>6.67</td>
<td>0.70</td>
</tr>
</tbody>
</table>
Table 8. Calculation of the mass per SQM for rebars.

<table>
<thead>
<tr>
<th>Rebar Material</th>
<th>Diameter</th>
<th>Spacing</th>
<th>Area</th>
<th>Density</th>
<th>Mass per Unit Length Total Length per SQM Total Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>8</td>
<td>200</td>
<td>0.000050</td>
<td>7850</td>
<td>0.394</td>
</tr>
<tr>
<td>GFRP</td>
<td>8</td>
<td>200</td>
<td>0.000050</td>
<td>2100</td>
<td>0.106</td>
</tr>
<tr>
<td>GFRP</td>
<td>8</td>
<td>300</td>
<td>0.000050</td>
<td>2100</td>
<td>0.106</td>
</tr>
</tbody>
</table>

The table above illustrates the calculations for steel rebars at 200 mm spacing, GFRP rebars at 200 mm spacing, and GFRP rebars at 300 mm spacing. It can be observed that the linear density for steel and GFRP is 0.394 kg/m and 0.106 kg/m, respectively. Additionally, the total mass for each proposed design is provided.

3.2.2. Case Study Life Cycle Assessment

Figure 8 below presents the results of the life cycle assessment for the three rebar designs used in the screed. For further details, Table 10 can be referenced for additional illustration.

**Figure 8.** Life cycle assessment for the case study.

**Table 10.** Details of the LCA for the case study.

<table>
<thead>
<tr>
<th>Design</th>
<th>A1–A3 (Product Stage)</th>
<th>A4 (Transport)</th>
<th>B4–B5 (Replacement)</th>
<th>C1–C4 (End of Life)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass fiber reinforced polymer (GFRP) rebars, 84,4032 ton</td>
<td>316,804</td>
<td>3607</td>
<td>316,804</td>
<td>700</td>
</tr>
<tr>
<td>Glass fiber reinforced polymer (GFRP) rebars, 126,604 ton</td>
<td>211,204</td>
<td>2405</td>
<td>211,204</td>
<td>466</td>
</tr>
<tr>
<td>Steel reinforcement bars, 473.26 ton</td>
<td>1,431,190</td>
<td>3743</td>
<td>1,431,190</td>
<td>19,152</td>
</tr>
</tbody>
</table>

3.2.2. Case Study Life Cycle Assessment

Figure 8 below presents the results of the life cycle assessment for the three rebar designs used in the screed. For further details, Table 10 can be referenced for additional illustration.

**4. Discussion**

The main objective of conducting the comparative life cycle assessment (LCA) is to assess the environmental impacts associated with the production, use, and disposal of both
steel and GFRP rebars. This assessment is essential for understanding the sustainability implications of these materials in construction applications. The LCA encompasses the entire life cycle of the materials, from cradle to grave, including material extraction, manufacturing, transportation, use in construction, and end-of-life disposal or recycling. By considering the entire life cycle, the assessment provides a comprehensive understanding of the environmental footprint of steel and GFRP rebars.

Initially, the LCA analyzes the environmental impact of 1 kg of steel and GFRP rebars, allowing for a direct comparison of the environmental performance of the two materials on a unit basis. As shown in Figure 7, 1 kg of GFRP exhibits a lower environmental impact compared to 1 kg of steel, with details provided in Table 11 for each stage.

Table 11. LCA results for 1 kg of steel and GFRP rebars.

<table>
<thead>
<tr>
<th>Design</th>
<th>A1–A3 (Product Stage)</th>
<th>A4 (Transport)</th>
<th>B4–B5 (Replacement)</th>
<th>C1–C4 (End of Life)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP rebars, 1 kg</td>
<td>2.5</td>
<td>0.03</td>
<td>2.5</td>
<td>0.01</td>
</tr>
<tr>
<td>Steel rebars, 1 kg</td>
<td>3.02</td>
<td>0.01</td>
<td>3.02</td>
<td>0.04</td>
</tr>
</tbody>
</table>

In total, steel rebars emit 6.09 kg of CO$_2$e, whereas GFRP emits 5.04 kg of CO$_2$e, indicating that GFRP rebars emit 17% less CO$_2$e.

The LCA is further extended to assess the environmental impact of using steel and GFRP rebars in a real-world construction project located in Riyadh. The analysis considers project-specific details such as material quantities, transportation distances, and other factors relevant to the construction. But before conducting the LCA for the construction project, the required quantities of steel and GFRP rebars are calculated based on project specifications. This includes determining the mass per unit area of rebars and calculating the total mass required for the project.

Based on the data presented in Table 8, it is evident that the steel mesh has a mass of 3.94 kg, while the GFRP mesh at 200 mm spacing weighs 1.06 kg and the GFRP mesh at 0.3 mm spacing weighs only 0.7 kg.

Applying this information to a construction project with a total floor plan area of 300 square meters and comprising 400 villas, the results are obtained and presented in Table 9 for use in the case study life cycle assessment (LCA).

The total mass of steel required in the project is 3.74 times greater than the total mass of GFRP at the same spacing and 5.61 times greater than the GFRP at 300 mm spacing. This significant disparity in quantity will amplify the environmental impact between the two materials to more than 17%.

The LCA results are outlined in Table 10, providing a breakdown of the environmental impacts associated with the various designs and quantities of steel and GFRP.

Table 12 below illustrates the difference in percentages between steel bars and GFRP at different stages, i.e., Product, Transport, Replacement and End of Life stage.

Table 12. Difference between GFRP and steel.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>A1–A3 (Product Stage)</th>
<th>A4 (Transport)</th>
<th>B4–B5 (Replacement)</th>
<th>C1–C4 (End of Life)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP @200/Steel @200</td>
<td>77.86%</td>
<td>3.63%</td>
<td>77.86%</td>
<td>96.35%</td>
</tr>
<tr>
<td>GFRP @300/Steel @200</td>
<td>85.24%</td>
<td>35.75%</td>
<td>85.24%</td>
<td>97.57%</td>
</tr>
</tbody>
</table>

Finally, the total CO$_2$ emissions for GFRP at 200 mm, GFRP at 300 mm, and steel at 200 mm spacing is 637,915 kg, 425,279 kg, and 2,885,275 kg, respectively, meaning that the GFRP at 200 mm compared to steel at 200 mm spacing emits 77.89% less CO$_2$e, while GFRP at 300 mm emits 85.26% less in the whole life cycle.
5. Conclusions

The comparative life cycle assessment (LCA) between steel and Glass Fiber-Reinforced Polymer (GFRP) rebars serves as a crucial tool in evaluating the environmental sustainability of construction materials. By considering the entire life cycle, including material extraction, manufacturing, transportation, use in construction, and end-of-life disposal or recycling, the assessment provides a comprehensive understanding of their environmental footprint. The findings of the LCA reveal the following:

1. The initial analysis comparing the environmental impact per kilogram of steel and GFRP demonstrates that GFRP exhibits a clear advantage, emitting 17% less CO$_2$ equivalent (CO$_2$e) throughout its life cycle. This reduction in emissions emphasizes the potential of GFRP to mitigate environmental impacts associated with construction or non-construction activities;

2. The calculations reveal that GFRP requires substantially less mass compared to steel for the same project, resulting in a dramatic reduction in CO$_2$e emissions ranging from 77.89% to 85.26% across different spacing configurations. This difference underscores the importance of considering material quantities and project-specific requirements in sustainability assessments;

3. The findings suggest that GFRP rebars offer a promising solution for reducing the environmental impact of construction activities. By choosing GFRP over steel, construction projects can significantly lower their carbon footprint and contribute to environmental conservation efforts;

4. Moreover, beyond the environmental benefits, the adoption of GFRP rebars could also have positive economic implications. While initial costs may vary, the long-term savings associated with reduced material quantities and lower environmental impact could result in significant cost savings over the life cycle of a construction project.

In conclusion, the comprehensive LCA highlights the potential of GFRP rebars as a more sustainable alternative to steel in construction applications. By integrating environmental considerations into material selection processes, stakeholders can make informed decisions that prioritize sustainability without compromising performance or safety. Embracing innovative materials like GFRP represents a step toward building a more sustainable future for the construction industry and other industries. The results obtained in this research can be applied in different countries by considering the different aspects of the procurement conditions specific to each region.

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