

# SUSTAINABLE CONSTRUCTION THROUGH LIFE CYCLE ASSESSMENT: EVALUATING ENVIRONMENTAL IMPACT ACROSS BUILDING STAGES

<sup>1</sup>Ms. A. S. Bhoyar, <sup>2</sup>Dr. A. B. Ranit, <sup>3</sup>Prof. P. V. Khandve

<sup>1</sup>Student, <sup>2</sup>Assistant Professor, <sup>3</sup>Head of Department

<sup>1</sup>Department of Civil Engineering,

<sup>1,2,3</sup>Prof. Ram Meghe College of Engineering and Management, Badnera, Amravati, Maharashtra

**Abstract:** The construction is contributed the most to the environment due to high consumption of energy and natural resources; therefore, it is necessary to do a Life Cycle Assessment of the infrastructure. This study focuses on the life cycle assessment to evaluate the environmental impact across the building stages. In this study, An Institutional Building which is located in Yavatmal, Maharashtra, is selected for the analysis. This analysis follows ISO 14040 and ISO 14044 standards and is carried out using the OpenLCA software. A cradle to use system boundary is considered, with production, construction and operation stages over a 50-year lifespan. Inventory data were developed using BAFU and ELCD databases. The building includes materials such as 4,238 tonnes of cement, 594 tonnes of steel, 5,881.94 m<sup>3</sup> of concrete, and approximately 1.79 million bricks. The annual operational energy consumption is estimated at 2,228,751 kWh, resulting in a total lifetime energy demand of 111,437,550 kWh.

The environmental impacts were assessed using the ReCiPe 2016 Midpoint (H) method. The results show that Global Warming Potential contributes the largest share (about 38.3%), followed by human toxicity (24.9%) and terrestrial ecotoxicity (24.8%), while fossil resource depletion accounts for around 7.3%. These findings indicate that material production plays a significant role in overall environmental impact.

A comparison between conventional and sustainable construction scenarios was also conducted. In the sustainable case, fly ash bricks and AAC blocks replaced traditional bricks, and solar photovoltaic (PV) systems were introduced for the operation stage. The PV system generates about 118,866,720 kWh over 50 years, which is sufficient to offset nearly 100% of the building's operational energy demand.

Overall, the results show that the operational phase has the highest impact, followed by material production, while the construction stage contributes relatively less. The study highlights that using sustainable materials and renewable energy can significantly reduce environmental impacts. It also shows that LCA is a useful tool for identifying key problem areas and supporting better decision-making for sustainable construction.

**Keywords:** Life Cycle Assessment (LCA), OpenLCA, ReCiPe 2016 Midpoint (H), Sustainable, Global Warming Potential (GWP), Environmental Impact

## I. INTRODUCTION

The construction industry accounts for nearly 40% of global energy consumption and contributes approximately 35–39% of total CO<sub>2</sub> emissions (IEA, 2023). As a result, it is considered one of the major drivers of climate change and environmental degradation. In conventional construction practices, energy-intensive materials such as cement, steel, and aluminium are widely used, through which significant embodied carbon is generated during extraction, processing, and manufacturing. With the continuous growth in demand for infrastructure and buildings, increasing pressure is being placed on the sector to adopt sustainable practices, so that resource consumption can be reduced, waste can be minimized, and greenhouse gas emissions can be lowered.

Traditionally, the operational phase of buildings—such as heating, cooling, and electricity use—has been the primary focus of sustainability assessments. However, the environmental impacts associated with material extraction, production, transportation, construction, maintenance, and end-of-life disposal have often been overlooked. As a result, incomplete evaluations of a building's overall environmental performance have been produced.

To address this limitation, Life Cycle Assessment (LCA) is widely recognized as a comprehensive and scientific approach through which environmental impacts across all stages of a building's life cycle can be evaluated, from cradle to grave. A holistic understanding of environmental performance is provided by considering raw material extraction, manufacturing processes, construction activities, operational use, and end-of-life scenarios such as demolition or recycling. Through this approach, environmental hotspots can be identified, and informed decisions can be made regarding material selection, design strategies, construction techniques, and disposal methods.

In the context of sustainable construction, LCA has been established as an essential tool for architects, engineers, contractors, and policymakers. By using LCA, reductions in both embodied and operational emissions can be achieved, while improvements in resource efficiency and long-term environmental performance can be supported. With life cycle thinking increasingly being

incorporated into international standards and green building certification systems, the application of LCA is becoming highly relevant.

In this study, the role of LCA in sustainable construction is examined, and the methodology adopted for the case study is outlined. Environmental impacts across all stages of the building life cycle are quantified, and key areas for improvement are identified. Through this analysis, a better understanding of sustainable construction practices is developed, and strategies for achieving low-carbon and resource-efficient buildings are supported.

## Objectives of the Study

The main objectives of this study are:

1. To understand the basic concept and importance of sustainable construction and its role in reducing environmental impacts.
2. To apply the Life Cycle Assessment (LCA) method to a building project in order to evaluate its environmental performance.
3. To analyze environmental impacts at different stages of the building life cycle, including material production, transportation, construction, and operation.
4. To identify the stages or materials that contribute the most to environmental impact (hotspots) using openLCA software.
5. To suggest simple and practical strategies for reducing environmental impacts and improving sustainability in construction.

## II. LITERATURE REVIEW

### 2.1 Introduction

The construction industry is widely recognized as one of the major contributors to environmental degradation, mainly due to its high consumption of energy and raw materials, along with significant greenhouse gas emissions. Buildings alone account for a considerable share of global energy demand and carbon emissions, which highlights the urgent need to adopt sustainable construction practices.

In this context, Life Cycle Assessment (LCA) is considered a comprehensive and systematic method for evaluating environmental impacts throughout the entire life cycle of a building. This includes stages such as material production, construction, operation, and end-of-life (International Organization for Standardization, 2006a; 2006b). Compared to traditional approaches, LCA provides a more complete understanding of environmental performance.

Recent studies have further highlighted the scale of environmental challenges in the construction sector. Large amounts of natural resources are consumed every year, and the sector continues to contribute significantly to global carbon emissions (Waqar et al., 2024). However, despite this awareness, the practical adoption of comprehensive assessment tools is still limited. This indicates a clear need for wider use of tools like LCA to support better decision-making and promote sustainable construction.

### 2.2 Development of Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) has gradually developed into a well-established scientific method for evaluating environmental impacts associated with products, processes, and systems across their entire life cycle. The methodology has been standardized under ISO 14040 and ISO 14044, which define its principles, structure, and guidelines (International Organization for Standardization, 2006a; 2006b). These standards help ensure consistency, transparency, and comparability in LCA studies.

The LCA process is typically divided into four main phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. Each phase plays an important role in systematically analyzing environmental impacts—from defining the system boundaries to interpreting the final results.

Earlier studies have played a key role in shaping LCA. Guinée (2002) provided a detailed operational framework, while Rebitzer et al. (2004) explained its applications across different sectors. Later, Finnveden et al. (2009) contributed to improving impact assessment methods and data quality.

More recent work by Hauschild et al. (2018) has focused on uncertainty analysis and enhancing LCA as a decision-support tool. With the advancement of digital technologies, tools such as OpenLCA and databases like Ecoinvent have made LCA more accessible and efficient. However, one important limitation is that global databases may not always reflect local conditions accurately, which can affect the reliability of results.

### 2.3 Application of LCA in Buildings

LCA has been widely applied in the building sector to evaluate environmental impacts across all stages of a structure's life cycle. Due to the long lifespan and complexity of buildings, it is important to consider impacts from material production to demolition.

Research has shown that both material production and operational stages contribute significantly to environmental impacts (Ortiz et al., 2009). The distinction between embodied energy and operational energy is especially important. Embodied energy includes energy used in material extraction, manufacturing, and transportation, while operational energy refers to energy consumed during the building's use phase (Cabeza et al., 2014).

Although operational energy often accounts for the largest share of total energy use, embodied energy is also significant, particularly in the early stages (Ramesh et al., 2010). Case studies, such as that by Asif et al. (2007), have demonstrated how LCA can be used to analyze stage-wise impacts.

Comparative studies have shown that alternative materials like fly ash bricks and AAC blocks can reduce environmental impacts compared to conventional materials (Kulkarni and Sivakumar, 2023; Pamu et al., 2022). However, their adoption is still influenced by practical factors such as cost, availability, and local practices.

## 2.4 Environmental Impacts of Building Materials

Building materials play a crucial role in determining the environmental performance of construction projects. A large portion of environmental impact is generated during the material production stage due to high energy use and emissions.

Materials such as cement, steel, and conventional bricks are known for their high embodied energy and carbon emissions (Dixit et al., 2012; Moncaster and Song, 2012). Therefore, reducing embodied carbon through alternative materials and better design strategies has become an important focus (Pomponi and Moncaster, 2016).

While traditional materials are widely used, their environmental impact can vary depending on factors such as transportation distance and local availability (Shukla et al., 2009). In contrast, sustainable materials like fly ash bricks and AAC blocks generally show lower environmental impacts. The use of industrial by-products such as fly ash is particularly beneficial, as it reduces waste and conserves natural resources.

## 2.5 Impact of Construction and Operational Stages

Environmental impacts in buildings occur across multiple stages, with construction and operation being the most significant.

During the construction phase, impacts arise from material transportation, equipment use, and on-site activities. These are mainly linked to fuel consumption and logistics (Bilec et al., 2010). Although this phase is short in duration, it still contributes meaningfully to overall impacts.

The operational phase, on the other hand, is typically the largest contributor due to continuous energy use over the building's lifetime. Studies have shown that it accounts for the majority of total energy consumption (Sartori and Hestnes, 2007; Pérez-Lombard et al., 2008).

Factors such as building design, climate, and occupant behavior strongly influence operational performance (Hong et al., 2017). Recent approaches like dynamic LCA attempt to capture these variations over time, although their practical use is still limited (Negishi et al., 2018). Improving energy efficiency and integrating renewable energy systems can significantly reduce these impacts.

## 2.6 Sustainable Construction Practices

Sustainable construction aims to minimize environmental impacts while balancing economic and social aspects. It focuses on efficient resource use, energy conservation, and waste reduction throughout the building life cycle.

This approach involves using eco-friendly materials, energy-efficient designs, and responsible construction practices (Kibert, 2016). Its importance in reducing environmental degradation has been widely recognized (Zuo and Zhao, 2014).

In countries like India, the need for sustainable construction is increasing due to rapid urbanization. Although frameworks such as ECBC, GRIHA, and IGBC have been introduced, their implementation is still growing.

There is also increasing emphasis on integrating LCA with modern, data-driven management systems to improve sustainability outcomes (Waqar et al., 2024).

## 2.7 LCA Tools and Databases

The application of LCA is supported by various tools and databases that help in accurate modeling and analysis. Software like OpenLCA is widely used to perform environmental assessments, while databases such as Ecoinvent provide standardized data.

Impact assessment methods like ReCiPe 2016 are commonly used to evaluate environmental impacts using different indicators. These tools allow researchers to compare different construction scenarios and support better decision-making.

However, reliance on international databases remains a limitation, as they may not fully represent local conditions.

## 2.8 Research Gap

Despite significant research in this field, several gaps still exist, especially in developing countries like India.

Many studies focus only on either embodied impacts or operational energy, with limited integration of both. The use of generic databases often does not reflect local conditions accurately, which can affect the reliability of results. In addition, stage-wise analysis of institutional buildings has not been widely explored.

Comparative studies between conventional and sustainable construction methods using standardized tools are also limited. The use of advanced tools such as OpenLCA in academic research is still developing.

Furthermore, there is a lack of integration between LCA and modern project management systems. To address these gaps, the present study conducts a detailed stage-wise LCA of a G+2 institutional building using region-specific data and OpenLCA. A comparison between conventional and sustainable construction approaches is also carried out.

### III. METHODOLOGY

The methodology adopted in this study is based on the Life Cycle Assessment (LCA) framework to evaluate the environmental impacts of a G+2 institutional building. ISO 14040 and ISO 14044 standards are followed to ensure a systematic and reliable assessment. The step-wise procedure is described below:

#### 1. Goal and Scope Definition

The objective of the study is to assess the environmental impacts of the building throughout its life cycle. The functional unit is defined as 1 m<sup>2</sup> of built-up area over a 50-year lifespan. A cradle-to-use system boundary is adopted, covering material production, transportation, construction, and operational stages.

#### 2. Data Collection

The required data are collected from project drawings, Bill of Quantities (BOQ), and standard material specifications. Information related to material quantities, construction activities, energy consumption, and transportation distances is included for analysis.

#### 3. Life Cycle Inventory (LCI) Development

All input and output data are compiled and organized in a structured format. Materials such as cement, steel, bricks, sand, and aggregates, along with energy inputs like electricity and diesel, are considered. These represent the total resource flows and emissions within the system.

#### 4. Modelling in OpenLCA

The building is modelled using OpenLCA software by creating a product system. Material and energy processes are defined and linked with standard databases such as BAFU and ELCD Database. Transportation, construction activities, and operational energy use are also incorporated.

#### 5. Selection of Impact Assessment Method

An appropriate impact assessment method is selected within the software. The ReCiPe Midpoint (H) 2016 method is used to calculate carbon emissions (CO<sub>2</sub>-equivalent and other environmental impacts).

#### 6. Life Cycle Impact Assessment (LCIA)

Environmental impacts are calculated across all selected life cycle stages using OpenLCA. Impacts from material production, transportation, construction, and operation are included.

#### 7. Interpretation of Results

The results are analyzed to identify environmental hotspots. Major contributing materials and stages, such as cement, steel, and electricity use, are examined to understand their impact on overall performance.

#### 8. Comparative Scenario Analysis

Two scenarios are developed: a conventional scenario representing standard practices, and a sustainable scenario incorporating fly ash bricks, AAC blocks, and renewable energy systems. A comparison is carried out to evaluate environmental improvements.

#### 9. Recommendations

Based on the results, recommendations are provided to reduce environmental impacts, improve efficiency, and promote sustainable construction practices.<sup>3</sup>

## IV. CASE STUDY

This study applies the Life Cycle Assessment (LCA) methodology to an institutional building in order to evaluate the environmental impacts associated with different stages of its life cycle, including production, construction, and operation. The analysis is carried out to identify the stages and components that contribute significantly to environmental burdens and to support informed decision-making for sustainable construction practices.

### Case Study Description

The selected case study is a G+2 institutional building located in Yavatmal, Maharashtra, India. The building is chosen to represent a typical institutional structure, allowing a practical assessment of environmental performance under real conditions.

### Building Specifications

- i. Building Type : Institutional (G+2)
- ii. Location : Yavatmal, Maharashtra, India
- iii. Built-up Area : 14,858.34 m<sup>2</sup>
- iv. Structural System : Reinforced Cement Concrete (RCC) frame with brick masonry walls

The building is composed of an RCC framework, which includes columns, beams, and slabs, while the partitions and enclosures are constructed using burnt clay bricks.

## V. RESULT AND DISCUSSION

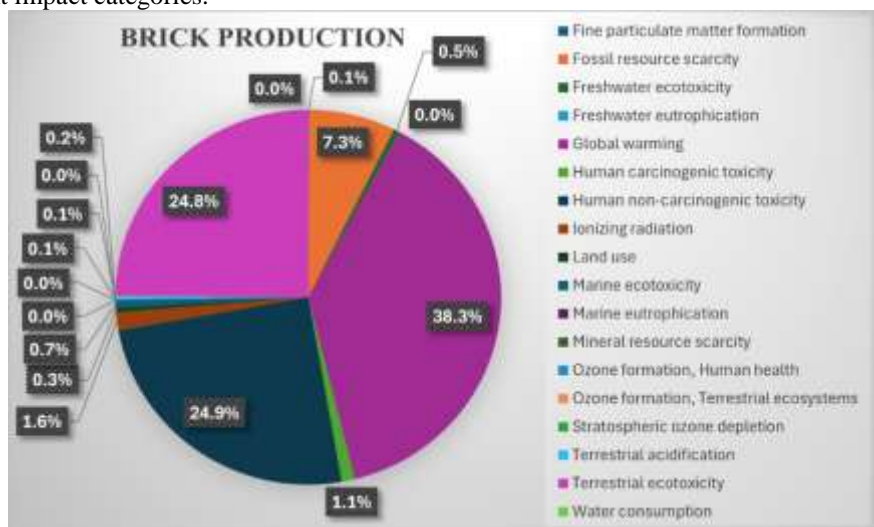
The results obtained from the Life Cycle Assessment (LCA) of the selected G+2 institutional building. The analysis is carried out using OpenLCA software based on the Life Cycle Inventory (LCI) developed. The results are interpreted to identify the environmental impacts associated with the building's different life cycle stages.

The discussion focuses on stage-wise environmental contributions, comparison between conventional and sustainable scenarios, and sensitivity analysis to understand the influence of key parameters.

### 5.1 Material-wise contribution

#### 5.1.1 Burnt Clay Bricks

The environmental impacts associated with burnt clay brick production are presented in Fig. 5.1, which shows the percentage contribution of different impact categories.



**Fig. 5.1 Percentage Contribution of Environmental Impact Categories in Burnt Clay Brick Production**

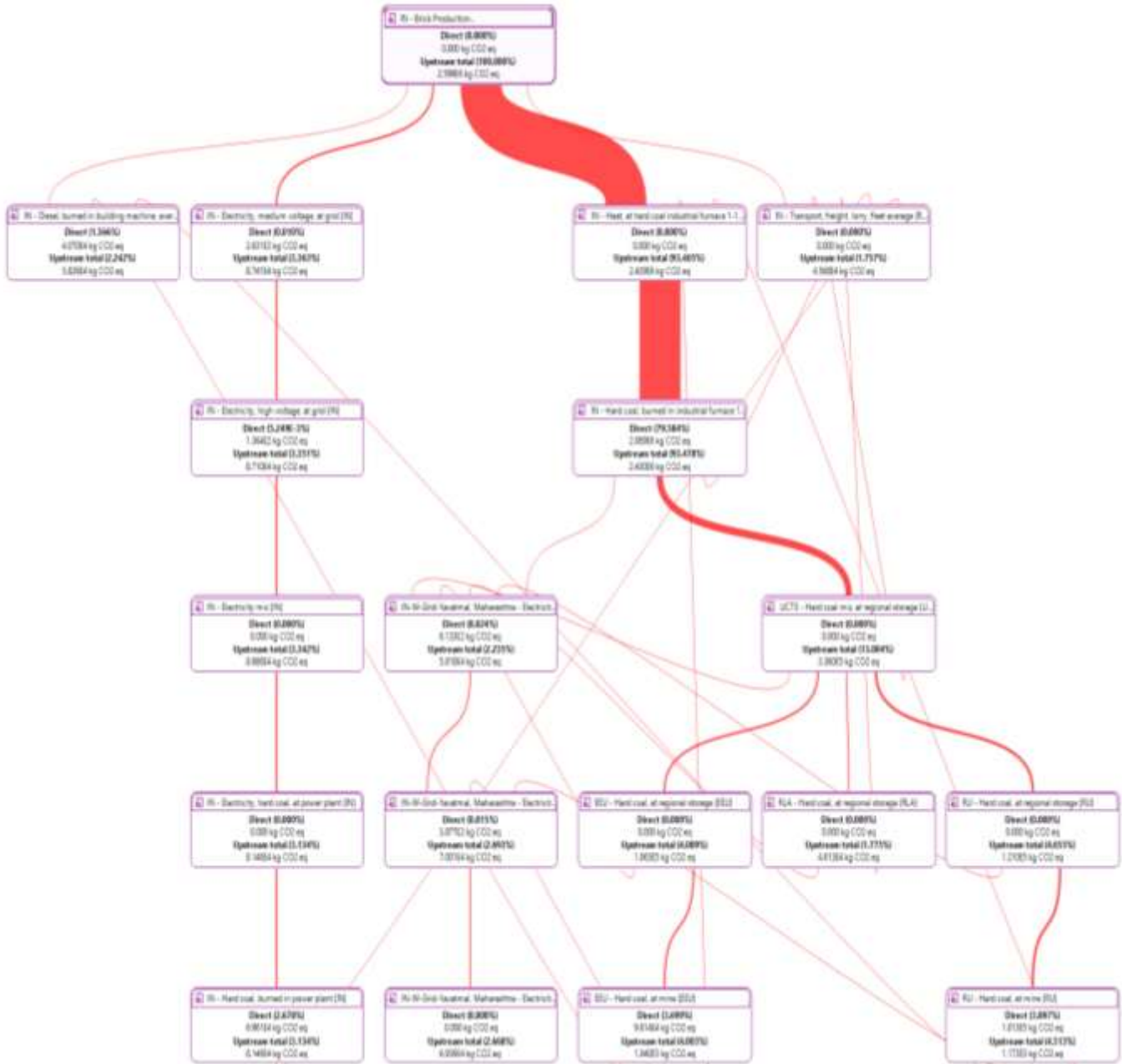
As shown in Fig. 5.1, global warming potential (38.3%) is the dominant impact, mainly due to fossil fuel combustion in brick kilns. This is followed by human non-carcinogenic toxicity (24.9%) and terrestrial ecotoxicity (24.8%), indicating significant impacts on human health and ecosystems.

A moderate contribution is observed in fossil resource scarcity (7.3%), while terrestrial acidification (1.6%) and water consumption (1.1%) show relatively smaller impacts. Other categories contribute negligibly to the overall environmental burden.

**Table 5.1 Environmental Impact Assessment Results for Brick Production**

<b>Impact categories</b>	<b>Brick Production</b>	<b>Unit</b>
Fine particulate matter formation	4677.36247	kg PM2.5 eq
Fossil resource scarcity	494071	kg oil eq
Freshwater ecotoxicity	32930.1	kg 1,4-DCB
Freshwater eutrophication	978.06898	kg P eq
Global warming	2599300	kg CO2 eq
Human carcinogenic toxicity	76100.1	kg 1,4-DCB
Human non-carcinogenic toxicity	1693790	kg 1,4-DCB
Ionizing radiation	106907	kBq Co-60 eq
Land use	22257.4	m2a crop eq
Marine ecotoxicity	46989.9	kg 1,4-DCB
Marine eutrophication	64.95826	kg N eq
Mineral resource scarcity	756.34833	kg Cu eq
Ozone formation, Human health	6097.91602	kg NOx eq
Ozone formation, Terrestrial ecosystems	6166.17755	kg NOx eq
Stratospheric ozone depletion	0.42972	kg CFC11 eq
Terrestrial acidification	14304.3	kg SO2 eq
Terrestrial ecotoxicity	1687790	kg 1,4-DCB
Water consumption	-229.52781	m3

The results in Table 5.1 confirm that global warming and toxicity-related impacts dominate brick production.



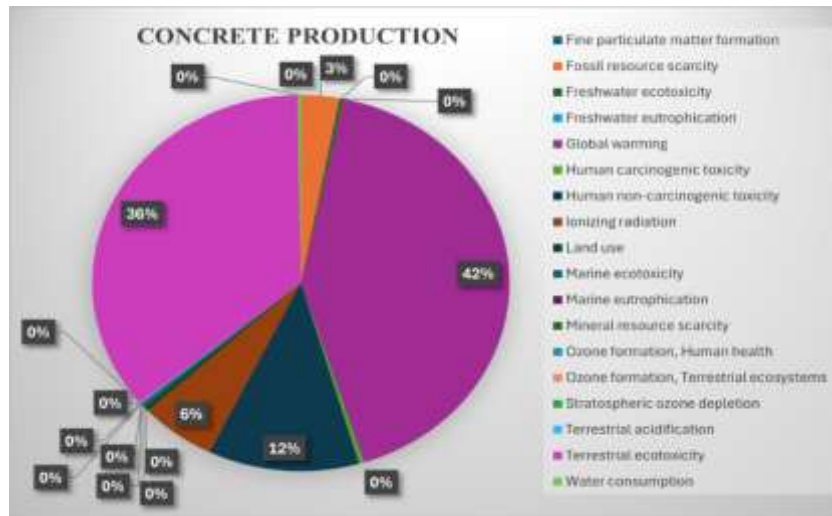
**Fig. 5.2 Sankey Diagram of Environmental Impact for Brick Production**

The Sankey diagram (Fig. 5.2) indicates that the major contribution arises from hard coal combustion in brick kilns, followed by upstream processes such as mining and transportation. Electricity contributes moderately, while diesel usage has a minor impact.

Overall, brick production is mainly influenced by fuel consumption and emission-intensive processes, suggesting the need for improved kiln efficiency and cleaner alternatives.

### 5.1.2 Concrete

The environmental impacts associated with concrete production are illustrated in Fig. 5.3, showing the percentage contribution of different impact categories.



**Fig. 5.3 Percentage Contribution of Environmental Impact Categories in Concrete Production**

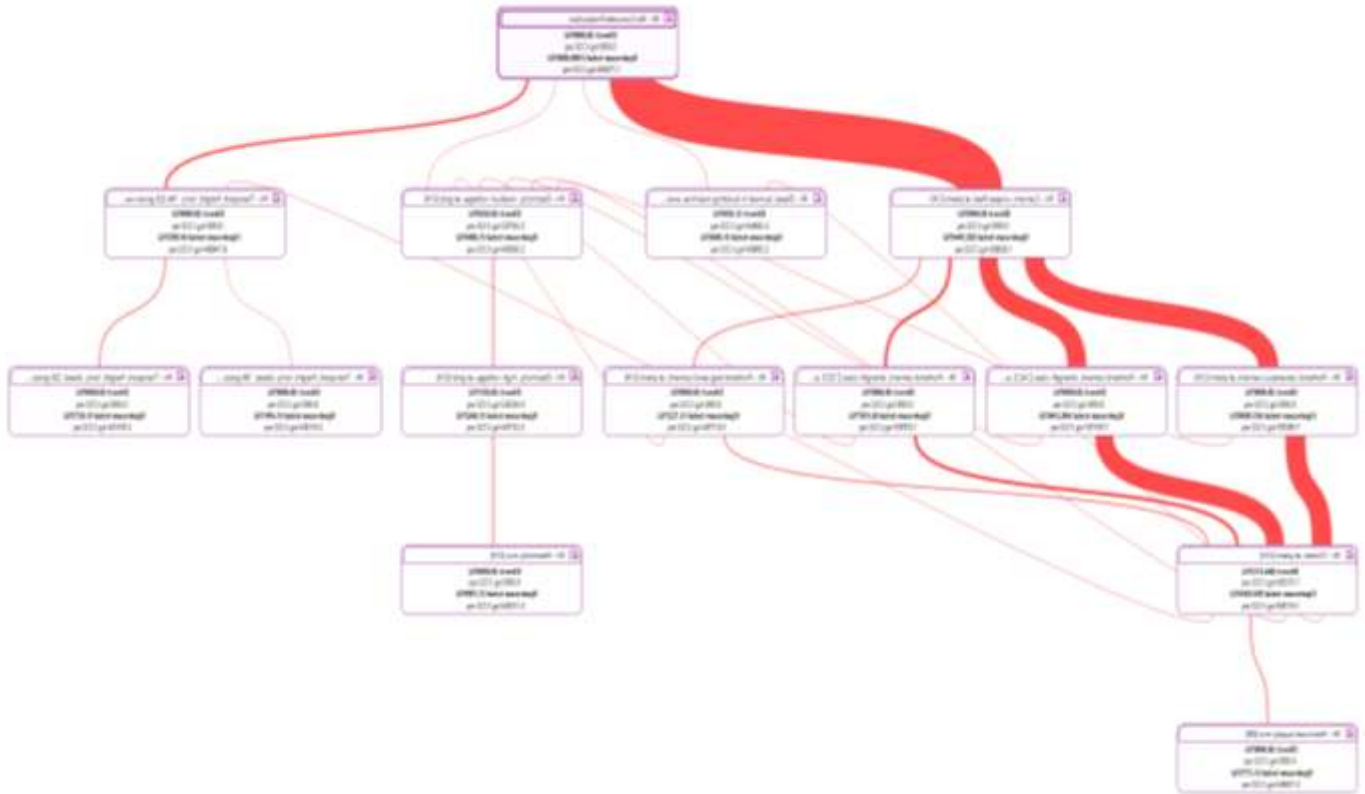
As shown in Fig. 5.3, global warming potential (42%) is the dominant impact, mainly due to CO<sub>2</sub> emissions from cement manufacturing. This is followed by terrestrial ecotoxicity (36%), associated with raw material extraction. Human non-carcinogenic toxicity (12%) also contributes significantly, indicating the presence of harmful emissions.

Other impacts such as ionizing radiation (6%) and fossil resource scarcity (3%) show moderate contributions, while the remaining categories contribute negligibly.

**Table 5.2 Environmental Impact Assessment Results for Concrete Production**

Impact categories	Concrete Production	Unit
Fine particulate matter formation	677.77376	kg PM2.5 eq
Fossil resource scarcity	124326	kg oil eq
Freshwater ecotoxicity	11233.8	kg 1,4-DCB
Freshwater eutrophication	256.14547	kg P eq
Global warming	1751910	kg CO2 eq
Human carcinogenic toxicity	17312.7	kg 1,4-DCB
Human non-carcinogenic toxicity	490829	kg 1,4-DCB
Ionizing radiation	248062	kBq Co-60 eq
Land use	12608.8	m2a crop eq
Marine ecotoxicity	16369.7	kg 1,4-DCB
Marine eutrophication	21.53042	kg N eq
Mineral resource scarcity	1101.94197	kg Cu eq
Ozone formation, Human health	2597.25834	kg NOx eq
Ozone formation, Terrestrial ecosystems	2662.7308	kg NOx eq
Stratospheric ozone depletion	0.16757	kg CFC11 eq
Terrestrial acidification	2105.04943	kg SO2 eq
Terrestrial ecotoxicity	1494420	kg 1,4-DCB
Water consumption	-10880.1	m3

The results in Table 5.2 confirm that global warming and ecotoxicity-related impacts dominate concrete production.



**Fig. 5.4 Sankey Diagram of Environmental Impact for Concrete Production**

The Sankey diagram (Fig. 5.4) indicates that cement production, particularly clinker manufacturing, contributes the highest environmental impact. Electricity and transportation show moderate contributions, while diesel and auxiliary inputs have relatively lower impacts.

Overall, the environmental footprint of concrete is primarily driven by cement production, highlighting the need for alternative materials and improved manufacturing practices.

### 5.1.3 Steel

The environmental impacts associated with steel production are illustrated in Fig. 5.5, showing the percentage contribution of different impact categories.



**Fig. 5.5 Percentage Contribution of Environmental Impact Categories in Steel Production**

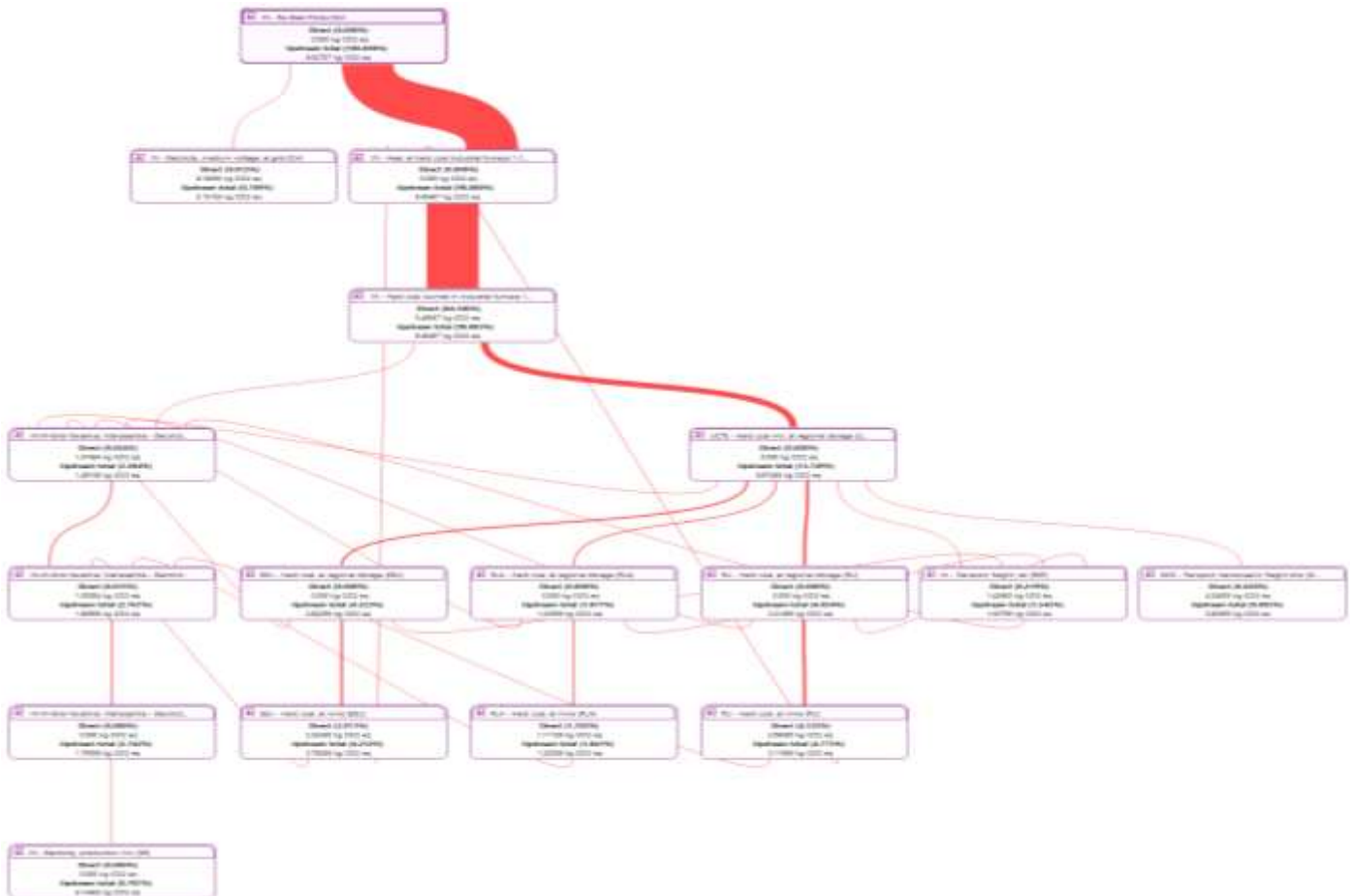
As shown in Fig. 5.5, global warming potential (39.4%) is the dominant impact, mainly due to carbon-intensive processes such as blast furnace operations and coke combustion. This is followed by human non-carcinogenic toxicity (24.5%) and terrestrial ecotoxicity (21.4%), indicating significant impacts from emissions and mining activities.

Moderate contributions are observed in fossil resource scarcity (7.3%) and ionizing radiation (3.6%), while the remaining categories contribute minimally to the overall impact.

**Table 5.3 Environmental Impact Assessment Results for Steel Production**

Impact categories	Steel Production	Unit
Fine particulate matter formation	126451	kg PM2.5 eq
Fossil resource scarcity	12095100	kg oil eq
Freshwater ecotoxicity	810409	kg 1,4-DCB
Freshwater eutrophication	24870.5	kg P eq
Global warming	65273800	kg CO2 eq
Human carcinogenic toxicity	1848430	kg 1,4-DCB
Human non-carcinogenic toxicity	40653500	kg 1,4-DCB
Ionizing radiation	5969110	kBq Co-60 eq
Land use	523228	m2a crop eq
Marine ecotoxicity	1152290	kg 1,4-DCB
Marine eutrophication	1618.15798	kg N eq
Mineral resource scarcity	1170410	kg Cu eq
Ozone formation, Human health	153919	kg NOx eq
Ozone formation, Terrestrial ecosystems	155320	kg NOx eq
Stratospheric ozone depletion	10.0467	kg CFC11 eq
Terrestrial acidification	368931	kg SO2 eq
Terrestrial ecotoxicity	35447000	kg 1,4-DCB
Water consumption	-3743.02114	m3

The results in Table 5.3 confirm that global warming and toxicity-related impacts dominate steel production.



**Fig. 5.6 Sankey Diagram of Environmental Impact for Steel Production**

The Sankey diagram (Fig. 5.6) indicates that heat generation using hard coal is the primary contributor to environmental impacts, followed by electricity consumption. Upstream processes such as coal extraction and transportation also contribute significantly, while auxiliary processes have minor impacts.

Overall, steel production is highly energy-intensive, with impacts largely driven by fossil fuel consumption.

### 5.2 Stage-wise Contribution Analysis

The environmental impacts of the building were assessed across three life cycle stages: production, construction, and operational phases. The results were normalized by considering the highest contribution in each category as 100%.

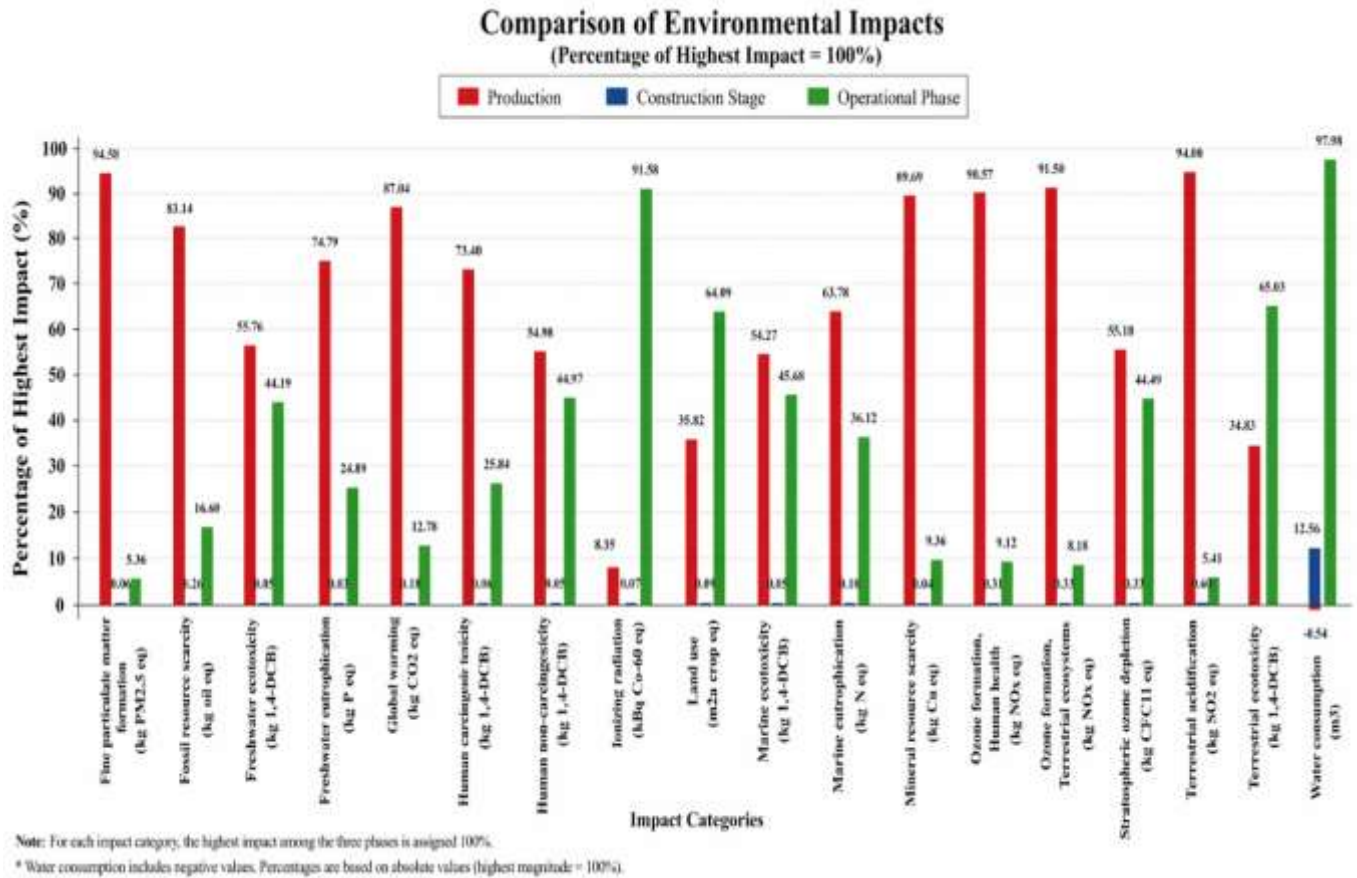


Fig. 5.7 Comparison of Production, Construction and Use Stage

The results indicate that the production stage dominates most impact categories, followed by the operational phase, while the construction stage contributes minimally.

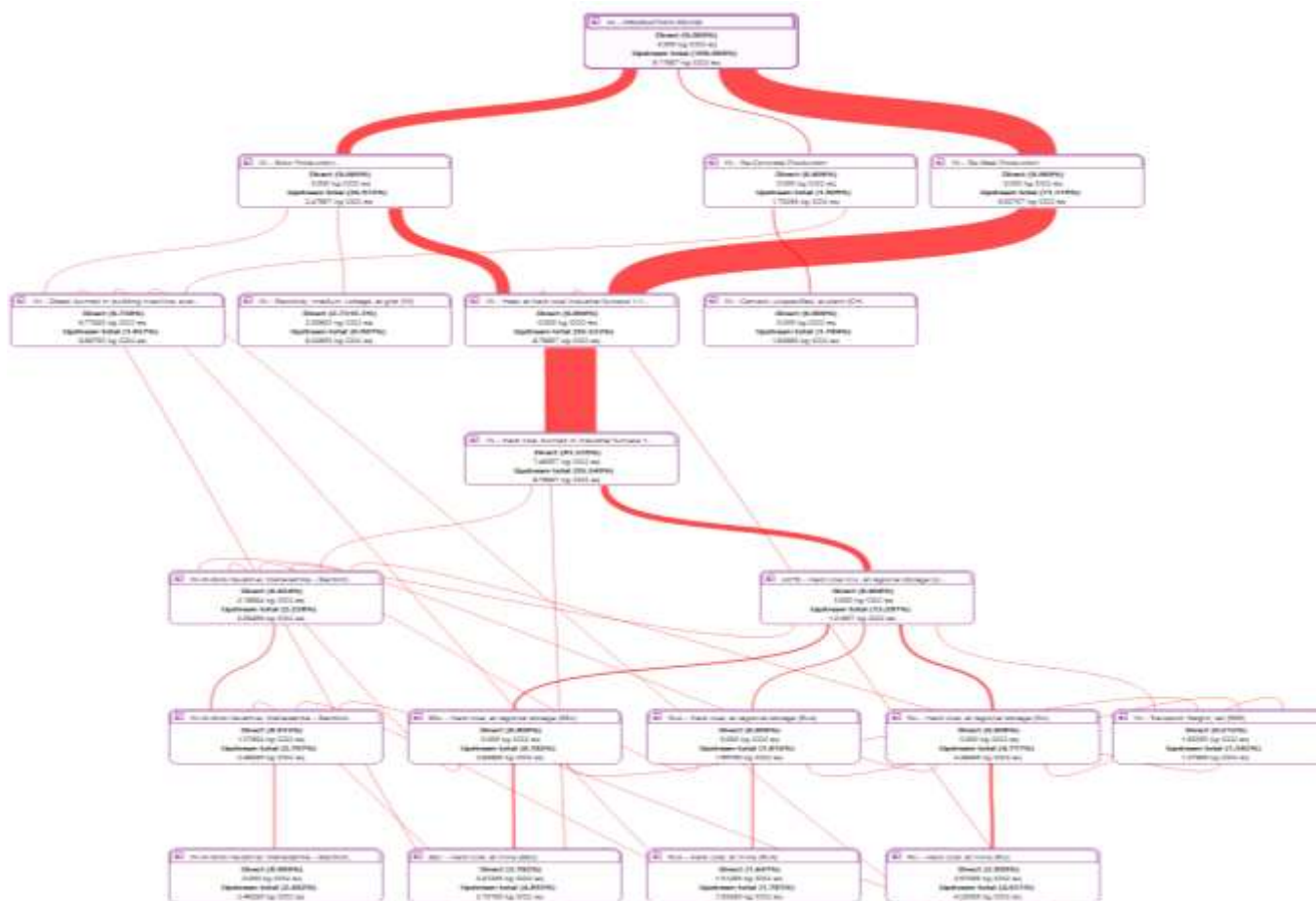
Table 5.4 Stage-wise Environmental Impact Assessment Results

Impact categories	Unit	Production	Construction Stage	Operational Phase
Fine particulate matter formation	kg PM2.5 eq	171675	117.62867	9070.81573
Fossil resource scarcity	kg oil eq	16924900	53927.6	3151790
Freshwater ecotoxicity	kg 1,4-DCB	1135260	989.59413	914974
Freshwater eutrophication	kg P eq	34441.6	13.62988	11475.2
Global warming	kg CO2 eq	91780900	193659	12750500
Human carcinogenic toxicity	kg 1,4-DCB	2590500	2196.22658	912526
Human non-carcinogenic toxicity	kg 1,4-DCB	57275600	51529.8	46818400
Ionizing radiation	kBq Co-60 eq	7235330	60393.8	79655500
Land use	m2a crop eq	747812	1842.29012	1341920
Marine ecotoxicity	kg 1,4-DCB	1616180	1581.46815	1314230
Marine eutrophication	kg N eq	2258.33818	3.71037	1276.84467
Mineral resource scarcity	kg Cu eq	1178720	532.18222	123202
Ozone formation, Human health	kg NOx eq	214592	736.18534	17604
Ozone formation, Terrestrial ecosystems	kg NOx eq	216709	775.64848	18415.7
Stratospheric ozone depletion	kg CFC11 eq	14.30686	0.08476	11.55413
Terrestrial acidification	kg SO2 eq	507267	321.46815	21656.2

Terrestrial ecotoxicity	kg 1,4-DCB	53015600	223395	98684500
Water consumption	m3	-16809	3924.47949	3032010

### 5.2.1 Production Stage

The production stage shows the highest contribution in major categories such as global warming, fossil resource scarcity, particulate matter formation, and ozone formation, mainly due to material manufacturing and resource extraction. Moderate contributions are observed in toxicity-related impacts, while lower contributions are seen in land use and terrestrial ecotoxicity.

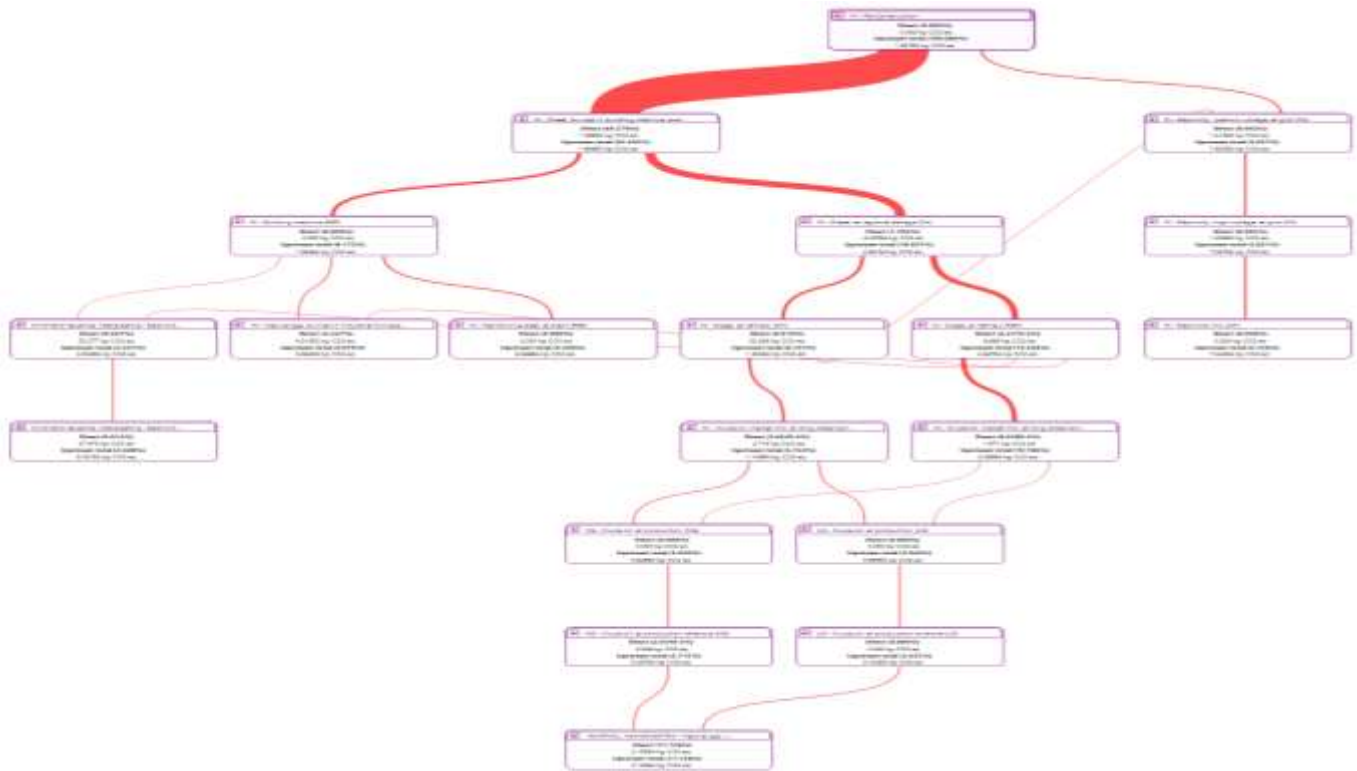


**Fig. 5.8 Sankey Diagram of Environmental Impact for Production Stage**

The Sankey diagram (Fig. 5.8) indicates that brick production and coal-based energy use are the primary contributors, highlighting fossil fuel dependency as the key driver of emissions.

### 5.2.2 Construction Stage

The construction stage contributes negligibly (generally <1%) across most impact categories. Slightly higher contributions are observed in water consumption and ozone formation, but overall impact remains minimal.

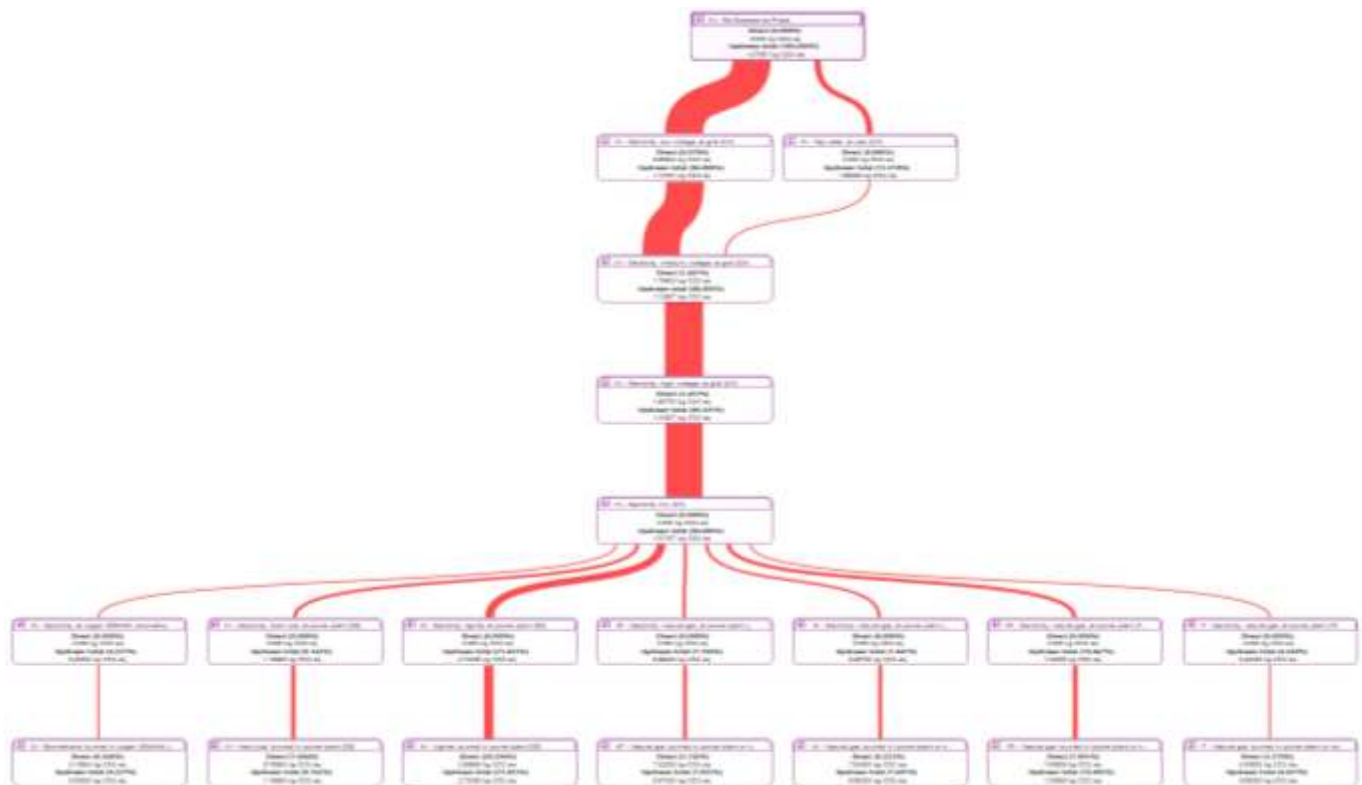


**Fig. 5.9 Sankey Diagram of Environmental Impact for Construction Stage**

The sankey diagram (Fig. 5.9) shows that diesel consumption in machinery is the main contributor, followed by electricity use, while other activities have minor impacts.

### 5.2.3 Operational Stage

The operational phase shows significant contributions in water consumption, ionizing radiation, land use, and ecotoxicity-related categories, mainly due to long-term energy and resource use. Moderate contributions are observed in toxicity categories, while lower contributions are seen in global warming and fossil resource use.



**Fig. 5.10 Sankey Diagram of Environmental Impact during Operational Stage**

The Sankey diagram (Fig. 5.10) highlights that grid electricity consumption is the dominant contributor, with major upstream impacts from energy generation processes.

### 5.3 Comparative Analysis (Conventional vs Sustainable Scenario)

A comparative analysis was carried out to evaluate the environmental performance of different construction materials and energy systems.

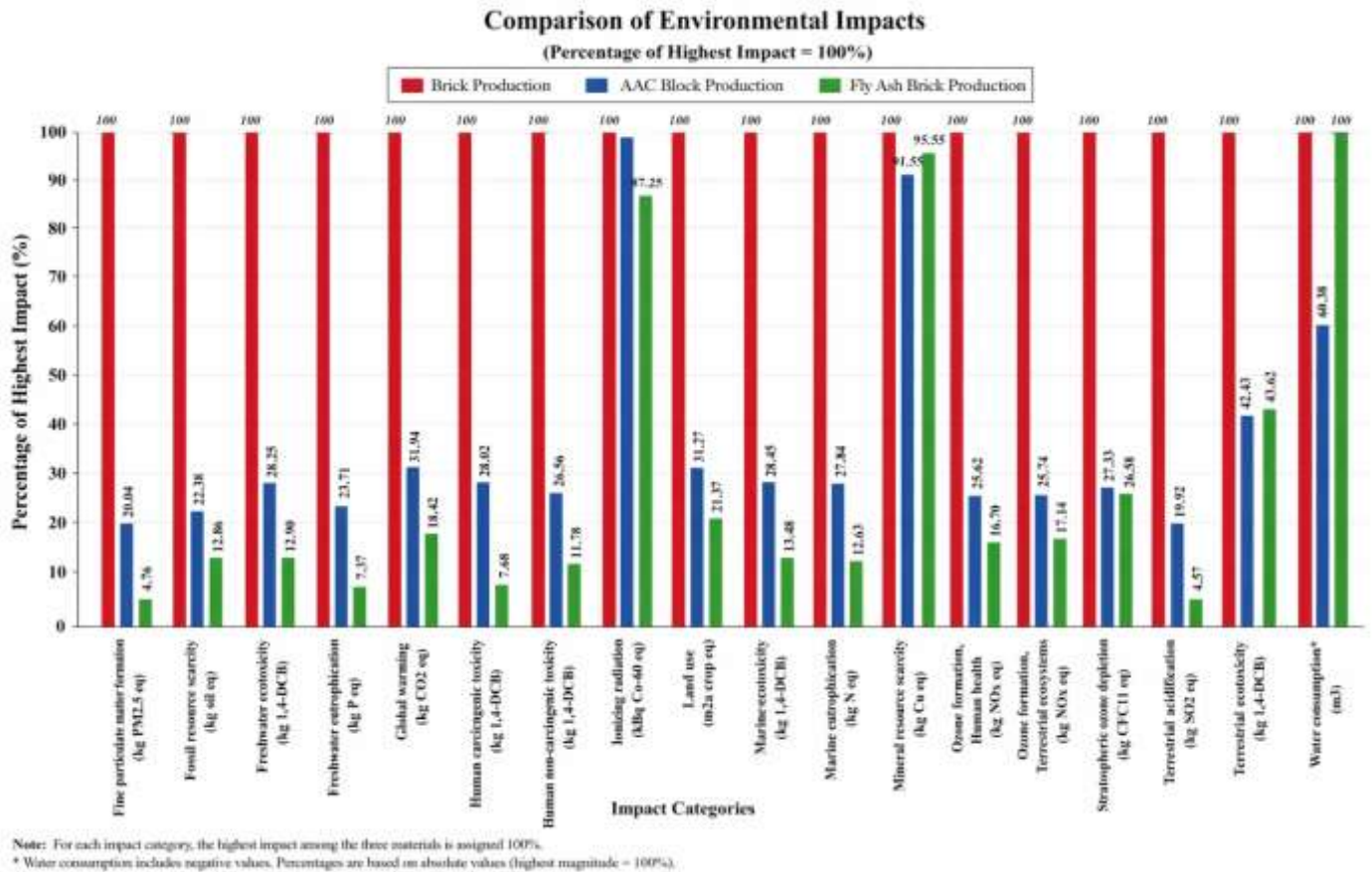


Fig. 5.11 Comparison of AAC Blocks, Conventional Clay Bricks, and Fly Ash Bricks

The results indicate that burnt clay bricks exhibit the highest environmental impact across all categories, while fly ash bricks show the lowest impact, followed by AAC blocks. Significant reductions are observed in global warming, fossil resource use, and toxicity-related impacts when alternative materials are used. However, limited improvement is observed in ionizing radiation and mineral resource scarcity. Higher water consumption is noted for AAC and fly ash bricks compared to conventional bricks.

Table 5.5 Comparative Environmental Impact Assessment of Construction Materials

Impact categories	Unit	Brick Production	AAC Block Production	Fly Ash Brick Production
Fine particulate matter formation	kg PM2.5 eq	4677.36247	937.98565	222.75884
Fossil resource scarcity	kg oil eq	494071	110534	63561.2
Freshwater ecotoxicity	kg 1,4-DCB	32930.1	9303.99864	4247.82528
Freshwater eutrophication	kg P eq	978.06898	231.87748	72.07166
Global warming	kg CO2 eq	2599300	830868	479274
Human carcinogenic toxicity	kg 1,4-DCB	76100.1	21312.8	5846.65137
Human non-carcinogenic toxicity	kg 1,4-DCB	1693790	449894	199565
Ionizing radiation	kBq Co-60 eq	106907	198927	173563
Land use	m2a crop eq	22257.4	6956.95086	4751.03111
Marine ecotoxicity	kg 1,4-DCB	46989.9	13368.5	6335.06464
Marine eutrophication	kg N eq	64.95826	18.08958	8.20595
Mineral resource scarcity	kg Cu eq	756.34833	692.44052	722.72636
Ozone formation, Human health	kg NOx eq	6097.91602	1562.1661	1016.81455

Ozone formation, Terrestrial ecosystems	kg NOx eq	6166.17755	1586.51429	1056.99038
Stratospheric ozone depletion	kg CFC11 eq	0.42972	0.11746	0.11419
Terrestrial acidification	kg SO2 eq	14304.3	2847.3656	653.30422
Terrestrial ecotoxicity	kg 1,4-DCB	1687790	716925	736885
Water consumption	m3	-229.52781	709.02846	-1174.50147

### 5.3.1 Production Phase Comparison

In the production phase, both AAC blocks and fly ash bricks demonstrate substantial reductions in most impact categories compared to burnt clay bricks. The global warming potential is reduced significantly, along with improvements in ecotoxicity and resource-related impacts. Overall, fly ash bricks perform best, followed by AAC blocks.

### 5.3.2 Operational Phase Comparison (Grid vs Solar PV)

A comparison between conventional grid electricity and solar PV systems was conducted to assess operational impacts.

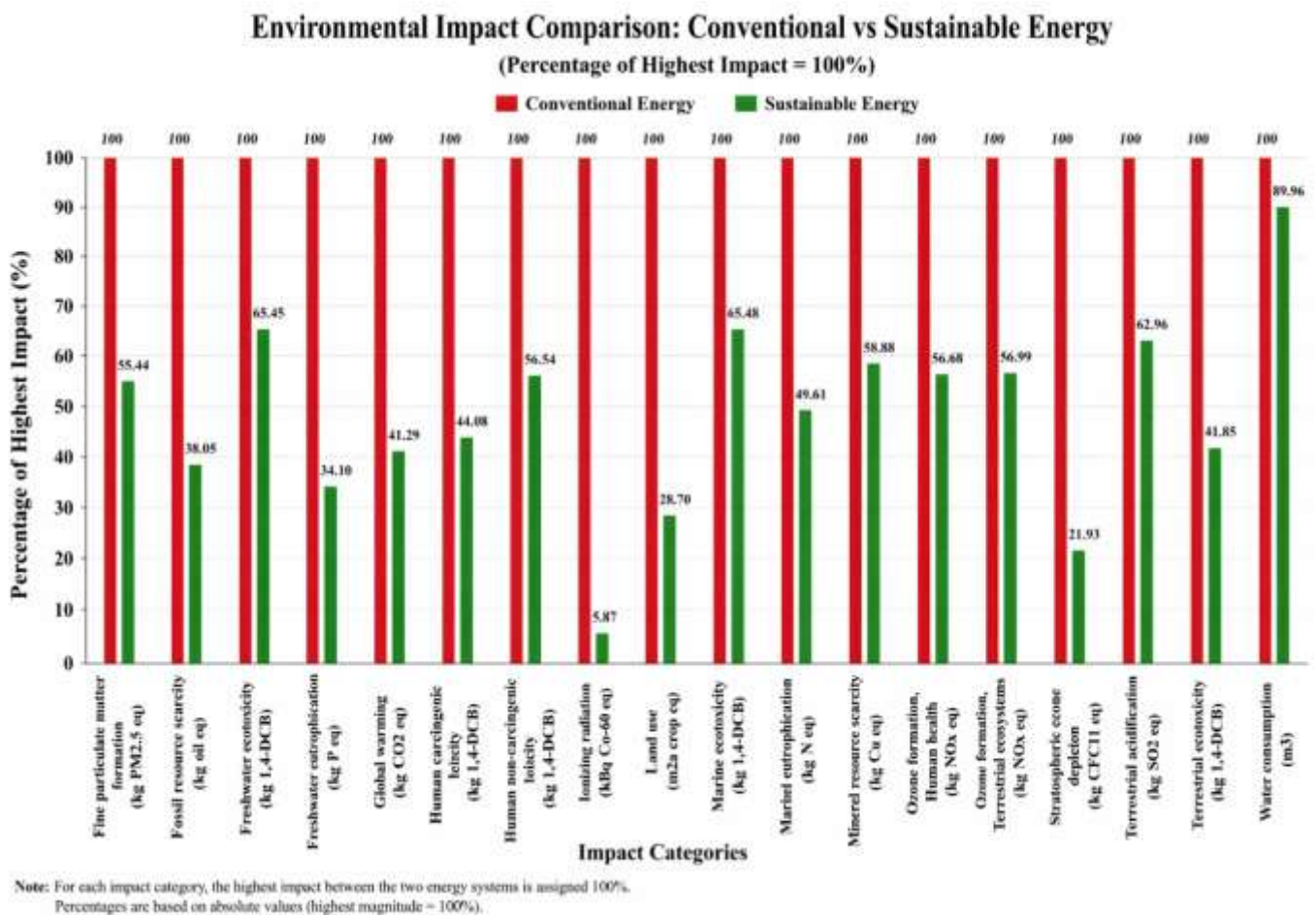


Fig. 5.12 Comparison of Operational Phases

The results show that the conventional energy system has the highest environmental impact, while the solar PV system significantly reduces impacts across all categories. Major reductions are observed in global warming, fossil resource scarcity, ionizing radiation, and ozone depletion.

However, water consumption remains relatively high in the solar PV scenario due to panel cleaning and manufacturing processes.

Table 5.6 Comparative Environmental Impact of Energy Systems

Impact categories	Unit	Conventional Energy	Sustainable Energy
Fine particulate matter formation	kg PM2.5 eq	9070.81573	5029.66153
Fossil resource scarcity	kg oil eq	3151790	1199450

Freshwater ecotoxicity	kg 1,4-DCB	914974	599270
Freshwater eutrophication	kg P eq	11475.2	3915.46831
Global warming	kg CO2 eq	12750500	5265280
Human carcinogenic toxicity	kg 1,4-DCB	912526	402565
Human non-carcinogenic toxicity	kg 1,4-DCB	46818400	26480600
Ionizing radiation	kBq Co-60 eq	79655500	4677070
Land use	m2a crop eq	1341920	385146
Marine ecotoxicity	kg 1,4-DCB	1314230	861033
Marine eutrophication	kg N eq	1276.84467	633.29172
Mineral resource scarcity	kg Cu eq	123202	72475.7
Ozone formation, Human health	kg NOx eq	17604	9978.1913
Ozone formation, Terrestrial ecosystems	kg NOx eq	18415.7	10496.8
Stratospheric ozone depletion	kg CFC11 eq	11.55413	2.53369
Terrestrial acidification	kg SO2 eq	21656.2	13635.4
Terrestrial ecotoxicity	kg 1,4-DCB	98684500	41302700
Water consumption	m3	3032010	2727990

#### 5.4 Interpretation of Results

The results of the Life Cycle Assessment highlight that the environmental performance of the G+2 institutional building is strongly influenced by a few dominant impact categories and processes. Across all materials and life cycle stages, global warming, toxicity-related impacts, and resource consumption emerge as the most significant contributors.

Among the materials, burnt clay bricks show high environmental burden, mainly due to emissions from kiln operations and fossil fuel use. Similarly, concrete production is largely impacted by cement manufacturing, which contributes significantly to carbon emissions and resource extraction impacts. In the case of steel, the impacts are slightly more distributed but remain dominated by energy-intensive processes such as furnace operations and mining activities.

The stage-wise analysis reveals that the production stage is the major contributor to most environmental impacts, primarily due to raw material extraction and manufacturing processes. In contrast, the construction stage contributes very little, indicating that on-site activities such as transportation and equipment usage have limited influence on the overall impact.

The operational phase, however, becomes important for specific categories such as water consumption, ionizing radiation, and land use, mainly due to long-term energy and resource usage. This shows that while emissions are largely driven by production, resource consumption continues throughout the building's life.

The comparative analysis further indicates that fly ash bricks perform significantly better than conventional materials, showing substantial reductions in emissions and resource use. Similarly, the adoption of solar PV systems leads to major reductions in environmental impacts, particularly in energy-related categories.

However, certain trade-offs are observed. Water consumption remains relatively high, especially in the sustainable scenario, due to requirements for solar panel maintenance and manufacturing processes.

Overall, the results suggest that maximum environmental benefits can be achieved by combining sustainable materials with renewable energy systems, although further improvements are needed to address resource-related impacts such as water use.

#### 5.5 Discussion

The findings of this study clearly demonstrate that the environmental performance of buildings is mainly controlled by material selection during the production stage and energy use during operation.

##### i. Materials and Environmental Impacts

A significant reduction in environmental impacts is observed when fly ash bricks are used instead of conventional clay bricks. Since fly ash bricks utilize industrial waste, the need for natural resource extraction is reduced, leading to improvements in land use and resource conservation.

Major reductions are observed in global warming, particulate emissions, and fossil resource use, indicating a lower carbon footprint and improved air quality. Toxicity-related impacts and ecosystem-related impacts are also reduced considerably, showing clear environmental and health benefits.

However, not all impacts are eliminated. Categories such as ionizing radiation and water consumption remain relatively high, highlighting that alternative materials also involve certain trade-offs.

## ii. Clean Energy vs Conventional Grid

The comparison between conventional electricity and solar photovoltaic (PV) systems shows that renewable energy significantly improves environmental performance.

The use of solar PV reduces carbon emissions, fossil fuel dependence, air pollution, and toxicity impacts, making it a highly effective strategy for sustainable building operation. Improvements are also observed in ecosystem-related impacts and ozone-related categories.

These results confirm that energy consumption during the operational phase is a key factor, and shifting to renewable sources can substantially reduce long-term environmental impacts.

## iii. Water Trade-off

Despite the overall benefits, water consumption remains a concern in the sustainable scenario. This is mainly due to water requirements for solar panel cleaning and manufacturing processes.

This highlights the importance of integrating water-efficient practices, such as optimized cleaning methods and recycling systems, to further enhance sustainability.

## iv. Sankey-Based Contribution Insights

The Sankey diagrams provide a clear visual understanding of how impacts are distributed across processes. It is observed that a few high-energy processes dominate the overall impact, such as coal combustion in brick production, clinker manufacturing in concrete, and electricity generation in the operational phase.

In comparison, processes like transportation and auxiliary activities contribute relatively less. This indicates that targeting key high-impact processes can lead to maximum environmental improvement.

## v. Final Summary

Overall, the sustainable scenario performs significantly better than the conventional approach across most impact categories. The combined use of fly ash bricks and solar PV systems results in substantial reductions in emissions, resource use, and environmental impacts.

Although some limitations remain, particularly in water consumption, the study clearly demonstrates that the environmental footprint of buildings can be greatly reduced through informed material selection and adoption of renewable energy systems at the design stage.

## VI. CONCLUSIONS

The Life Cycle Assessment of the G+2 institutional building shows that the production and operational stages are the major contributors to environmental impacts, while the construction stage has minimal influence.

Among materials, burnt clay bricks have the highest impact, whereas fly ash bricks perform the best, offering significant reductions in emissions and resource use.

The use of solar PV systems greatly reduces operational impacts, especially in global warming and energy-related categories. However, water consumption remains relatively high, indicating a trade-off.

Overall, the study confirms that combining sustainable materials and renewable energy can reduce environmental impacts by over 80–90%.

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## REFERENCES

- [1] Asif, M., Muneer, T., & Kelley, R. (2007). Life cycle assessment: A case study of a dwelling. *Building and Environment*, 42(3), 1391–1394.
- [2] Bilec, M. M., Ries, R. J., Matthews, H. S., & Sharrard, A. L. (2010). A hybrid life-cycle assessment of construction processes. *Journal of Infrastructure Systems*, 16(2), 88–98.
- [3] Bureau of Energy Efficiency. (2017). *Energy conservation building code (ECBC)*. Government of India.

- [4] Cabeza, L. F., Ürge-Vorsatz, D., McNeil, M. A., Barreneche, C., & Serrano, S. (2014). Life cycle assessment of buildings: A review. *Renewable and Sustainable Energy Reviews*, 29, 394–416.
- [5] Dixit, M. K., Fernández-Solís, J. L., Lavy, S., & Culp, C. H. (2012). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, 42(8), 1238–1247.
- [6] Dutt, G., Nair, G., & Garg, V. (2018). Low-carbon pathways in India. *Energy and Buildings*, 160, 145–154.
- [7] Ecoinvent Association. (2023). *Ecoinvent database v3 documentation*.
- [8] Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., ... Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management*, 91(1), 1–21.
- [9] Frischknecht, R., Jungbluth, N., Althaus, H. J., Bauer, C., Doka, G., Dones, R., ... Nemecek, T. (2005). The ecoinvent database: Overview and methodological framework. *International Journal of Life Cycle Assessment*, 10(1), 3–9.
- [10] Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2016). *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level*.
- [11] GreenDelta. (2023). *openLCA user manual*.
- [12] GRIHA Council. (2019). *GRIHA rating system*.
- [13] Guinée, J. B. (Ed.). (2002). *Handbook on life cycle assessment: Operational guide to the ISO standards*. Kluwer Academic Publishers.
- [14] Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (2018). *Life cycle assessment: Theory and practice*. Springer.
- [15] Hong, T., Yan, D., D'Oca, S., & Chen, C. F. (2017). Ten questions concerning occupant behavior in buildings. *Building and Environment*, 114, 518–530.
- [16] Indian Green Building Council. (2020). *IGBC green building rating systems*.
- [17] International Organization for Standardization. (2006a). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*.
- [18] International Organization for Standardization. (2006b). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*.
- [19] Kulkarni, A., & Sivakumar, M. (2023). Life cycle assessment of building components using openLCA. *Journal of Material Sciences & Applied Engineering*.
- [20] Lalmi, A., Boumalia, B., Fernandes, G., & Sassi Boudemagha, S. (2025). Identifying traditional project management practices in the construction industry. *Procedia Computer Science*, 256, 1756–1763.
- [21] Mahapatra, D. M., et al. (2017). Life cycle assessment of construction materials in India. *Sustainable Cities and Society*, 32, 205–215.
- [22] Moncaster, A. M., & Song, J. Y. (2012). A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *International Journal of Sustainable Building Technology and Urban Development*, 3(1), 26–36.
- [23] Negishi, K., et al. (2018). Dynamic life cycle assessment of buildings. *Building and Environment*, 140, 34–45.
- [24] Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23(1), 28–39.
- [25] Pamu, S., et al. (2022). Life cycle assessment of residential building using sustainable materials. *Materials Today: Proceedings*.
- [26] Pérez-Lombard, L., Ortiz, J., & Pout, C. (2008). A review on buildings energy consumption information. *Energy and Buildings*, 40(3), 394–398.
- [27] Pomponi, F., & Moncaster, A. (2016). Embodied carbon mitigation and reduction in the built environment. *Journal of Environmental Management*, 181, 687–700.
- [28] Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings. *Energy and Buildings*, 42(10), 1592–1600.

- [29] Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., ... Pennington, D. (2004). Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*, 30(5), 701–720.
- [30] Sartori, I., & Hestnes, A. G. (2007). Energy use in the life cycle of conventional and low-energy buildings. *Energy and Buildings*, 39(3), 249–257.
- [31] Shukla, A., Tiwari, G. N., & Sodha, M. S. (2009). Embodied energy analysis of adobe house. *Building and Environment*, 44(4), 755–761.
- [32] Waqar, A., Nisar, S., Muddassir, M., & Benjeddou, O. (2025). An integrated management system (IMS) approach to sustainable construction development and management. *Journal of Infrastructure Intelligence and Resilience*, 4, 100126.
- [33] Zuo, J., & Zhao, Z. Y. (2014). Green building research—Current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, 30, 271–281.



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