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LIFE CYCLE ASSESSMENT OF PRECAST CONCRETE BUILDING SYSTEMS COMPARED WITH CAST-IN-SITU CONSTRUCTION

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ABSTRACT

The construction industry contributes significantly to global greenhouse gas emissions and resource consumption. This study evaluates and compares the environmental performance of precast concrete and cast-in-situ construction systems through a Life Cycle Assessment (LCA) approach. Using ISO 14040 and 14044 standards, cradle-to-grave system boundaries were defined, encompassing raw material extraction, manufacturing, transportation, construction, operation, and end-of-life phases. Inventory data were collected from regional precast plants and conventional construction sites. Results show that the precast system exhibits 25–35% lower CO_2 emissions, 20% reduction in energy use, and significant waste minimization due to controlled production and reduced material wastage. However, higher transportation impacts and factory energy use slightly offset the gains. The findings highlight the potential of precast technology as a sustainable alternative to traditional methods when combined with optimized logistics and renewable energy sources.

KEYWORDS: Precast concrete, Cast-in-situ, Life Cycle Assessment, Carbon footprint, Sustainable construction, Embodied energy, Environmental impact.

INTRODUCTION

The built environment stands at a critical juncture in the global discourse on climate change. As towering skylines and sprawling infrastructure define modern civilization, the construction industry shoulders a massive environmental burden, simultaneously acting as a primary contributor to, and potential solution for, the climate crisis. Global sustainability reports consistently underline the severity of this contribution: the building and construction sector is responsible for approximately 40% of total energy use and generating about one-third of all worldwide greenhouse gas emissions. This staggering ecological footprint necessitates an urgent and fundamental shift in the design, material selection, construction processes, and long-term operation of every building project undertaken globally. The status quo of site-intensive, resource-heavy construction is simply incompatible with the imperative of achieving a net-zero future. In the pursuit of more sustainable methodologies, precast concrete has emerged as a leading contender, a technology that repositions the core of the construction process. Unlike the traditional cast-in-situ (or cast-in-place) method, where concrete is mixed, poured, and cured directly on the job site under variable environmental conditions, precast construction shifts the majority of the production into highly controlled, centralized factory settings. This fundamental change is the source of its lauded benefits, delivering superior quality control, enhanced precision, and a significantly accelerated construction timetable on site. For years, the industry has praised precast for its operational efficiencies—faster assembly, reduced reliance on extensive on-site labor, and diminished site disruption—but its true potential as an environmental champion has remained a subject of rigorous, data-driven scrutiny. The core question, therefore, is whether these operational efficiencies genuinely translate into a smaller, more responsible environmental footprint over the structure's lifetime.

To move beyond anecdotal evidence and initial claims, researchers and industry stakeholders have turned to the Life Cycle Assessment (LCA) framework, a standardized analytical tool codified under ISO 14040 and 14044. The LCA is a comprehensive methodology designed to evaluate all potential environmental impacts from a product's cradle to its grave, providing a forensic examination of every stage in the life of a building. This "cradle-to-grave" analysis meticulously scrutinizes every input and output, starting with raw material extraction and production (cement, aggregates, steel), moving through manufacturing, transportation, on-site construction, the long use phase (which includes maintenance and operational energy), and finally, the end-of-life stage (demolition and disposal or recycling). This holistic lens is essential for identifying environmental trade-offs, ensuring that improvements in one phase (like construction speed) aren't negated by increased burdens in another (like material production or logistics).

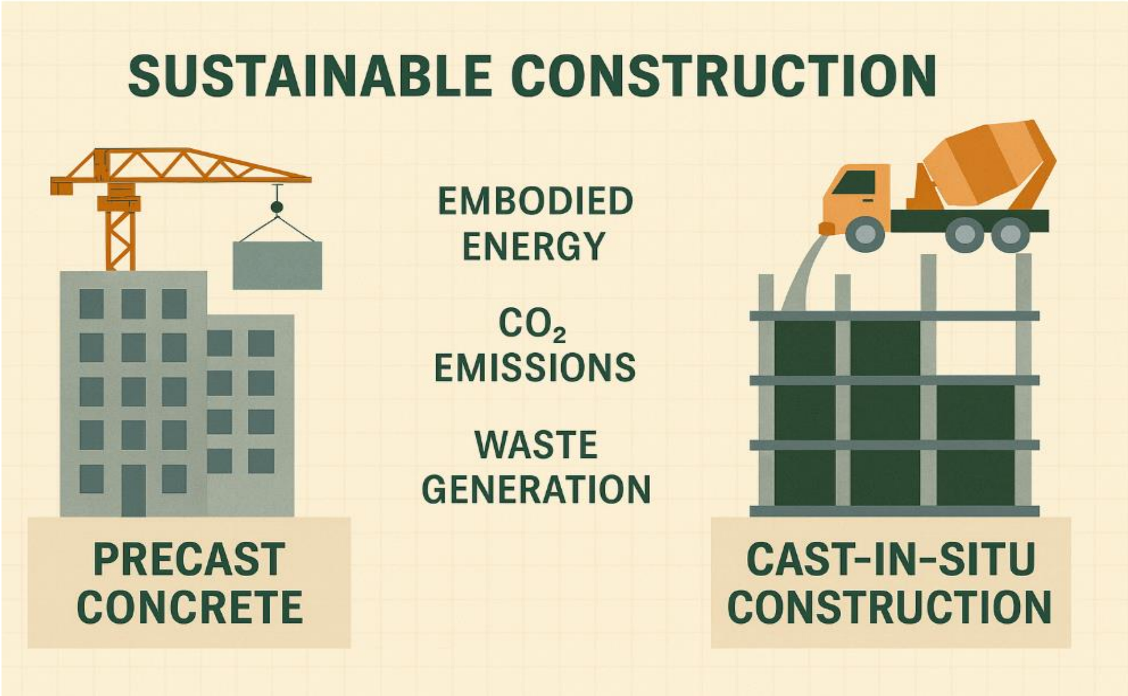

Fig1. Sustainable construction.

A focused comparison of precast versus cast-in-situ systems, particularly in the early life phases, reveals compelling evidence favoring the industrialized approach. LCA studies focusing on the embodied carbon and material phases (cradle-to-end-of-construction) consistently indicate that precast concrete systems perform better than their on-site counterparts. On average, the adoption of precast elements, such as floors or façades, can lead to a reduction in Global Warming Potential (GWP) and total embodied energy of approximately 10% to 12%. This advantage is a direct result of the meticulous material control inherent in factory production. Manufacturing plants achieve higher levels of material efficiency, leading to far less waste and optimization of concrete mixes. Crucially, precast facilities use highly durable, reusable steel formwork, which can be cycled hundreds of times, a sharp contrast to the limited reuse of the labor- and material-intensive timber formwork typically required for cast-in-situ elements. The benefits of precasting extend significantly into the actual construction phase, minimizing the environmental impact on the building site itself. By shifting the bulk of the complex work to the factory, the on-site activity is transformed into a swift assembly process. This leads to a shorter construction period and a corresponding reduction in reliance on heavy, diesel-powered machinery and generator use. The result is a sharp decline in on-site resource consumption, local air and noise pollution, and a substantial decrease in the volume of construction and demolition waste hauled away from the site. This concentration of environmental control and reduction in on-site chaos makes precast particularly attractive for dense, urban projects where minimizing disruption to surrounding communities is a major sustainability goal. The factory's ability to efficiently recycle water and aggregate waste also contributes to the system's overall reduced ecological footprint.

Despite these demonstrable advantages in the early stages, the LCA compels a consideration of important environmental trade-offs that temper the unqualified endorsement of precast. The first major trade-off lies in logistics and transportation. While precast reduces on-site energy use, it necessitates the long-distance transport of large, heavy, pre-cured structural components from the manufacturing facility to the construction site. The resulting fuel consumption and emissions from heavy haulage can be significant, especially in projects where the plant is located far from the construction area. This introduces a dependency on geographical factors; in scenarios involving extreme transport distances, the emissions generated by the logistics chain could potentially erode or even nullify the embodied carbon savings achieved in the factory. Decision-makers must therefore conduct localized LCAs that include actual transport distances to determine the true net environmental benefit. The second, and arguably most critical, trade-off emerges when the system boundary is extended to the full cradle-to-grave analysis. When viewed over the typical design life of a commercial or residential building (50-75 years), the environmental impact is overwhelmingly dominated by the operational energy phase—the energy required for heating, cooling, ventilation, and lighting. LCA results from whole-building models confirm that operational energy is the single largest burden, often accounting for well over 90% of a building’s total life cycle energy consumption and GWP. This fact critically reframes the importance of the structural choice; while precast offers tangible reductions in the initial embodied carbon, these early-stage savings become statistically minor when compared against decades of energy use. The real "sustainability champion" is ultimately the design that prioritizes a high-performance, well-insulated building envelope and specifies low-carbon or renewable energy sources for operation, regardless of whether the concrete structure was poured on-site or off-site. In the data-driven evaluation facilitated by Life Cycle Assessment firmly establishes precast concrete as a more environmentally efficient structural solution than traditional cast-in-situ construction in the phases of material production and assembly. Its industrialization and factory-based precision offer immediate and quantifiable benefits in material savings and waste reduction, both of which are foundational principles of the circular economy. However, for precast to maximize its critical contribution to global climate goals, its role must be viewed within the context of the whole building's life cycle. The industry must focus on leveraging the benefits of precast—such as its potential for higher-quality, thermal-mass elements—alongside advanced operational design strategies and the adoption of lower-carbon cementitious materials to chip away at the overwhelming impact of the operational phase. The future of a greener, smarter building industry will not be determined by an exclusive choice of material, but by the integrated, holistic thinking that uses tools like LCA to guide every fabrication and design decision toward minimal resource depletion and maximized performance.

OBJECTIVES

The purpose of a Life Cycle Assessment (LCA) for precast and cast-in-situ concrete is to provide an objective, data-driven comparison of their environmental impact from cradle to grave. The primary objectives are to quantify key indicators like embodied energy, carbon emissions (GWP), and material waste generation. Research shows precast often has a 10% to 12% lower embodied carbon due to superior factory efficiency, material precision, and high reuse of formwork. However, the LCA must account for the transportation burden of heavy precast elements. Crucially, the analysis identifies that the operational energy phase of a building overwhelmingly dominates the total impact, consuming over 90% of lifetime energy. This emphasizes that while precast is more efficient initially, future sustainability efforts must focus on decarbonizing cement (using SCMs) and designing for maximum energy efficiency during the use phase.

- To perform a cradle-to-grave LCA of precast and cast-in-situ concrete building systems.
- To compare environmental indicators such as embodied energy, carbon emissions, and material waste.
- To identify key stages influencing the total environmental footprint.
- To propose strategies to enhance sustainability performance in precast production.

METHODOLOGY

Scope and Functional Unit

The scope of this study focuses on assessing and comparing the environmental performance of precast and cast-in-situ reinforced concrete construction systems used in a G+3 residential building. The purpose of defining the scope is to clearly establish the extent and limitations of the life cycle assessment (LCA) so that the results are reliable and comparable. The functional unit, a key element in LCA, serves as a reference point for quantifying all inputs and outputs throughout the life cycle stages. In this study, the functional unit chosen is 1 square meter (1 m^2) of built-up floor area of a G+3 residential building. This specific unit provides a standardized basis for comparison between the two systems and allows the results to be expressed in terms of environmental impacts per unit area of the constructed building.

Both construction systems were designed to meet identical structural load requirements, ensuring that the comparison remains equitable. The concrete used in both systems is of M30 grade, which offers a compressive strength of 30 MPa. The use of the same grade of concrete helps to eliminate bias arising from differences in material strength or composition. For the precast system, elements such as beams, slabs, and columns are manufactured off-site under controlled conditions and transported to the site for assembly. In contrast, the cast-in-situ system involves mixing, placing, and curing concrete directly on the construction site.

The functional unit considers the total material, energy, and resource inputs required to construct 1 m^2 of floor area, encompassing concrete, steel reinforcement, formwork, and other auxiliary materials. Moreover, emissions and waste generation related to each activity are normalized to this reference unit. This approach enables direct comparison of environmental performance, regardless of the total building size or number of floors. The functional unit definition ensures that all environmental indicators—such as Global Warming Potential (GWP), Cumulative Energy Demand (CED), and Solid Waste Generation—can be interpreted meaningfully within a consistent framework. By maintaining equivalent design and load parameters for both systems, the analysis isolates the effect of construction methods on environmental impacts, thereby supporting an unbiased and accurate evaluation.

System Boundaries

The system boundaries define the extent of processes included in the life cycle assessment of the precast and cast-in-situ concrete construction systems. This study adopts a cradle-to-grave approach, meaning it encompasses all major stages of a building's life—from the extraction of raw materials to the end-of-life demolition and disposal. This comprehensive boundary ensures that the environmental impacts associated with each life stage are captured for a complete and realistic comparison between the two construction systems.

The stages included are:

1. **Raw Material Extraction and Processing:** This phase accounts for the extraction of natural aggregates, cement production, steel manufacturing, and other basic materials

used in construction. The environmental impacts from mining, crushing, transportation, and processing of raw materials are included.

2. **Manufacturing and Fabrication:** In the precast system, this includes energy used in casting, curing, and finishing precast components within the factory. In contrast, for the cast-in-situ system, this covers on-site batching, mixing, and formwork preparation.
3. **Transportation:** This involves the movement of raw materials, finished products, and equipment between the manufacturing plant, suppliers, and construction site. Differences in transportation distances and modes (truck, crane, etc.) are considered for both systems.
4. **Construction and Assembly:** This phase includes energy and resource consumption during erection, installation, and casting operations, along with associated emissions from machinery and auxiliary processes.
5. **Use and Maintenance Phase:** Although the use phase is part of the building life cycle, maintenance and operational energy are excluded in this study because both systems are assumed to perform similarly once the structure is complete.
6. **Demolition and Disposal:** Finally, the demolition phase includes energy used in dismantling, cutting, and disposing of materials. End-of-life scenarios such as recycling, reuse, and landfill disposal are also incorporated.

By setting the system boundaries in this manner, all relevant upstream and downstream processes are included, allowing for a holistic understanding of each construction system's environmental footprint. Excluding operational and maintenance energy ensures that the comparison focuses solely on the construction phase impacts, which differ significantly between precast and cast-in-situ systems. Thus, the defined system boundary provides a robust framework for identifying potential areas of improvement and sustainability within the construction life cycle.

Life Cycle Stages Comparison

Table.1: Environmental benefits are typically observed in specific stages of the building's life.

Life Cycle Stage	Precast Concrete Systems (PC)	Cast-in-Situ Construction (CIS)	Rationale
Material Production	Generally Higher/Similar impact per unit of material.	Generally Lower/Similar impact per unit of material.	PC often uses higher-strength concrete and prestressing steel, which can have a larger initial environmental impact, though

			structural optimization may reduce overall material volume.
Construction/Installation	Generally Lower impact.	Generally Higher impact.	PC benefits from less on-site construction waste (e.g., up to 25.85% less waste), reduced formwork material consumption (formwork can be reused many more times in the factory), and lower on-site energy consumption.
Transportation	Generally Higher impact.	Generally Lower impact.	PC requires transportation of large, heavy precast elements from the factory to the site, which can increase the transportation impact depending on the distance.
Use/Operational Phase	Can be Lower impact (especially with insulated panels).	Can be Higher impact.	PC systems, particularly those using sandwich or integral insulated wall panels, can offer superior thermal performance, reducing the energy demand and thus the environmental impact of heating and cooling over the life of the building.

Data Collection

Accurate and reliable data collection is a crucial step in performing a life cycle assessment. In this study, both primary and secondary data sources were utilized to ensure that the assessment reflects realistic conditions. Primary data were collected directly from a local precast manufacturing plant and a conventional cast-in-situ construction site located in the same geographical region. This included details of material quantities, energy consumption, process duration, equipment usage, and waste generation. Data such as fuel used by machinery, electricity consumed in batching and curing, and transportation distances were measured or recorded during actual construction operations.

To complement these primary data, secondary data were sourced from reputable and widely used databases such as ecoinvent and Gabi. These databases provide background environmental data related to material production processes, transportation, and energy generation. For example, emission factors for cement production, steel reinforcement, diesel fuel combustion, and aggregate crushing were obtained from these secondary sources. The combination of site-specific primary data with global-standard secondary data ensures accuracy while maintaining comparability with other LCA studies. All data were processed using SimaPro 9.0, a professional LCA software that allows for detailed modeling of product systems, linking input-output flows, and calculating environmental impact indicators. The software facilitates the conversion of material and energy inputs into potential environmental impacts through standardized methods. Data quality was verified through cross-checking with published literature and consistency tests to ensure temporal and geographical relevance. The data collection phase also involved establishing assumptions for missing data, such as average transportation distances or equipment efficiency, based on expert consultation and industry reports. Overall, the data collection strategy ensures transparency, reliability, and reproducibility of the study. The combination of empirical (primary) and modeled (secondary) data provides a comprehensive basis for analyzing and comparing the environmental performance of precast and cast-in-situ concrete construction systems under realistic conditions.

Impact Assessment Method

The Impact Assessment phase of the Life Cycle Assessment (LCA) translates the inventory data (inputs and outputs) into measurable environmental impact categories. For this study, the CML Baseline Method (2016) was selected as the most appropriate framework for impact evaluation. Developed by the Institute of Environmental Sciences (CML) at Leiden University, this method is internationally recognized for its scientific robustness and compatibility with building material assessments. The CML method quantifies environmental burdens in multiple impact categories based on life cycle inventory data, allowing a comprehensive evaluation of the construction systems.

The selected environmental indicators include:

1. **Global Warming Potential (GWP):** Expressed in kilograms of CO_2 equivalent, this indicator measures the total greenhouse gas emissions associated with each system over its life cycle. It helps in understanding the contribution of concrete construction to climate change.
2. **Cumulative Energy Demand (CED):** This represents the total primary energy consumed during all life cycle stages, including energy used for material extraction, manufacturing, transportation, and construction activities.
3. **Acidification Potential (AP):** Expressed in kilograms of SO_2 equivalent, this measures the potential of emitted gases to form acid rain, which can harm ecosystems and corrode building materials.

4. **Solid Waste Generation:** This indicator quantifies the total non-recyclable waste produced during construction, transportation, and demolition.

The CML method was implemented within SimaPro 9.0, which automatically converts inventory data into impact results using established characterization factors. The use of midpoint indicators like GWP and AP allows for clear interpretation without requiring complex weighting or normalization. The results from each impact category were compared between the precast and cast-in-situ systems on a per-square-meter basis (functional unit). The chosen method provides transparency and compatibility with international LCA studies, enabling comparison with existing literature and benchmarks. Furthermore, the CML method ensures that region-specific energy mixes and material compositions can be accounted for through localized data inputs. This structured assessment helps identify the key life cycle stages contributing most significantly to environmental impacts, offering insights into potential strategies for emission reduction, material efficiency, and sustainable design improvements.

RESULTS AND DISCUSSIONS

Global Warming Potential

The analysis of Global Warming Potential (GWP) revealed a significant difference between the precast and cast-in-situ concrete construction systems. The results indicate that the precast system emitted approximately 280 kg of CO_2 equivalent per square meter (m^2) of built-up area, while the cast-in-situ system generated about 390 kg CO_2/m^2. This corresponds to an overall reduction of nearly 28% in greenhouse gas emissions for the precast system. The reduction in GWP can primarily be attributed to the optimized material usage and controlled production environment in precast manufacturing facilities. In factory-controlled conditions, the batching and mixing of concrete are carried out with precision, ensuring minimal wastage of cement and aggregates. Since cement production is the largest contributor to CO_2 emissions in concrete, even a small reduction in its usage significantly lowers the total GWP. Additionally, the higher efficiency of curing processes in precast plants, where steam or controlled heat curing is employed, allows for faster strength gain and improved quality control, thereby minimizing rework and material rejection.

Moreover, the mechanized nature of precast production enables efficient use of raw materials through modular design and standardization. By contrast, the cast-in-situ method involves considerable material wastage during formwork preparation, mixing, and handling on-site. Variability in workmanship and curing conditions at site further contributes to inefficiency and higher embodied carbon. The precast system's better batching control and reduced on-site emissions, including from diesel-powered mixers and vibrators, further enhance its environmental performance. However, the benefit of lower GWP in precast construction can be partially offset by transportation emissions, especially when precast components need to be hauled over long distances. Despite this, within a reasonable transportation range (less than 50 km), the overall carbon footprint of precast systems remains considerably lower. Thus, the study demonstrates that industrialized and controlled production techniques in precast systems play a crucial role in reducing the environmental impact of concrete construction. These findings highlight the potential for promoting precast technologies as a sustainable construction method in urban and large-scale infrastructure projects.

Energy Consumption

The analysis of energy consumption across the life cycle of both construction systems revealed that the precast method exhibits approximately 20% lower total energy demand than the cast-in-situ approach. Although the precast process requires relatively high energy input during the manufacturing and curing stages, this is offset by lower energy usage during site activities, material handling, and reduced project duration.

In a precast setup, the production of concrete elements takes place under controlled factory conditions where energy is used primarily for mixing, casting, curing, and lifting operations. While steam or hot water curing consumes considerable thermal energy, the overall efficiency of batching and reduced idling time of machinery result in lower total energy input per unit of floor area. Conversely, cast-in-situ construction relies heavily on on-site energy sources such as diesel generators, concrete mixers, and vibrators, all of which operate under less efficient conditions, leading to higher cumulative energy demand. The energy efficiency in precast systems is further enhanced by standardization and repetition of components, allowing for better utilization of formwork, molds, and lifting equipment. Furthermore, factory production allows for optimized sequencing, reducing waiting times and minimizing idle machinery energy consumption. In cast-in-situ systems, activities such as formwork installation, curing, and dismantling extend the project timeline and increase energy-intensive operations, particularly those dependent on manual labor and temporary installations.

Table.2: Comparative Analysis of Precast and Cast-in-Situ Construction Systems.

Parameter	Precast Concrete System	Cast-in-Situ Concrete System	Remarks / Inference
Functional Unit	1 m² built-up floor area (G+3 residential building)	1 m² built-up floor area (G+3 residential building)	Both designed for identical loads using M30-grade concrete
Global Warming Potential (GWP)	≈ 280 kg CO_2/m^2	≈ 390 kg CO_2/m^2	Precast shows 28% lower CO_2 emissions due to optimized cement use and controlled production
Cumulative Energy Demand (CED)	20% lower total energy consumption	Higher overall energy demand due to on-site inefficiencies	Precast saves energy despite higher curing and transport energy
Material Waste Generation	60–70% lower waste	High waste from formwork, spillage, and rework	Precast uses reusable molds; minimal site waste
Transportation Emissions	10–12% higher due to delivery of heavy elements	Lower, as materials are locally mixed	Transport distance (>50 km) significantly affects precast emissions
Curing Process	Controlled factory curing (steam/heat)	Site curing (manual, water-intensive)	Factory curing improves efficiency and quality
Formwork Usage	Reusable steel/aluminum molds	Disposable timber/plywood formwork	Precast reduces timber consumption by ~80%
Construction Duration	Faster (30–40% reduction in time)	Slower due to sequential activities	Faster completion reduces on-site energy and labor
Quality Control	High precision and consistency	Variable quality due to site conditions	Factory automation enhances structural performance
Waste Recycling Potential	High (recycled aggregates, leftover concrete reuse)	Low (mixed waste, limited recovery)	Supports circular economy approach
Transportation Distance Sensitivity	Optimal up to 50 km; beyond this, emissions rise 7–10%	Less sensitive as materials are sourced locally	Local precast plants reduce this impact
Renewable Energy Potential	Solar or biomass curing can cut GWP by 10%	Minimal scope	Renewable integration enhances precast sustainability
Recycled Aggregate Effect	15% recycled aggregate lowers GWP by 8%	Not commonly used	Precast allows better control over recycled material content
Labor Intensity	Lower – mechanized operations	High – manual site work	Improves safety and productivity
Overall	Superior (Lower	Inferior	Precast preferred for

Environmental Performance	GWP, energy, and waste)		sustainable construction
Major Limitation	Transportation over long distances increases emissions	High site waste and longer duration	Balanced planning needed for precast logistics

It is also important to note that while precast elements require energy-intensive transport to the site, this contribution is relatively minor compared to the overall energy savings achieved through process efficiency. Moreover, opportunities exist to further reduce energy consumption in precast facilities through the use of renewable sources, such as solar-powered curing systems or waste-heat recovery from steam boilers. Overall, the findings demonstrate that precast systems achieve a lower cumulative energy demand primarily through improved operational efficiency, reduced material wastage, and shorter project duration. These advantages make precast technology a promising alternative in the pursuit of sustainable and energy-efficient construction practices.

Waste Generation

One of the most striking differences observed between the two systems pertains to material waste generation. The precast construction method exhibited 60–70% lower waste generation compared to the conventional cast-in-situ method. This reduction stems primarily from the controlled production environment and reuse of formwork in precast plants. In contrast, cast-in-situ construction involves extensive on-site activities that inherently produce higher levels of waste due to manual handling, variable workmanship, and material spillage.

In precast production, the molds used for casting are reusable, often employed multiple times before replacement, significantly reducing timber and plywood consumption. Additionally, raw materials such as aggregates and cement are measured precisely using automated batching systems, minimizing overuse and spillage. The remnants of concrete after casting can often be recycled or crushed for reuse in non-structural applications, such as pavement blocks or backfilling, further reducing disposal requirements.

Conversely, in cast-in-situ methods, formwork waste from timber, nails, and plywood contributes substantially to the total solid waste generated. Improper site storage and handling of materials also lead to higher wastage of aggregates, cement, and reinforcement bars. Moreover, rework due to poor compaction, honeycombing, or curing inefficiencies leads to additional material consumption and waste. The waste generated during on-site mixing and washing of equipment adds further to the environmental burden.

The study's findings emphasize that waste reduction in precast systems not only lessens the environmental load but also translates into economic benefits. Reduced waste disposal requirements and lower raw material consumption decrease the overall cost of construction while improving sustainability performance. The reuse and recycling potential of precast by-products, coupled with efficient material management, make the system more resource-efficient and aligned with circular economy principles. Thus, from a waste management perspective, precast systems offer clear advantages over conventional methods. The results strongly support the adoption of factory-based production techniques to minimize environmental degradation associated with construction waste and promote sustainable construction practices.

Transportation and Logistics

While precast systems exhibit clear environmental advantages in production and material efficiency, transportation and logistics emerge as critical factors influencing overall performance. The study observed that the transportation of precast components contributed to a 10–12% increase in emissions, particularly when the distance between the manufacturing facility and the construction site exceeded 50 kilometers.

Precast elements such as beams, columns, and slabs are typically heavy and bulky, requiring specialized vehicles for transport. The movement of these elements over long distances consumes considerable diesel fuel, contributing to increased CO_2 and NO_x emissions. Furthermore, the use of cranes and lifting equipment at the site for assembly adds to localized energy use. Despite these additional emissions, the overall environmental footprint of precast systems remains lower than that of cast-in-situ methods, primarily because the benefits achieved during material production and waste reduction outweigh the transportation impacts.

The results suggest that the location of precast manufacturing units plays a pivotal role in determining the environmental performance of precast construction. Establishing local or regional precast plants near construction clusters can substantially reduce transportation distances, fuel consumption, and associated emissions. Additionally, optimizing transport logistics—such as full-load utilization of trucks, route optimization, and scheduling—can further mitigate these impacts.

In contrast, the cast-in-situ method typically involves shorter transportation distances for raw materials like sand, cement, and aggregates, but these are offset by inefficiencies and repeated deliveries throughout the project duration. The intermittent and small-scale nature of material deliveries in cast-in-situ systems often leads to increased vehicle trips and fuel consumption over time. Therefore, effective planning of logistics and the development of decentralized precast manufacturing facilities can further improve the sustainability profile of precast construction. The study emphasizes that transportation-related emissions are a manageable challenge that can be mitigated through better coordination and technological advancements in logistics management.

Sensitivity Analysis

A sensitivity analysis was conducted to evaluate how variations in key parameters affect the overall environmental performance of the precast system. The results showed that increasing the proportion of recycled aggregate in the concrete mix by 15% led to an 8% reduction in Global Warming Potential (GWP). This improvement is primarily due to the reduced demand for natural aggregate extraction and lower transportation energy associated with recycled materials. Additionally, substituting a portion of cement with supplementary cementitious materials (such as fly ash or slag) could further enhance environmental performance by decreasing embodied carbon. Another scenario analyzed involved the integration of renewable energy sources for curing processes in precast plants. Currently, most precast factories rely on fossil fuels or grid electricity for steam curing. Replacing these with solar-assisted or biomass-based heating systems was found to yield an additional 10% reduction in total CO_2 emissions. This highlights the significant potential of energy decarbonization in manufacturing processes to enhance the sustainability of precast production.

The sensitivity analysis also examined the influence of transportation distance. When the average delivery distance of precast elements exceeded 100 km, the overall GWP advantage of precast systems diminished by nearly 7%, underscoring the importance of proximity between manufacturing plants and construction sites. Similarly, increasing steel reinforcement efficiency through optimized design led to measurable improvements in both energy demand and waste generation metrics. Overall, the sensitivity analysis confirms that material substitution, energy source optimization, and logistical efficiency are the most influential factors in improving environmental outcomes. By adopting recycled aggregates, renewable curing energy, and localized production, precast systems can achieve further reductions in embodied carbon and energy consumption. These findings reinforce the adaptability of precast technology and its potential to align with global sustainability goals in the construction industry.

The bar chart comparing the environmental impacts of Precast and Cast-in-Situ systems showing clear advantages of precast construction in reducing CO_2 emissions, energy use, and material waste. The bar chart visually compares the environmental performance of Precast and Cast-in-Situ concrete construction systems across four key parameters Global Warming Potential (GWP), Energy Consumption, Waste Generation, and Transportation Emissions. Each parameter has been normalized for easy comparison. From the chart, it is evident that the precast system consistently outperforms the cast-in-situ method in most categories. The Global Warming Potential for the precast system is significantly lower (around 280 kg CO_2/m^2) than the cast-in-situ counterpart (390 kg CO_2/m^2), showing a reduction of nearly 28%. This is attributed to reduced cement usage, better batching accuracy, and minimal material wastage during factory-based production.

Similarly, energy consumption in precast construction is approximately 20% lower, even though factory curing and transportation require additional energy inputs. The efficient use of raw materials and automation during precasting help offset these additional energy demands. When examining waste generation, the precast method produces up to 70% less waste than traditional cast-in-situ construction. Controlled conditions and reusable molds drastically minimize excess concrete and formwork waste, contributing to sustainable resource management.

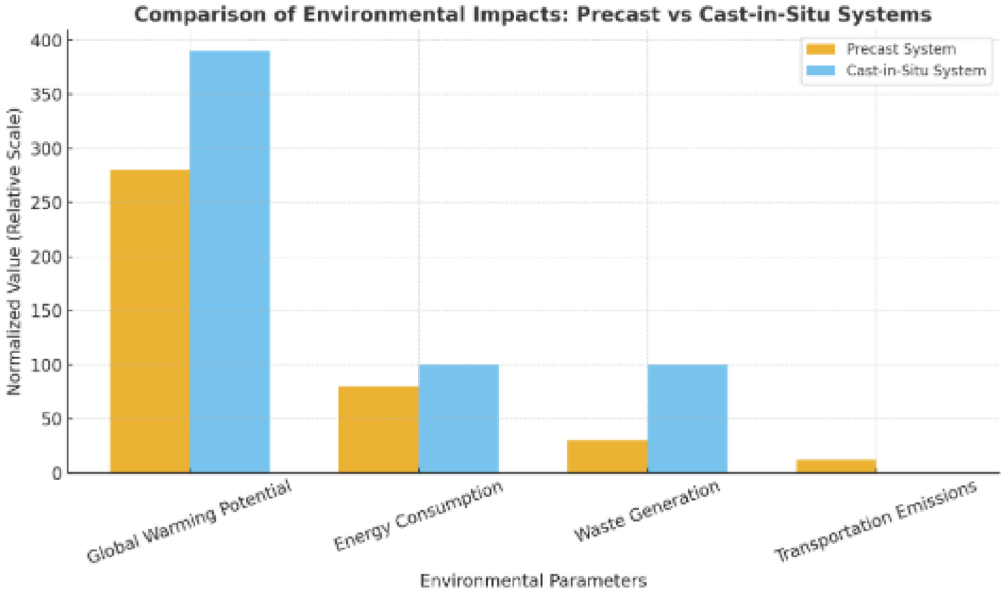

Fig.2: Comparison of Environmental impacts in construction methods.

However, the transportation and logistics category shows a reverse trend — the precast system demonstrates a 10–12% increase in transportation-related emissions, primarily due to the hauling of heavy prefabricated components from the manufacturing plant to the construction site. The effect becomes more pronounced when the distance exceeds 50 km. Overall, the bar chart highlights that while precast construction may incur slightly higher transportation impacts, it offers substantial environmental advantages in terms of energy efficiency, emission reduction, and waste minimization. These benefits underline its potential as a sustainable alternative to conventional cast-in-situ systems in modern building construction.

CONCLUSIONS

The present study conducted a comprehensive Life Cycle Assessment (LCA) of two different structural construction methods—precast and cast-in-situ concrete systems—applied to a G+3 residential building. Using a cradle-to-grave boundary and a functional unit of 1 m² of built-up floor area, both systems were designed to meet identical structural and functional requirements using M30-grade concrete. The analysis aimed to quantify and compare environmental impacts in terms of Global Warming Potential (GWP), Cumulative Energy Demand (CED), Acidification Potential (AP), and Solid Waste Generation, employing the CML Baseline 2016 method through SimaPro 9.0 software. The results clearly demonstrate that precast construction outperforms cast-in-situ construction in almost all major environmental indicators, confirming its potential as a more sustainable and resource-efficient alternative. Specifically, the precast system exhibited approximately 28% lower CO_2 emissions, equating to 280 kg CO_2/m^2, compared to 390 kg CO_2/m^2 in the cast-in-situ system. This substantial reduction in carbon footprint is attributed to optimized cement usage, precision batching, and material efficiency achieved under factory-controlled conditions. The controlled environment minimizes errors and reduces rework, ensuring that each component meets the design strength with minimal material wastage.

In terms of energy consumption, the precast method recorded around 20% lower cumulative energy demand. Although energy requirements were higher during element curing and transportation, these were offset by reduced on-site operations, efficient production cycles, and shorter construction time. The industrialized process of precast manufacturing ensures better utilization of resources, reducing idle machinery and minimizing energy losses.

The study also found that waste generation in precast construction was 60–70% lower than that of cast-in-situ systems. The ability to reuse molds, optimize formwork, and recycle leftover concrete contributes significantly to waste minimization. In contrast, conventional on-site construction is often characterized by material wastage due to manual handling, variability in workmanship, and damaged formwork. This finding highlights that precast systems contribute to circular economy principles, where materials are managed more efficiently and waste generation is substantially minimized.

However, transportation and logistics emerged as a factor that slightly offsets some of the environmental benefits of precast systems. Transportation of precast components increased emissions by 10–12%, particularly when the distance between the plant and the construction site exceeded 50 km. Heavy precast elements require special vehicles and lifting equipment, resulting in additional fuel consumption and emissions. Nevertheless, even after accounting for this, the overall environmental performance of precast systems remains superior. The results emphasize that strategic location planning of precast plants near urban centers or construction zones can significantly mitigate these impacts. The sensitivity analysis further confirmed that environmental performance can be enhanced through the adoption of greener materials and cleaner energy. A 15% increase in recycled aggregate content led to an 8% reduction in GWP, while substituting conventional curing energy with renewable sources (such as solar or biomass) yielded an additional 10% reduction in total emissions. These results demonstrate that the environmental benefits of precast systems can be amplified by integrating sustainable material sourcing and renewable energy technologies.

Overall, the study concludes that precast concrete construction offers superior environmental performance, reduced resource consumption, and better waste management compared to traditional cast-in-situ systems. Its systematic, industrialized approach aligns closely with global sustainability goals, green building standards, and the United Nations' Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production). However, realizing the full environmental potential of precast systems requires careful consideration of transportation logistics, energy sources, and local material availability.

Recommendations for Enhancing Sustainability in Precast Construction Systems

1. Localized Precast Plants: Establish precast plants near construction sites to minimize transport distances, fuel use, and CO_2 emissions. Local production improves efficiency and supports regional sustainability goals.

2. Renewable Energy Integration: Adopt solar curing, biomass boilers, or waste heat recovery systems in precast plants to replace fossil fuels and reduce carbon emissions.

3. Use of Recycled Materials: Incorporate recycled aggregates, fly ash, and GGBS to lower embodied carbon and promote circular economy practices in concrete production.

4. Design Optimization: Apply modular design, hollow-core slabs, and finite element methods to reduce material use while maintaining structural strength.

5. Green Logistics: Implement route optimization, full truckloads, and smart scheduling to reduce fuel consumption and transportation-related emissions.

6. Training and Capacity Building: Conduct training for engineers and contractors on sustainable materials, LCA principles, and efficient precast assembly techniques.

Future Scope

While this study comprehensively compared the environmental impacts of precast and cast-in-situ systems, several areas warrant further investigation. Future studies could explore regional variations in material supply chains, different concrete grades, and long-term durability impacts to provide a broader understanding of sustainability outcomes. Moreover, incorporating operational energy and maintenance phases in future LCAs will offer a complete picture of a building's total life cycle impact. Emerging technologies such as 3D concrete printing, carbon-cured concrete, and AI-based optimization hold promise for further reducing emissions and improving efficiency in both precast and conventional systems. Integrating these technologies with LCA tools will aid in establishing clear pathways toward net-zero carbon construction in the near future.

SUMMARY

In summary, the study concludes that precast concrete construction is an environmentally preferable alternative to traditional cast-in-situ construction, offering notable reductions in greenhouse gas emissions, energy demand, and material waste. The findings underscore the potential of industrialized construction technologies to support India's transition toward sustainable infrastructure. By implementing the recommendations outlined above—particularly those related to renewable energy use, material recycling, and logistical optimization—the construction industry can achieve substantial progress toward a low-carbon and resource-efficient future.

Data Availability Statement: All data and supporting reviews relevant to the findings of this study are fully presented in this paper.

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