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Life Cycle Assessment of a Sustainable Prefabricated Housing System: A Cradle-to-Site Approach Based on a Small-Scale Experimental Model

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Abstract: India is in need of rapid construction technology with sustainability and environmentally friendly aspects. Prefabrication is a well-known technique that lowers carbon emissions and reduces environmental impacts. Life cycle assessment (LCA) evaluates these impacts of developed product/process. A new-age construction product was designed from a locally available agro-industrial waste called co-fired ash (CFA). Expanded polystyrene beads, fly ash, and crushed sand were also used in designing lightweight (LW) sustainable prefabricated panels. The effect of incorporating sustainable alternates into the mix designs is to be studied. An experimental small-scale model house was erected and LCA for the same was carried out with cradle-to-site approach. Based on the inventory, the environmental impact was assessed for four different indicators: acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and ozone depletion potential (ODP) were evaluated. Carbon emissions of the respective CFA-based concrete and LW prefabricated mix were found to be 0.162 kgCO_2e/kg and 0.268 kgCO_2e/kg, respectively. The impact of energy required during production, transport, and indirect emissions were found to contribute 3%, 3%, and 94%, respectively, to the proposed prefabricated system. Comprehensively, the phase involving mixing of LW mix contributed majorly towards all the impact indicators followed by mould preparation and material transport. The presented data helps the academia to quantify and recognise the possibilities to enhance their products' performance.

Keywords: sustainability; prefabrication; life cycle assessment; global warming potential

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1. Introduction

With global population clocking at 8 billion, India is set to become most populous country surpassing China by 2023 [1]. The current population stands at 1.4 billion as of August 2022. The urban population is also on a steep rise with 35% of the population residing in the urban areas. The migrating community, especially the low-income groups and economically weaker sections need shelter. Indian government has initiated 'Housing for all' scheme [2] and various novel construction techniques are being introduced to implement them [3–5]. Prefabrication is a well-known technique that has proven to be quick and affordable. Along with this, the new age buildings have to be designed with the sustainability and energy efficiency approach such that they contribute less towards the environmental damage [6–9].

Urbanization and industrialization have forced India to encounter challenges regarding waste management [10]. As huge construction activities are comprehended to attain the accommodation targets, conventional materials are exploited and hence a need to shift towards sustainable alternates is a valid solution. Agro-industrial wastes, such as fly ash, silica fume, rice husk ash, and ground granulated blast furnace slag, that are sustainable alternates are being recommended as pozzolanas by Indian standard codes [11]. Along with these, few locally available bio-ashes were also utilized in development of construction products. These bio-ashes include sugarcane bagasse ash [12], recycled paper mill waste [13], bio-briquette ash [14], and co-fired blended ash [15]. These have enhanced the properties of the products along with benefiting the environment.

Construction sector is the second largest industry and is responsible for around 39% of the CO_2 emissions [16,17]. India at CoP26 has committed to net zero emissions by the year 2070 [18]. With carbon emissions at 2.88 Gt, plans are imminent to reduce it by 1 billion tons till the end of the year 2030. These emissions are related to greenhouse gas (GHG) and include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and others [19]. Among these, CO_2, CH_4, and N_2O were majorly considered as GHG emissions related to construction projects [20].

As the concern for environmental impacts is being focused, there is a need to consider life cycle assessment (LCA) for the construction products and activities that are being executed [21]. One of the criterion to evaluate sustainability concept is through LCA and it interprets the environmental impacts created during a product's life cycle [22]. LCA has the capability to assess these impacts of building operations along with waste generation, which can help recognize opportunities for enhancing efficiency [23]. The primary objective achieved through LCA is emission quantification. Its goal is to conduct a thorough evaluation of the resources utilised and potential environmental consequences at each stage of the life cycle [16]. The assessment of environmental impact is necessary for the urban planners to improve its related performance of future built environment [24]. Thermal insulation of buildings was observed to be a key factor in this and incorporating insulation materials in mix design lowers environmental impact [16].

Based on the reviewed literature, the impact indicators are recorded [25–29] and are mentioned in Figure 1. The most assessed indicators are found out to be acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and ozone depletion potential (ODP). The reference substances to be measured against these indicators are SO_2, phosphate, CO_2, and R11 (tri chlorofluoro methane) for AP, EP, GWP, and ODP, respectively.

The application of LCA needs a database of the materials and the emission information. There are various databases, such as EcoInvent, GaBi, PlasticsEurope Eco-Profile, Athena, ProBas, and others [30]. GaBi is known to be the biggest LCA database [31] among these with material processes involved from other databases too.

The aim of the current study is to develop rapid construction technology with a sustainability approach, which is an absolute necessity. Prefabrication was found to reduce environmental impacts, and lower carbon emissions on comparison with conventional construction practices [32]. A sustainable prefabricated system was designed with an energy-efficiency approach. The end products were evaluated for their properties and functionality with the help of a small-scale experimental model [33,34]. This system involves sustainable alternates as raw materials, and hence, there is a need to find out its contribution towards the emissions. A cradle-to-site life cycle assessment was carried out to determine the environmental impact created by this proposed prefabricated system. The objectives of this study lie in defining the scope and sources of the emissions during the execution of this prefabricated system. Emissions at each phase of the prefabricated system are to be estimated with their impact being assessed and the results being interpreted.

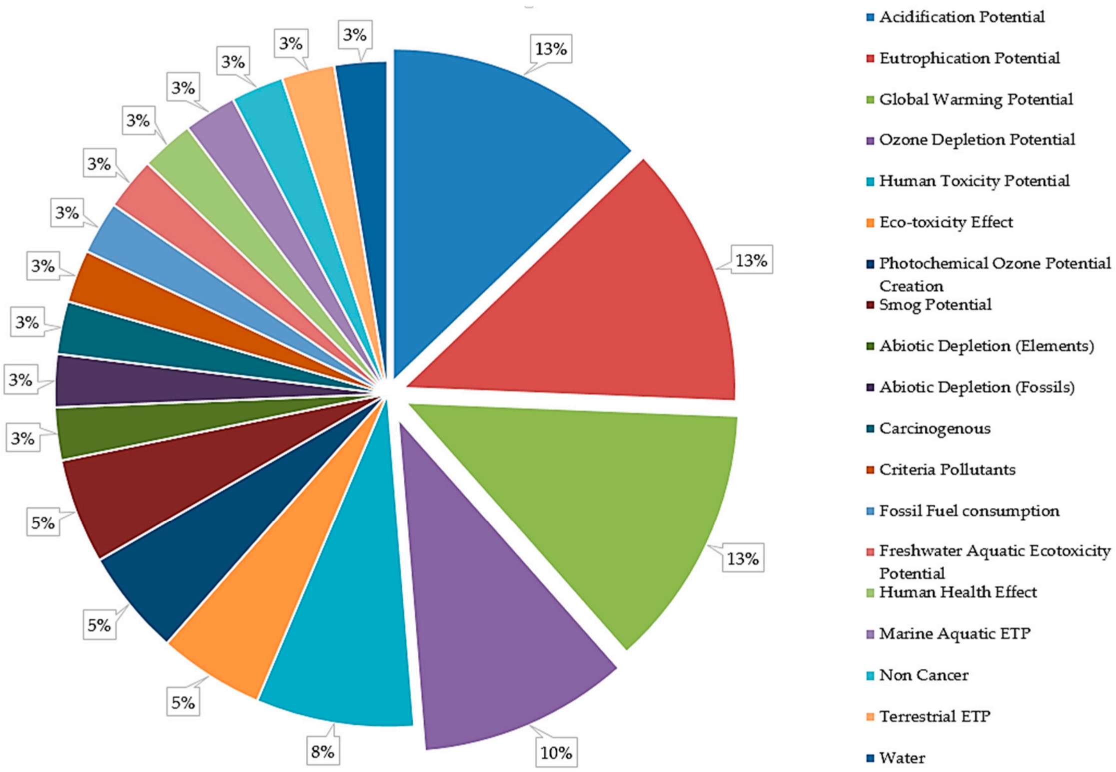

Figure 1. Major impact indicators of LCA.

2. Materials and Product Design

The need for introducing sustainable alternatives into the design of construction products was earlier discussed. This study briefs the mix designs for concrete and prefabricated mix. The conventional raw materials were partially replaced to obtain the desired mix designs.

2.1. Materials

Locally available agro-industrial waste called co-fired ash (CFA) was acquired from a paper mill industry (Figure 2). It is located at around 37 km from the city of Nagpur, India. This raw material is the by-product after co-firing coal and saw dust in the industrial burners. The unused ash was acquired and tested for its suitability as a construction material. Various characterization tests have proved its applicability as fine aggregate and was partially replaced [15,33].

Figure 2. Co-fired ash—Agro-industrial waste.

Fly ash was acquired from a local thermal power plant (Figure 3). It was replaced as a cementitious alternate because of its pozzolanic property. Crushed sand is another sustainable alternative to the conventional river sand (Figure 4), which is a by-product after the crushing process. Expanded polystyrene (EPS) beads were used as an insulation material and to make the walling members less dense. Along with these alternate raw materials, conventional materials, such as cement, river sand, gravel, and chemical admixtures were used in the design process of end products.

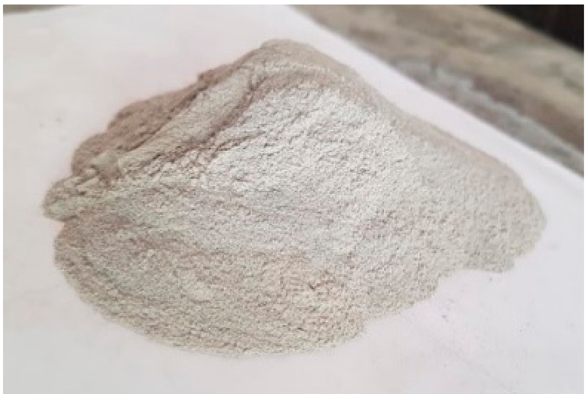

Figure 3. Fly ash—cementitious alternate.

Figure 4. Crushed sand—alternate for fine aggregates.

2.2. Mix Design and Testing

Two products were designed in this study:

1. Concrete: CFA-based concrete for the structural applications and other;
2. LW mix: CFA-based lightweight (LW) mix for the prefabricated walling members.

After numerous mix trials, the optimum mixes for both the products were finalized based on the density and compressive strength (Table 1). The final mixes have undergone various physico-mechanical and functional tests as per their respective codal standards (Table 2).

Table 1. Mix design of the CFA-based products (All values in kg).

Product	Cementitious	Aggregates	Water	Admixtures
Concrete	3.92 Cement	5.42 + 1.36 + 11.72 River sand + CFA + gravel	1.86	0.0005 + 0.016 Aeration agent + super plasticizer
LW mix	1.98 + 1.97 Cement + fly ash	2.46 + 0.27 + 0.0276 Crushed sand + CFA + EPS	1.18	0.0041 + 0.041 + 0.022 Polymer + accelerator + super plasticizer

Table 2. Physico-mechanical and functional properties of proposed products.

Product	Density	Water Absorption	Compressive Strength	Flexural Strength	Tensile Strength	Thermal Conductivity
	(kg/m^3)	(%)	(MPa)	(MPa)	(MPa)	(W/mK)
Concrete	2342	5.8	26.91	4.02	1.83	0.81
LW mix	1312	7.6	7.05	2.16	1.27	0.40
Codal compliance	IS 2185:2005 (Part 1) [35]			IS 516:1959 [36]	IS 5816:1999 [37]	ASTM C177 [38]

3. Methodology

The LCA of a residential building considers the activities starting from raw material supply, manufacturing of products, and application phase to demolition and disposal stage. This assessment provides an overview of the major environmental impacts at different phases of construction. LCA was implemented based on the ISO 14040 standard [39]. The framework includes 4 stages viz. defining goal and scope, life cycle inventory analysis, impact assessment, and interpretation of results (Figure 5). The first stage defines the goal, background, and need of the study. Inventory analysis lists the raw materials and products that are inputs at various phases of the system. Impact assessment identifies the major indicators that are responsible for environmental effects and the last stage interprets the results obtained and evaluated [40–42].

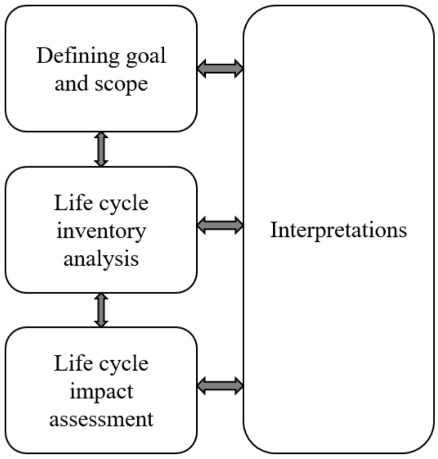

Figure 5. Framework of LCA.

Erection of Small-Scale Model House

For the purpose of evaluation of the designed products, small-scale modelling technique was applied. It is one of the established methods that demonstrated the end results to be similar to real scale methods [13,43]. Hence, a prefabricated model was scaled down to one-third of its original size and was proposed for construction. Various phases involved during the erection of the prefabricated model are shown in Table 3.

Table 3. Phases of the model house construction.

Phase Code	Name of the Phase
A	Mould preparation
B	Mixing of Concrete
C	Mixing of LW mix
D	Casting of beams and columns
E	Casting of prefabricated LW panels
F	Erection of model house
T	Raw material transport (RMT)

4. Goal and Scope of the Study

The environmental implication of the proposed prefabricated system is to be evaluated. The application of various sustainable alternates into the proposed mix designs have proved the system to be lightweight, energy efficient, and thermally insulated [34]. Hence, this study investigates the environmental effects during their production phase to on-site erection phase. The effect of the energy involved and transport during all the phases were also taken into consideration.

System Boundaries

Materials and elements were designed and transported as per the requirements of the model. System boundaries were set accordingly in regard to all the phases (Phases A, B, C, D, E, and F) mentioned earlier in Table 3. The materials and product inputs at different phases along with their respective disposals were figured out. The system boundary flowchart was developed as shown in Figure 6. Phases A to F are inter-related with materials and products moving through the process as shown in the figure. Phase T is related to material transport that eventually proceeds all along the process.

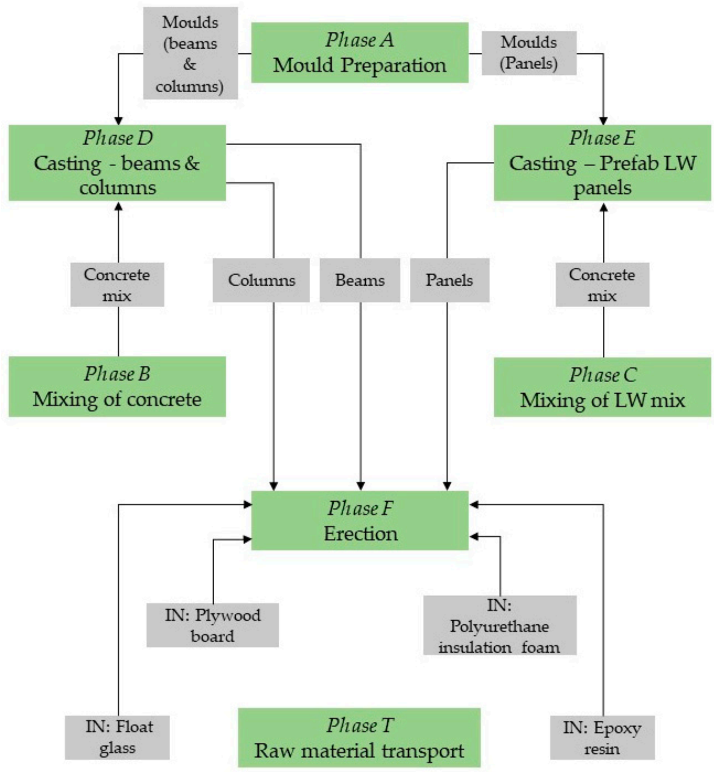

Figure 6. System boundaries and flowchart.

5. Inventory Analysis

This stage deals with all the quantified data of all the materials, products, energy, and transport that has gone into and produced from the phases. The phase-wise inventory along with the description of the phases are mentioned in this section.

5.1. Phase A

This phase involves the process of mould preparation. As the residential plan was reduced to one-third of its size, a structural plan was prepared accordingly (Figure 7). Structural elements and walling members were designed as per the plan and wooden moulds were prepared (Figure 8).

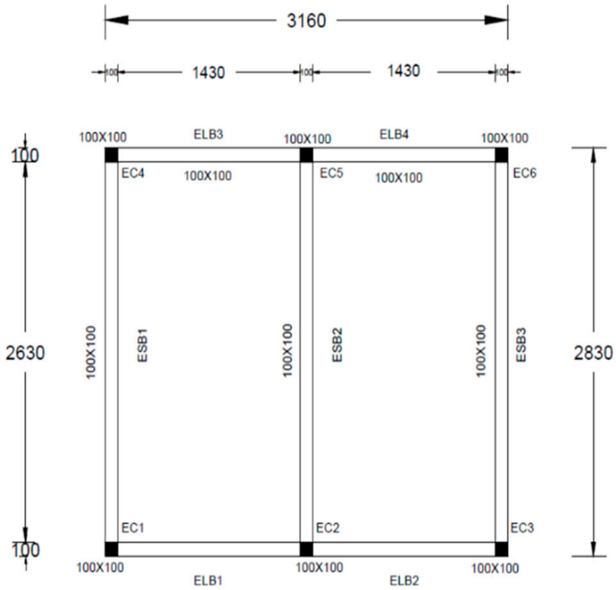

Figure 7. Structural plan of the model house.

Figure 8. Wooden moulds.

For the inventory data, inputs and outputs were figured out. Material inputs that go into the process give rise to moulds as output (Table 4). The disposal inventory was mentioned too and was given inputs to the LCA.

Table 4. Inventory details of Phase A—Mould preparation.

Sl. No.	Material Input	Quantity	Output	Quantity	Disposal	
1	Plywood	164 kg	Moulds	18 nos.	Nails (broken)—disposed into bins	0.4 kg
2	Nails	1.5 kg			Wood—some reused & some disposed	41 kg
3	Electricity (Wood cutter)	3.8 kWh			Wood—Wastage while finishing-disposed	24 kg

5.2. Phase B and C

Phases B and C involve mixing of the CFA-based concrete and LW mix, respectively. Raw materials were brought to the manufacturing plant from their source. A total of 8 and 30 batches of the optimized mix design of concrete and LW mix, respectively, were mixed in the concrete mixers (Figures 9 and 10).

Figure 9. Mixing of CFA-based concrete.

Figure 10. Mixing of CFA-based LW mix.

The raw materials utilized in this phase are listed in Tables 5 and 6. Their quantities were figured out and are given as material inputs. Energy data comprising of concrete mixer operation was calculated and presented. The capacity of the mixer, its energy rating, and time of mixing were considered for evaluating this energy inventory. Wet concrete is the resultant output in both the phases. Wastages from both phases were productively reused at the manufacturing plant.

Table 5. Inventory details of Phase B—Mixing of CFA-based concrete.

Sl. No.	Material Input	Quantity	Output	Quantity	Disposal
1	Mixer (electrical)	2 kWh	Concrete mix	465 kg	Waste concrete was cast as paver blocks (To be reused) Waste water after cleaning mixer was sprayed on gravel pathway
2	Cement	78.4 kg			
3	River Sand	108.48 kg			
4	CFA	27.12 kg			
5	20 mm gravel	117.2 kg			
6	10 mm gravel	117.2 kg			
7	Aeration Agent	0.01 kg			
8	Admixture	0.32 kg			
9	Water	37.2 kg			

Table 6. Inventory details of Phase C—Mixing of CFA-based LW mix.

Sl. No.	Material Input	Quantity	Output	Quantity	Disposal
1	Mixer (electrical)	22.5 kWh	LW mix	2110 kg	Waste concrete was cast as paver blocks (To be reused) Waste water after cleaning mixer was sprayed on gravel pathway
2	Cement	535.74 kg			
3	Fly ash	532.41 kg			
4	Polymer	1.11 kg			
5	Accelerator	5.55 kg			
6	CFA	73.92 kg			
7	EPS Beads	9.3 kg			
8	Crush sand	665.4 kg			
9	Admixture	5.94 kg			
10	Water	319.5 kg			

5.3. Phase D and E

Phases D and E involve casting of the wet concrete into the moulds. Reinforcements were placed in the moulds and concreting was done (Figures 11 and 12). After the elements were set, they were demoulded, stacked, and cured as per codal standards.

Figure 11. Casting of beams and columns.

Figure 12. Casting of prefabricated panels.

Output of phase A (mould) was used as one of the inputs for both phases D and E. Additionally, the output product from phases B and C (wet concrete) was used for placing into these moulds. The additional material inputs were figured out and stated in Tables 7 and 8. While casting these elements, no material wastage was discovered and hence, no disposal inventory was presented. Phase D utilizes a hand grinder for cutting of the reinforcement rods. Its energy data was taken into consideration. Waste oil was collected after recycling it from the automobiles of the manufacturing plant. This was used for oiling the moulds before placing concrete. Water required for curing of the products was also considered.

Table 7. Inventory details of Phase D—Casting of precast beams and columns.

Sl. No.	Material Input	Quantity	Output	Quantity
1	Concrete	465 kg		
2	8 mm rod	9 kg	Precast columns	6 Nos.
3	Mould	5 nos.		
4	Electricity (Hand grinder)	0.25 kWh		
5	Waste oil from automobiles (For oiling moulds)	Lump sum	Precast beams	7 Nos.
6	Water (Curing)	Lump sum		

Table 8. Inventory details of Phase E—Casting of prefabricated panels.

Sl. No.	Material Input	Quantity	Output	Quantity
1	Concrete LW mix	2110 kg		
2	Chicken Mesh	2.5 kg		
3	Mould	13 nos.	Prefabricated walling panels	40 Nos.
4	Waste oil from automobiles(For oiling moulds)	Lump sum		
5	Water (Curing)	Lump sum		

5.4. Phase F

This phase includes the process of erection of the prefabricated elements into a model house. The cured prefabricated elements were transported from the manufacturing plant to the site. They were placed in their respective slots as per the design (Figure 13). The elements were joined with the help of epoxy grout (Figure 14). Minor gaps after the complete erection of elements were filled with grouting material. The completed small-scale model house is as shown in Figure 15. A solar photovoltaic (PV) panel was embedded into the roof of the model with an approach of generating on-site energy to meet the in-house demands.

Figure 13. Erection of prefabricated elements.

Figure 14. Application of grouting material.

Figure 15. Small-scale prefabricated model.

This phase uses the products developed in phases D and E (prefabricated elements) to be transported and erected at site. Its respective material inventory was recorded and presented in Table 9. Polyurethane foam was used to fix the solar PV panel into the roof. No major disposal activity was found during this phase.

Table 9. Inventory details of Phase F—Erection of prefabricated elements.

Sl. No.	Material Input	Quantity	Output	Quantity
1	Epoxy grout	6 kg	Model house	1 No.
2	Grouting material	10 kg		
3	Poly urethane foam	1200 ml		
4	Plywood (Doors and windows)	20 kg		
5	Glass (windows)	1.5 kg		

5.5. Phase T

The details of transportation required for the raw materials and products at each phase were included. The transport vehicles under consideration were diesel trucks (Bharat stage IV) of various capacities based on the quantity of material being transported. The distances travelled by them were measured in real time and are tabulated as shown in Table 10. Transport of raw materials, such as CFA, EPS beads, fly ash, and others, were calculated from their origin source, whereas the transport of products, such as moulds and prefabricated elements, were calculated from the location of their manufacture to their application.

Table 10. Transport inventory distance travelled by raw materials and products.

Transport Inventory (Distances Travelled in km)											
Mould Preparation		Mixing of Concrete		Mixing of LW Mix		Casting of Beams and Columns		Casting of Panels		Erection	
Plywood	7	Cement	2	Cement	2	8 mm rod	5	Steel chicken mesh	1	Panels + Columns + Beams	32
		River sand	2	Fly ash	2					Epoxy grout	32
		CFA	37	CFA	68					Grouting material	32
Nails	7	20 mm gravel	2	EPS beads	38	Mould	35	Mould	35	Poly urethane foam	1
										Plywood (Doors and windows)	1.5
		10 mm gravel	2	Crush sand	2					Glass (windows)	1

6. Impact Assessment and Interpretation of Results

6.1. Impact Assessment

In this stage, all the collected inventory data of the small-scale model along with their disposal and transport data were evaluated. The impact on potential human health and environment was assessed. Four impact indicators viz. acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and ozone depletion potential (ODP) have been considered based on the reviewed literature. These indicators were evaluated for each phase of the executed prefabricated system. Table 11 summarizes these impacts created by all the involved phases and the total impact was calculated accordingly.

6.2. Interpretation, Results and Discussion

The outcomes from the impact assessment were analysed and interpreted. The execution of prefabricated system was found to contribute around 3.23 kgSO_2 eq., 0.42 kg Phosphate eq., 873.95 kgCO_2 eq., and 4.53×10^{-8} kg R11 eq. towards AP, EP, GWP, and ODP. From the table, it is observed that the contribution of phase C viz., mixing of LW mix towards these indicators is maximum followed by phases A and B. This implies that the phases of product development contribute more towards the indicators than the process of erection.

Table 11. Impact assessment as per phases.

Impact Indicators	Phase A	Phase B	Phase C	Phase D	Phase E	Phase F	Phase T	Total
AP [kg SO_2 eq.]	0.6440	0.2510	2.0200	0.0228	0.0055	0.1897	0.0933	3.2262
EP [kg Phosphate eq.]	0.1160	0.0302	0.2210	0.0039	0.0011	0.0268	0.0201	0.4191
GWP [kg CO_2 eq.]	130.00	75.60	565.00	18.60	5.09	57.76	21.90	873.95
ODP [kg R11 eq.]	2.37×10^{-11}	5.99×10^{-14}	4.53×10^{-8}	6.01×10^{-13}	1.67×10^{-13}	3.19×10^{-12}	2.43×10^{-15}	4.53×10^{-8}

Among the indicators, the carbon footprint is estimated from GWP, and thus, these values are further analysed. GWP of the individual CFA-based concrete and LW mix were evaluated and resulted to be 75.6 $kgCO_2$ eq. and 565 $kgCO_2$ eq., respectively. These results inclusive of the energy required for mixing and the material transport involved. As the quantities of these end products were already cited in Tables 5 and 6, GWP of CFA-based concrete and CFA-based LW mix per unit weight were evaluated. These were found to be around 0.162 $kgCO_2e/kg$ and 0.268 $kgCO_2e/kg$, respectively. Concrete and masonry products were found to be in the range of 0.08–0.5 $kgCO_2e/kg$ and 0.23–0.60 $kgCO_2e/kg$, respectively [20,44,45]. Thus, in comparison with conventional products, the developed products were found to be around the lower limits of the specified ranges. Inclusion of alternate materials, such as fly ash, CFA, and insulation material, such as EPS, have resulted in lower emissions for walling material.

The percentage contribution of each impact indicator on different phases is presented in Figure 16. Phase C viz. mixing of CFA-based LW mix was observed as the major contributor towards impact indicators. This phase was observed to be a major activity in terms of raw material involved and the quantity of output. On comparison among other phases, this phase solely contributes over 62%, 52%, 64%, and 99% to AP, EP, GWP, and ODP, respectively. Following this, the next major contributor was observed to be phase A, then phases B, F, T, D, and E consecutively.

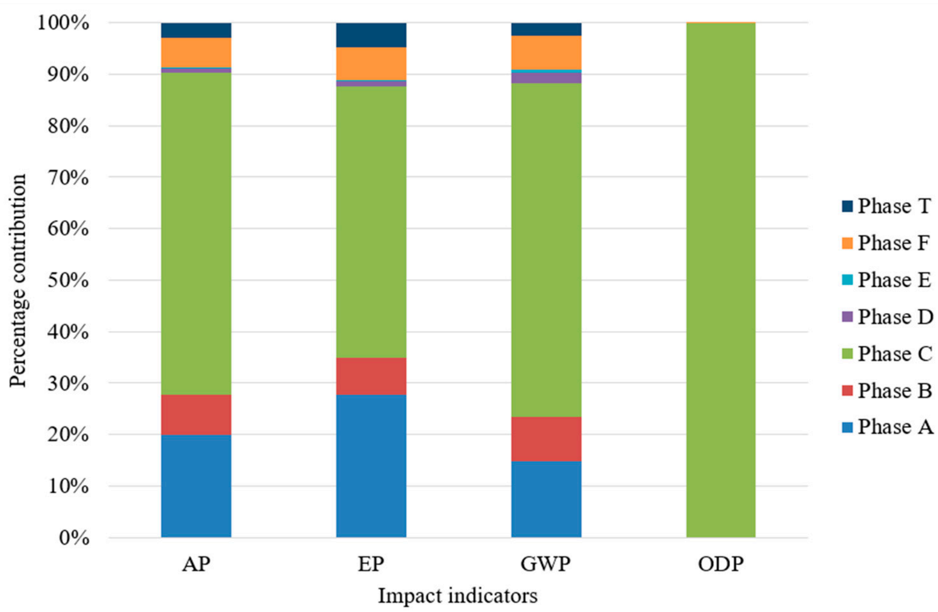

Figure 16. Percentage contribution of impact indicators on the phases of prefabricated system.

Carbon emissions were considered for both direct and indirect emissions. From the presented case study, direct emissions were calculated for energy consumption and material transport data. GWP due to the electricity during the whole process was found to be around 28.62 $kgCO_2$ eq. Thus, a 3% impact was observed from the energy required during establishing the prefabricated system. As cement, gravel, sand, and concrete are all heavy construction materials, their high-bulk nature increases the environmental impacts mostly because of the transportation [22]. The GWP impact of the material transport was evaluated and found to be 21.9 $kgCO_2$ eq., i.e., almost 3% of the total emissions.

Materials that were procured from other sources, such as cement, fly ash, gravel, crushed sand, EPS beads, and others contribute towards the carbon emissions. As these materials were not manufactured as a part of the case study, their contribution is considered indirect towards the emissions. The individual materials' carbon footprint along with their transport emissions while procuring from their source are estimated along the process of execution. This total impact was evaluated and found to contribute around 820 $kgCO_2$ eq., i.e., almost 94% of the total emissions.

7. Conclusions and Recommendations

This study has developed a prefabricated system that comprises concrete and walling material made from locally available sustainable alternates. Earlier studies on the material have proven the prefabricated walling element to be lightweight, energy efficient, thermally insulated, and quick in construction. Its structural and functional properties were found to be satisfactory as per the codal standards and applicable in the real time construction. A small-scale model house was made with these developed prefabricated elements. The life cycle assessment for the same was conducted with the help of GaBi Professional, v 10.5 software and, accordingly, data were collected and presented. The framework of LCA includes defining of goal and scope, inventory analysis, impact assessment, and interpretation of the results. The whole prefabricated system was classified into phases that involve mould preparation, mixing, and casting of CFA-based products, material transport, and erection of final end-products. The inventory details going into each phase were quantified and, furthermore, its impact on the environment was assessed. Transparency was maintained while presenting the data, which helped others to quantify and compare their results.

The design of novel sustainable products and processes have developed a need to study this LCA. The inclusion of sustainable alternates in place of conventional materials is an appropriate solution to reduce carbon emissions. Four impact indicators viz. acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), and ozone depletion potential (ODP) have been evaluated. GWP is the most studied indicator that needs to be evaluated to control carbon emissions. The CFA-based concrete and LW mixes have their carbon emissions as 0.162 $kgCO_2e/kg$ and 0.268 $kgCO_2e/kg$. Indirect emissions have contributed around 94% towards carbon emissions. Most of the raw materials were procured from various sources and the impact due to their transportation was responsible for these indirect emissions. The energy and transport contributions were found to be 3% each during the execution of the system. Overall, the phase that manufactures LW mix was found to be a major contributor towards the indicators with 62%, 52%, 64% and 99% contribution to AP, EP, GWP, and ODP, respectively. This phase was followed by the mould preparation phase with 20%, 27%, and 15% contribution towards AP, EP, and GWP, respectively. The LCA study helps in understanding the phase-wise process and recognizing the opportunity for further enhancing the process. Earlier studies have mentioned prefabricated technology to be faster, energy efficient and affordable. The results from this study imply that inclusion of sustainable and alternate materials in this technology have lowered the emissions.

The inventory data is limited to the proposed mix designs and prefabricated model. The raw materials of the system shall have a similar impact while scaling up the process. However, the transport and energy data may have a larger impact as the handling of full-scale prefabricated members requires mechanization. Since inventory analysis could vary depending on the location, it is desirable to enhance the accuracy of the LCA input data.

Author Contributions: R.C.: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft preparation; D.B.: software, formal analysis, data curation, writing—original draft preparation and reviewing; S.M.: software, data curation, writing—review and editing; A.B.: conceptualization, methodology, writing—review and editing; R.R.: conceptualization, methodology, investigation, writing—original draft preparation. All authors have read and agreed to the published version of the manuscript.

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